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Toshiaki SAWA, DIRECTOR

GEOLOGIC EVOLUTION, RESOURCES AND GEOLOGIC HAZARDS—INTERNATIONAL CENTENNIAL SYMPOSIUM OF THE GEOLOGICAL SURVEY OF JAPAN

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FOREWORD

It is my great pleasure to present this volume incorporating the papers presented at our International Centennial Symposium which was held in December 1982. At this symposium, it was most gratifying to find distinguished scientists from so may countries gathered to contribute to the discussions relating to the very wide spectrum of geosciences to-day.

Looking back when our Geological Survey was founded in 1882, it was half a century after the publication of the first edition of Charles Lyell's "Principles of Geology" and it was two years after the birth of Alfred Wegener. In Asia, it was thirty years after the establishment of the Geological Survey of India and systematic geological investigation had started in Indonesia many years before. Thus there has been a long tradition of geoscientific studies in Asia compared to other scientific disciplines, and we were not very early in systematically organizing our activities.

Now after a long cultural tradition of identifying ourselves together with nature rather than observing it objectively, our people became aware of the environment as objects of systematic study. And the growing interest in knowing the nature of our land and mineral resources for various purposes warranted the establishment of such institution.

The initial *raison d'être* for this new institution was geological mapping and the first edition of the geological map of the country at the scale 1:1,000,000 was published in 1898. The Geological Survey gradualy developed by drawing the experiences of the surveys mostly in Europe and North America, and with the turn of the century, our activities gradually expanded to include investigation of mineral resources, earthquake studies, marine geology and now we are concerned with all phases of geoscientific activity and also are involved in international cooperative work.

Through these activities, we became aware, among others, that mineral resources were not limitless as we had innocently took for granted, earthquakes became matters to be studied rather than just feared and also ocean floors became one of the most interesting frontiers of science.

During the past one hundred years, our view of the earth changed radically. Although Wegener's continental drift theory was once refuted by the geoscientific community, it is now accepted by most of us that the earth's crust does move laterally albeit from a totally different interpretation. Lyell's uniformitarianism is being considered from various aspects with approaches completely unexpected in his days. We have begun to search for the sources of various geological phenomena; concentration of mineral resources, tremors of the earth, volcanic eruptions, just to name a few. In other words, the past century had been an extremely exciting time for us geoscientists. Now, what lies ahead?

The most important aspect in conducting our work to-day is the fact that a global perspective is essential for all geoscientific efforts. All of our activities cannot be limited by national boundaries and we are now completely interdependent internationally. During the course of this symposium held within the ambitious framework of "Geologic evolution, resources and geologic hazards", we reviewed the present complex state of the art of the geosciences and the role of the geological surveys in various parts of the world and were able to obtain a glimpse of what lies ahead of us. Thanks to the efforts of the distinguished participants, I am assured that we can look forward to very exciting developments and a greater role for us in the geological surveys.

Toshiaki SAWA
Director
Geological Survey of Japan

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Gondwana Geology of Indian Plate—Its History of Fragmentation and Dispersion

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ABSTRACT

The Gondwanic rocks of India show a varied array of lithofacies spanning in age from Late Carboniferous to Early Cretaceous period and exhibit characteristic floral and faunal bondage with the homotaxial rocks of Southern Hemisphere. The fault bounded Gondwana troughs of Peninsular India are a mosaic of tilted blocks formed by major normal faults and the basin belts show broad similarity in their structural setting with that of East African Rift, Baikal Rift and Rhine Graben. Based on geophysical data, a mechanism of convective upwelling of mantle material has been invoked for Gondwana graben formation.

In the Extra Peninsular India, the faunal zones and correlative lithofacies of Gondwanic affinity occur not only in the frontal zone of the Himalayas but also in the Tethyan domain of Kashmir, Spiti, Nepal and Sikkim. It is, however, suggested that Gondwanic India, with its lithological and palacontelogical entity, extended northwards upto Indus-Tsangpo Suture and the Himalayan front is the Tethys-facing margin of Indian Gondwanic Plate.

The spatial and temporal relation of the Rajmahal volcanism with that of evolution of Late Gondwana east coastal troughs indicates that the initial phase of rifting and ocean floor spreading along the eastern margin commenced 100–105 million years ago and the ocean opening began with the continental rupture and uplift-generated triple junction formation. The fragmentation of western margin of Indian Gondwanic Plate was earlier considered to be a Late Cretaceous event but recent reappraisal of the age of Deccan volcanics, analysis of the evolutionary history of Cambay graben in the west coast and the pattern of Cretaceous marine transgression during the deposition of Lameta and Bagh beds prove beyond doubt that the fragmentation along western margin of India and the beginning of ocean floor spreading took place in Lower Cretaceous period. In other words, both the eastern and western margins of Gondwanic Plate of India bear coeval records of fragmentation and continental dispersal.

INTRODUCTION

The Gondwana rocks of Peninsular India are characterised by a thick sequence of predominant terrestrial rocks spanning in age from Upper Carboniferous to Lower Cretaceous, which have a characteristic floral and faunal bondage with homotaxial rocks of southern hemisphere. As such, the study of Gondwana and associated rocks has assumed considerable significance in the context of the recent developments in geotectonics. As a general rule, the Gondwana rocks are found occupying basin shaped depressions in older formations, each of which lies closely along a prominent river valley. The best known outcrops of Gondwana rocks are in the Damodar, Son, Mahanadi, Pranhita, Godavari and Narmada river valleys (Fig. 1). The alignments of Damodar, Son, Mahanadi Valley basins converge in the Rewa tract in the heart of Indian Peninsula. The Pranhita-Godavari Gondwana basin also extends beneath the cover of Deccan Trap lavas in Central India and the hidden extension of Gondwana basins below the Deccan volcanics in all probability runs through Gudagaon, Akot, Bhusawal, Vagadih to west coast as evidenced from a number of Gondwana inliers, supplemented by geophysical data. Besides these well defined belts, a master basin has been indentified in Rajmahal-Malda-

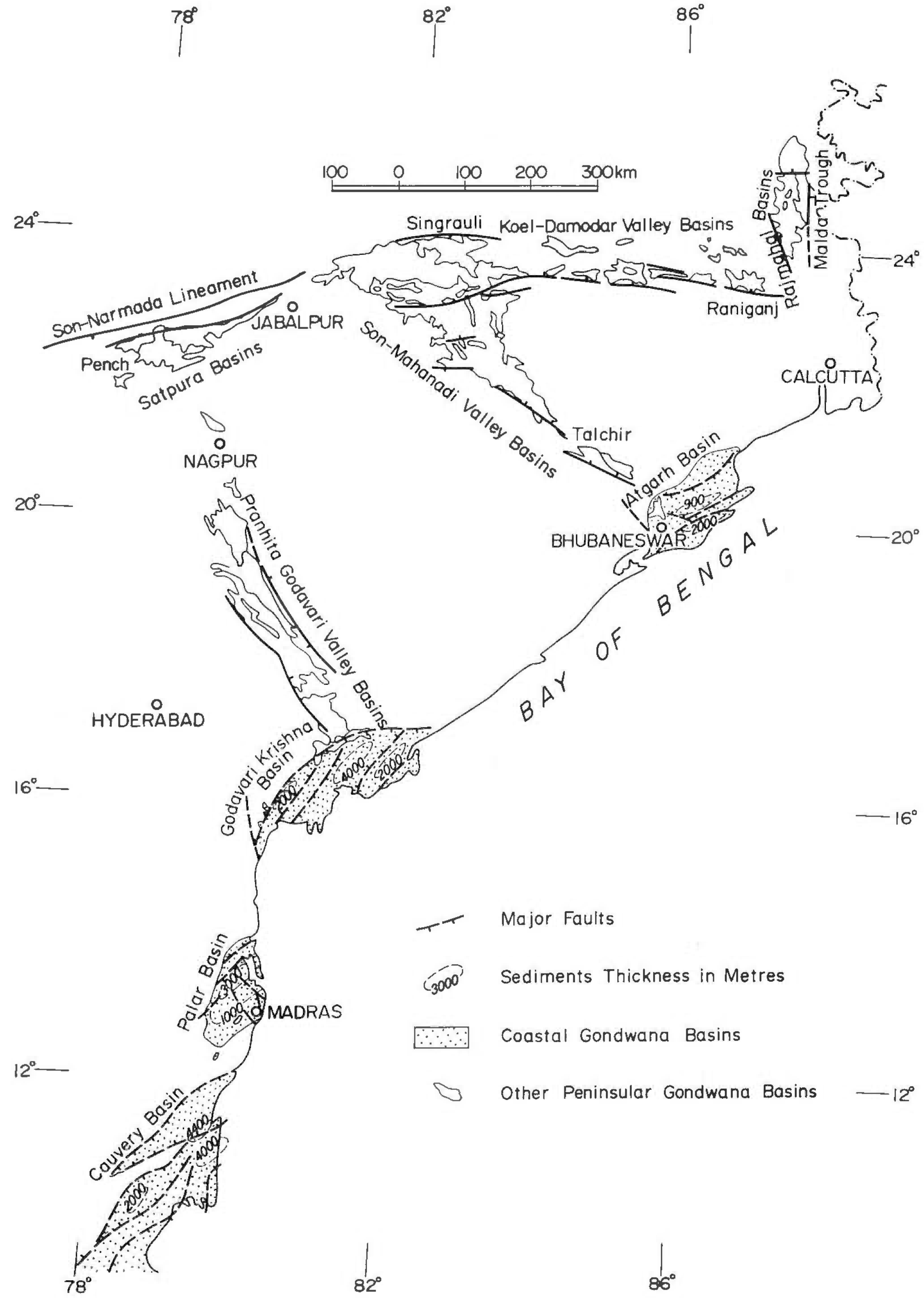

Fig. 1. Gondwana basins of east coast and Peninsular India.

Purnea area of Bihar and West Bengal, a major part of which is concealed beneath the basic volcanics, younger sediments and alluvium. The Gondwana basins of Bangladesh are apparently separate depositories.

In the Extra Peninsular region, a linear discontinuous belt of Gondwana sediments occurs along the foothills of the Himalayas from Arunachal Pradesh to Nepal. In addition, rocks of Gondwana affinity have been detected in Kashmir, Simla and Garhwal, Spiti and Nepal Himalayas.

TECTONIC SETTING OF GONDWANA BASINS

The different Gondwana basins of Peninsular India define prominent linear belts on Precambrian platform. Bouguer gravity survey along the Gondwana basins indicates that gravity lows are usually associated with Gondwana basins. A gravity survey in the Godavari and Satpura basins shows that gravity lows of the order of -50 milligals are associated with these basins (QURESHY *et al.*, 1968). The graben structure of the basinal areas is reflected by steep Bouguer gravity anomaly gradient at the basin edges. In Raniganj basin of Damodar Valley, Bouguer anomaly values of the order of -20 milligals are also reported (VERMA *et al.*, 1980). A steep gradient of the gravity contours along the southern flank of this basin also suggests that the southern boundary is steeply faulted. In South Rewa basin, gravity lows have been noted along the axial region of the Gondwana trough. The gravity surveys in the Wardha Valley have also shown that a gravity low of the order of -50 milligals is located near Wardha and the structural configuration of this basin is of a broad rift striking in a northwest-southeast direction.

The Gondwana basins of Peninsular India are composite in nature and display a complex tectonic setting of grabens, half-grabens and downwarps which have originated under varying tensional regime. The Giridih basin in Bihar provides an ideal example of narrow elongatged Gondwana graben, both the margins of which are defined by faults. In the Damodar Valley Gondwana basin, E–W trending major fault occurs over 87% of the southern margin, the remainder being accounted by overlap. Fewer and less extensive faults occur along the northern margin of this basinal area. In the Godavari Valley on the other hand, Gondwana sediments are found to be laid down in a well-defined block faulted trough. In other words, the prominent intra-cratonic Gondwana basins of Peninsular India have usually a fault bounded linear alignment. Within this broad structural framework, the Gondwana basins exhibit a mosaic of tilted blocks formed by normal faults. The major intra-basinal faults with long strike extension and appreciable throws most probably originate in the basement and they predetermine the position of the depressions, dispersal pattern of sediments and the process of sediment infilling. In fact, the growth faults, which were penecontemporaneous with sediment accumulation, have a dominant control on the distribution of facies organisation and geometry of the lithic fill. Borea fault and Govindpur-Pichri fault of Bokaro basin in Damodar Valley, Bamni-Chilpi fault in Sohagpur basin of Son Valley, Johilla fault in South Rewa, axial fault in Giridih basin etc. are but a few classic examples of such prominent intra-basinal faults of long strike extensions.

There is no consensus of opinion about the age of Gondwana faults (FOX, 1934; AUDEN, 1954; CHATTERJEE and GHOSH 1967; VERMA and SINGH 1979). Recent analysis of the major faults of the Gondwana basins, however, proves beyond doubt that these formed along the Pre-Gondwana precursor faults. The Gondwana basins of Peninsular India are again thought to mark lines of incipient crustal rupture. The evidence of fault along this prominent shear zones concomitant with sedimentation is documented by an abrupt facies change across the fault and thickening of coal seams in the down thrown block. The Bamni-Chilpi fault in Sohagpur basin for example brings in juxtaposition two different successions of varied lithology with differing metamorphism. In addition, the downthrown block of this fault, developed anticlinal closure near the faults. Likewise, in the downthrown block of the Borea fault in Bokaro basin, there is a marked increase in the thickness of the coal seams in the down thrown blocks in comparison with that in the upthrown block. Further, in the Auranga, Tatapani and Hasdo-Arand Coal Fields located in Damodar, Son and Mahanadi valleys, the movement along the boundary fault has induced rapid accumulation of fanglomerates along the flanks of the rising upland during the Lower Gondwana sedimentation (Roy CHOUDHURY *et al.*, 1975). The control of fault tectonism on Gondwana sedimentation is also well documented in the Raniganj basin. In the northwestern part of this basin, a fault marking the southern limit of the Gondwana rocks, becomes intra-basinal in the southeasterly direction. This fault defined the limit of the deposition of the lower units of the Gondwanas but during the later phase lost its dynamic behaviour when the present southern boundary fault was activated with a southerly shift of the basin axis.

The major and regional faults of the Gondwana grabens of Peninsular India are structures of Pre-Gondwana initiation. Their revival during the Gondwana sedimentation was responsible for the evolution of rift depressions. Very little studies have so far been made to decipher the major stages in the rift zone evolution of the Gondwana basins. The tectonic setting of the Gondwana basins is, however, remarkable similar to that of East African rift system, Rhine graben and Baikal rift zone. The study of the evolution of continental rift zones generally shows an identity in their deepseated formation and tectonic regimes. According to present day ideas (McCONNELL, 1977) rifting is the result of mantle process. Gravimetric and Deep Seismic Sounding (D.S.S.) in Rhine graben and East African rifts have shown it to be underlain by a subcrustal swell of mantle material. This is caused by an upwelling of anomalous mantle

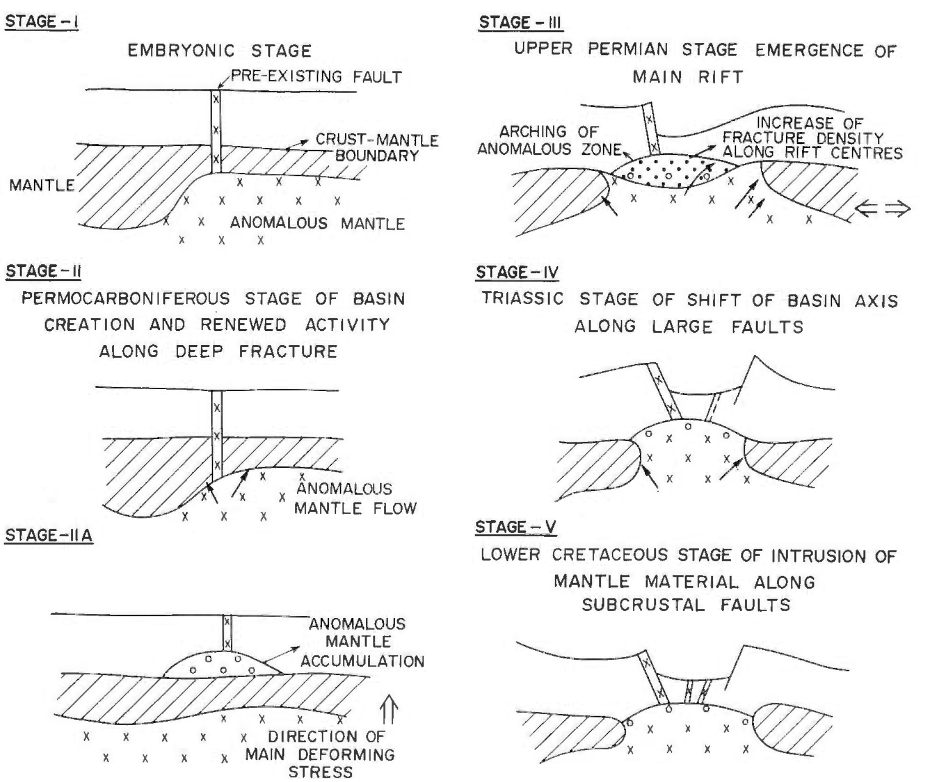

Fig. 2. Stages of Evolution of Gondwana Grabens.

through the asthenosphere. The uprise of anomalous mantle produces disjunctives in the asthenosphere and overlying lithosphere which, in turn, gave rise to extensional stresses particularly in the segment where the lithosphere is relatively thinner and cut by deep faults of antiquity (MUELLER *et al.*, 1969, ZAMARAYEV and RUZHICH, 1978). This process ultimately leads to crustal uparching and rifting. the same mechanism of convective upwelling of mantle material can be invoked for Gondwana graben formation. The recent D.S.S. profile along the Narmada graben shows the phenomenon of domal uplift beneath this graben. The anomalous mantle at depth beneath the Gondwana basins is also probably corroborated by the negative gravity anomalies. It is, however, surmised that the formation of the Gondwana rift depressions begins with the concomitant uprising of the mantle material. After a period of ensuing cooling new faults are formed and as such the formation of the Gondwana rifts is deemed to be a complex phenomenon.

Several stages of fault generation in course of the evolution of Gondwana basins have been identified based on the study of the nature of faults, history of igneous activities and nature of the lithic fill (Fig. 2). In the early stage of basinal evolution in Lower Permian period, the deepseated faults are reactivated during the upwelling of anomalous mantle material through the asthenosphere. This may be defined as the embryonic stage of Gondwana basin evolution and the rift zone morphology at this time was defined by shallow rift depressions. In the second stage (Upper Permian), the anomalous mantle flow caused renewed activity along existing faults and also favoured formation of transverse normal faults and oblique-slip faults. At this stage the Gondwana basins have asymmetric profile with deposition of thicker sediments near the boundary fault. The third stage of the graben evolution is denoted by major fracturing in the central segments of the rift zones in Triassic period. The basins become restricted along the rift axis due to the emergence of major faults along them. The final stage of this rift development is distinguished by local eruption of volcanic lava and intrusion of basic and ultrabasic bodies along extensional fissures in Lower Cretaceous period.

EXTRA PENINSULAR REGION

In the Extra Peninsular region, the detached exposures of Gondwanas are known from the frontal zone of the Eastern Himalayan foothills, window zone of Sikkim and from the Tethyan domain of Kashmir, Spiti, Nepal and Sikkim. The most well developed Gondwana rocks are in the Eastern Himalayas where they occur in two well defined tectonic belts. It is disposed as a schuppen belt in Darjeeling and Jalpaiguri area of North Bengal. This linear belt continues further east as a persistent litho-tectonic unit in Kameng, Subansiri and Siang districts of Arunachal Pradesh. The Gondwanas are also well exposed in the inner tectonic belt as isolated tectonic windows in the Rangit Valley in Sikkim and Kuruchu Valley in Bhutan.

The Gondwanas of the Eastern Himalayas occur as superficial nappes over-riding the autochthonous Siwalik Group (Miocene to Pleistocene) along the Main Boundary Fault. The Gondwana Formations are themselves overridden in turn by older rocks - the Daling Formation, Buxa Group, Miri Formation etc. Usually, the thrust plane is inclined northward at angles of 50° to 60°. The northern tectonic contact of the Gondwana sequence with the older formations is also defined by prominent thrusts. Leaving aside the two major tectonic contacts, subparallel east-west trending tectonic planes are also noted within the Gondwana sequence.

In the Rangit Valley in Sikkim, the Gondwana Formations rest unconformably on the older Proterozoic rocks but in the major part of the area, the contact of the Gondwana sequence with the older rocks is defined by a tectonised zone and the rocks are exposed in the form of a window.

All the rock units of the Gondwana succession are deformed by multiple folds. A set of east-west trending fold axis is seen to be refolded with almost perpendicular fold axis. This trend of fold axis, which is well preserved varies from NW–SE to NE–SW. The entire area is finally seen to be folded with east-west trending major folds.

In the Tethyan domain of the Eastern Himalayas, lying to the north of the central crystallines, continuity of continental and shallow marine Gondwanas have so far not been reported. But in the Lachi Series, the occurrence of diamictite horizon similar to those of the foothills is well known. The Lower Permian and Upper Permian marine fossils are also reported to have been found below the Lachi Pebble Bed and some plant remains are reported from the sandstones overlying the Lachi Beds. Beyond this, there is no unequivocal proof of the development of rocks of typical Gondwana affinity in the Tethyan domain of the eastern part of the Himalayas.

In the Tethyan domain of Kashmir, the Gondwana belts are represented by agglomeratic slates and beds containing Gangamopteris flora. The Permian Gondwanas of Kashmir are also interbedded with the Panjal Trap. The rocks of Gondwana affinity are also noted in the Blaini diamictites of the Simla Himalayas. The Late Palaeozoic diamictites, similar to those found in the Himalayas as well as rich Glossopteris Flora, are recorded from north of the Mount Everest (ACHARYYA *et al.*, 1979). It is, therefore, postulated by some workers (GANSSER, 1964) that Gondwana flora and fauna extend deep inside Asia upto the Indus-Tsangpo suture which is normally believed to define the northern limit of Gondwanic India.

STRATIGRAPHY OF GONDWANA BASINS OF PENINSULAR INDIA

The Gondwana basins of Peninsular India define prominent grabens on the Precambrian platform. The process of growth of these basins, was initiated and continued through a regional tensional regime and the sedimentation and faulting were concomitant over a greater part of the time. But the tectonic impulse was not continuous but spasmodic in nature. As sedimentation progressed in the fault-bounded linear belts, recurrent uplift along the rift shoulders created varying tectonic regime. This movement took place at varying rates in space and time. In other words, tectonic movements in different Gondwana basins of Peninsular India were waxing and waning at intervals. This is manifested in the local development of intraformational breaks and unconformities. An analysis of the structural style and the stratigraphic framework of the Gondwana basins of India, permits identification of several well defined domains of sedimentation with similar tectono-sedimentological history (Fig. 3).

Rajmahal-Malda-Purnea-Galsi Basin

This basin stretches over 10,000 sq km from east of the Damodar Valley basin to North Bihar beneath the cover of the Gangetic alluvium. The Gondwana sedimentation in this master basin was initiated by the deposition of glacial and peri-glacial sediments of Talchir Formation. The domain of sedimentation, however, attains its maximum extent during the deposition of the overlying Barakar Formation. This formation included thick coal seams (up to 40 m) and a repetitive sequence of arkose, carbonaceous shale and siltstones. Following the deposition of Barakar Formation, the depositional site was exposed to sub-aerial weathering and denudation which continued till the end of the Permian period. During the Lower Triassic period, a thick sequence of (800–900 m) Panchet Formation was developed in this north-south trending basin belt. The Panchet Formation comprise a thick sequence of chocolate clays, mottled green sandy clays and brownish sandstones. Following the deposition of Panchet sediments there was sub-aerial erosion and then the sedimentation commenced in the Upper Triassic period resulting in the deposition of 150 m thick sequence of Dubrajpur Formation. There is a prominent hiatus in the geological record after the deposition of Dubrajpur Formation. In the Lower Cretaceous period, this master basin was the site of widespread volcanic activity popularly known as Rajmahal volcanism. The Rajmahal volcanics in all probability extended further east upto Sylhet in Bangladesh. The flora of the intratrappean within the basalt pile as a whole has been dated as Middle Jurassic to Early Cretaceous (SASTRI

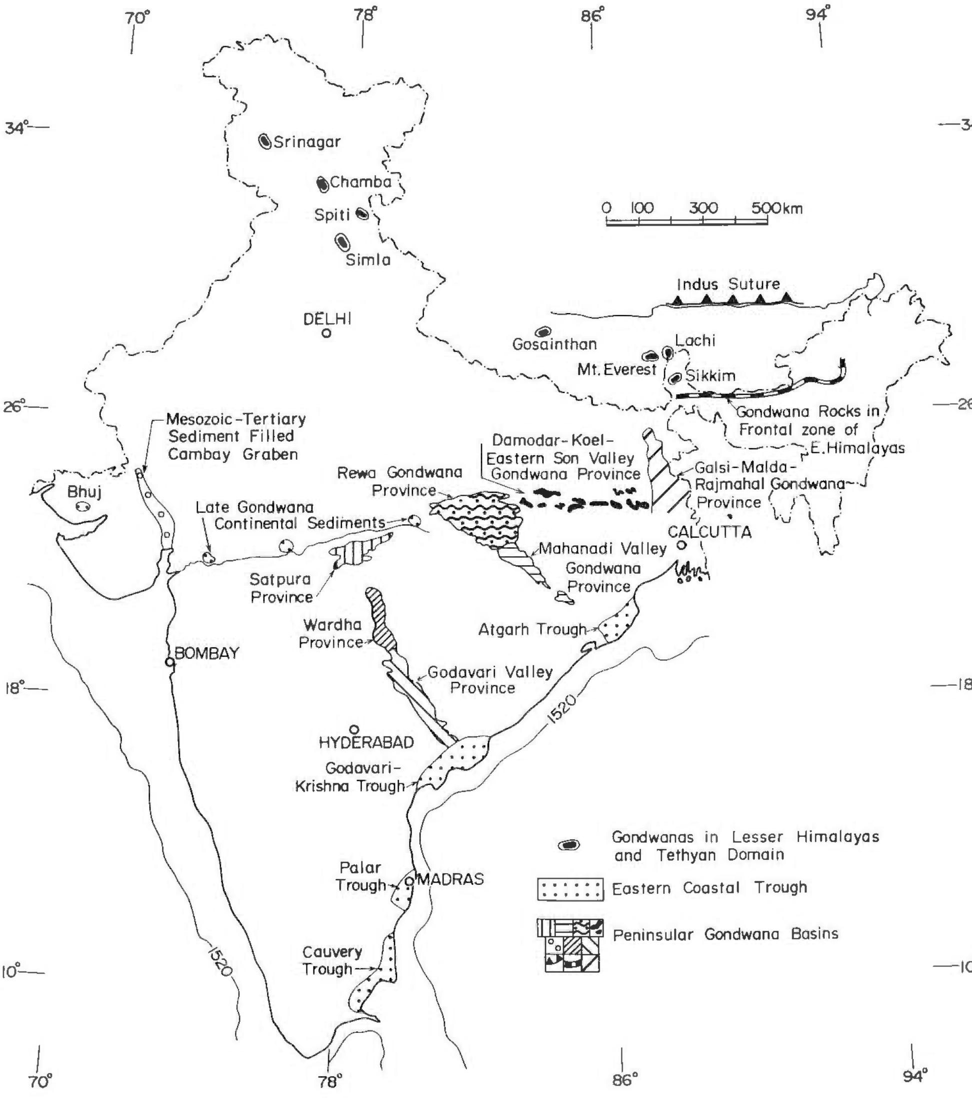

Fig. 3. Different Gondwana Provinces of Peninsular and Extra Peninsular India.

et al., 1977). McDougall and McElhinny (1970), however, reported concordant K–Ar ages of 100–105 million years for Rajmahal volcanics. This radiometric data shows Albian to Aptian age for the Rajmahal volcanics.

Damodar-Koel-Eastern Son Valley Province

This Gondwana sedimentary province comprises the Damodar Valley and adjoining Koel Valley basins and the Tatapani-Ramkola basin of Eastern Son Valley. There is a subsidiary parallel belt comprising Deogharh, Giridih and Daltonganj to the north. These basinal areas show the classic development of basal Talchir Formation and Permian coal measures-Karharbari, Barakar and Raniganj Formations. The major coal bearing unit, the Barakar Formation, has attained its maximum development in the central segment of this sedimentary basin where 900 to 1200 m of Barakar Formation is preserved. The Barakar Formation is succeeded by

400 m–600 m thick horizon, devoid of any coal seam which is popularly described as Barren Measures. Some segments of this province also show development of Upper Permian Raniganj Coal Measures.

The advent of Triassic heralded the deposition of Panchet Formation which rests over the Permian Raniganj Formation with an apparently conformably contact. Recent studies on the Permo-Triassic boundary in this province show that there may be a local break between the Permian and Triassic sequence. The Panchet Formation characterised by red bed and arkose association contains typical Triassic flora as Dicroidium and yield vertebrate fauna which include dicynodont Lystrosaurus and primitive cynodonts of Early Triassic age. (SASTRI *et al.*, 1977). Following the deposition of Panchet rocks, the basinal area witnessed a break in sedimentation in the Middle Triassic Period. The youngest unit of the Gondwana sequence of this sedimentary province is defined by a sequence of coarse conglomerates, ferruginous sandstones and red shales which has been described as Supra-Panchet Unit. This succession rests over the denuded surface of the Panchet Formation and is bereft of any identifiable fossil remains. The Gondwana sedimentation in this master basin ceased in all probability by the end of Triassic period. Nevertheless, this basin belt experienced volcanic activity in the form of intrusion of lamprophyre sills and dykes and dolerite dykes. The period of intrusion of the lamprophyres has been dated as 105–121 million years (SARKAR *et al.*, 1980).

Mahanadi Valley Basin

This province stretches from Talchir basin in Mahanadi valley across the Mand-Raigarh to Korba and Hasdo-Arand basins in Madhya Pradesh. This master basin forms the type area of glacial and periglacial Talchir Formation (BLANFORD *et al.*, 1856). This basinal area witnessed widespread advancement of glaciers from the different gathering grounds of ice and the Talchir sediments show a fairly thick development in the palaeo-topographic lows. The Talchir sequence has attained acme of development in this basin belt and a maximum thickness of 450 m is recorded from Hasdo-Arand basin. The Talchir sequence is succeeded by Karharbari coal measures which is a distinct lithological and palaeontological entity in this basin. The Barakar Formation forms the bulk of the clastic fill of this master basin and is characterised by very coarse feldspathic sandstones, carbonaceous shales and coal horizons as thick as 180 m. The Barakar sediment is conformably overlain by a thick sequence of black and grey shales with sandstone interbands and is considered to be homotaxial with the Barren Measures of the Damodar Valley basin. This, in turn, is overlain by Kamthi Formation which shows two broad lithological associations in its compositional make up. The Lower 250 m of the sequence is characterised by alternation of arkosic sandstones, grey shales, thin coal seams, ferruginous shales and shows a profusion of the Lower Gondwana plants. The upper unit of Kamthi Formation rests apparently with an angular discordance over the underlying sequence and shows a preponderance of ferruginous sandstones, pebble beds and red shales. A critical re-examination of the sedimentary organisation of the Kamthi Formation proves beyond doubt that the upper and lower successions are separated along an erosional surface. Based on fragmentary palynological evidence, it is visualised that this erosional contact may denote the Permo-Triassic boundary in this Mahanadi Graben. After the deposition of the upper member of Kamthi Formation this sedimentary province lost its dynamic behaviour and sedimentation ceased by the end of the Early Triassic period.

Rewa Basin

This basin occupies the heart of Indian Peninsula and includes in its ambit the major Gondwana basins of Son Valley. A large tract of this sedimentary province is covered by Talchir Formation which exhibits a wide spectrum of lithofacies. The dominant palaeogeomorphic features of this basinal area during the Talchir sedimentation were characterised by a very rugged basement topography dissected by subparallel E–W trending ridges, which were the gathering grounds of ice (CHOUDHURY, 1979). After the retreat of ice, this basement topography controlled the development, extent and nature of sediment infilling of the Karharbari Formation. The palaeovalleys excavated by advancing glaciers were infilled by pebbly sandstones and coarse arkose and conglomerates. The Karharbari Formation is succeeded by the Barakar Formation which does not show development of very thick coal seams as noted in other Gondwana provinces. Evidently the basins experienced repeated tectonic pulsations during the Barakar Formation which does not favour accumulation of thick coal seams. Succeeding the deposition of Barakar rocks, this basinal area witnessed uninterrupted deposition of thick sequence of rocks of Pali Formation, Recent reappraisal of the stratigraphic status of the Pali Formation shows that this unit corresponds to a tripartite subdivision, the lower, middle and upper Pali Members. The lower member with a sequence of greyish sandstones and variegated clays can be considered to be equivalent of Barren Measures of the type area on the evidence of miospore assemblage. The middle Pali Member shows development of impersistent coal seams and has rich floral assemblage of Upper Permian affinity. Recent geological studies, however, indicate that the middle Pali Member includes the classical Nidpur beds of Singrauli Coal Field, where several species of *Dicroidium* have been reported along with *Glossopteris, Vertebraria*, etc. This Nidpur flora is dated a little younger than Early Scythian (Roy CHOUDHURY, *et al.*, 1975). It is, therefore, reasonable to assume that the middle Pali Member straddles across the Permo-Triassic boundary and extends into Lower Triassic period. The upper Pali Member is conspicuously a 400 m thick sequence of ferruginous sandstones, green and red shales and siltstones. This member has yielded reptilian remains *Metaposaurus maleriensis, Pachygonia incurvata, Paradapedon huxleyi* and *Phytosaurus maleriensis* in the type locality of Tiki village. This faunal assemblage has been dated as Carnian to Lower Norian (CHATTERJEE and Roy CHOWDHURY, 1974). Thus, a large part of this sedimentary province witnessed sedimentation of Pali Formation from Late Permian to early Norian period without any recognisable hiatus in sedimentary succession

The Pali Formation is, in turn, succeeded unconformably by Parsora Formation which comprise medium to coarse grained sandstones, pebbly beds and violet to lilac coloured shales with a maximum thickness of 500 m. This formation has a rich floral assemblage viz. *Dicroidium odontopteroides, Pterophyllum Sahni* and *Marattiopsis sp.* which are dated as Rhaetic (ROY CHOWDHURY, *et al.*, 1975). Over the major part of this province the sedimentation ceased subsequent to the deposition of the Parsora Formation. But the northwestern extremity of this basin belt became the locii of accumulation of a thin unit of white sandstones and shales after a pronounced hiatus. This youngest formation designated as Bansa bed has yielded rich floral remains of *Ptilophyllum acutifolium, Onychiopsis paradoxus* and *Weichselia reticulata* which suggest a Lower Cretaceous age. It has been visualised that this restricted occurrence of upper Gondwana sediments of Early Cretaceous age in the northwestern extremity of this sedimentary province took place in response to resurgence of tectonic movement along the Son-Narmada lineament which represents a subcrustal fracture of great antiquity (RAO and MITRA 1978).

Godavari Basin

This NW–SE trending major sedimentary basin preserves a record of sedimentation of Permian, Triassic and Jurassic Gondwanas and as such is remarkably unique from other Gondwana sedimentary provinces. This basin documents widespread advances of glaciers along the periphery of the basin during the initiation of Gondwana sedimentation. During the Barakar period, the domain of sedimentation progressively widened over larger areas in this basin belt. The Barakar sediments show an intimate interbedding of coal, coarse sandstones and shales. They are succeeded by a 500 m thick unit of greenish sandstones with subordinate shales, which have been relegated to the Barren Measures as this unit is remarkably devoid of any coal seams. Succeeding the Barren Measures is the Kamthi Formation which has a large areal spread in this basin and attains its maximum development of 1400 m. Based on the gross lithological characters, this formation can be further subdivided into lower, middle and upper units. The lower unit (250 m.) is characterised by development of coal seams and has distinct floral assemblage of Raniganj affinity. The lower coal bearing member grades upward into a thick monotonous sequence of greenish sandstones and variegated shales which define the middle Kamthi Member with a thickness of 800 m. This member contains floral elements which are conspicuously developed in the upper units of Raniganj Formation of the Damodar Valley. The upper Kamthi Member shows coarse, arenaceous facies and is comprised of coarse grained sandstones, conglomerates, ferruginous sandstones and brick red siltstones. At places, the upper member overlaps older formations and as such its contact with the underlying unit of Kamthi Formation is considered to be a disconformable one. The Kamthi Formation contains the only reported Permian reptile *Kistecephalus* of Upper Permian age.

The Kamthi Formation grades upward conformably into a thick sequence of red clays, sandstones and lime pellet conglomerates which are grouped together as Maleri Formation. This formation has yielded a rich vertebrate fauna permitting identification of three well defined biozones. The lower Yerapalli biozone contains *Dicynodonts, Wadiasaurus indicus* and *Rechinisaurus cristarhynchus*, a cynodont tooth and the amphibian *Parotosaurus rajreddyi* (JAIN, *et al.*, 1964 CHATTERJEE and Roy CHOWDHURY, 1974). The dicynodonts and amphibian fauna indicate a Middle Triassic age.

The concordant contact between Yerrapalli biozone with the underlying Kamthi Formation points to the fact that the upper Kamthi Member extends upto Lower Triassic period. The Middle Maleri biozone includes Amphibians-*Metaposaurus maleriensis*, Reptiles-*Paradapendon huxleyi, Malerisaurus robinsoni*, and *Parasuchus hislopi*. The uppermost Dharmaram biozone of Maleri Formation has yielded condontosaurid *Prosauropod* and two more *Archosaurus* teeth. On the basis of occurrence of *Plateosaurus*, the top bed of the Maleri Formation is considered to be late Upper Triassic, i.e. Upper Norian to Rhaetic in age (KUTTY and Roy CHOWDHURY, 1970). Evidently, unlike the other sedimentary provinces, the Godavari basin displays an uninterrupted succession of Triassic Gondwanas with its unique history of reptilian evolution. Further, the basin also bears the only record of Lower Jurassic continental Gondwana sediments denoted by Kota Formation. It comprises medium to coarse grained sandstones, variegated and red clays and limestones. The floral assemblage of the Kota Formation includes *Ptilophyllum, Equisetites* sp., *Sphenopteris* sp., *Otozamites* sp., and *Araucarites cutchensis*. The fauna comprises fishes i.e. *Tetragonolepis* and *Paradapedium* which indicate a Lower Jurassic (Liassic) age (JAIN, 1973). The Sauropod dionosaur found in this also corroborates the Lower Jurassic age. After the deposition of the Kota Formation, there was widespread erosion during the remaining part of Jurassic period. In the Early Cretaceous period, there was deposition of arkosic sandstones, white clays and conglomerates of Gangapur and Chikiala Formations. These beds have yielded a floral assemblages which includes *Cladophlebis indica, Thinnfeldia odontopteroides, Ptilophyllum acutifolium, Otozamites* sp. and *Nilssonia* sp. Based on this, an age between Late Jurassic and Early Cretaceous is inferred for these beds. It is evident that the younger Gondwana formations occur successively towards the north-western part of this basin which points to a shifting of the basin axis towards the northeast with time.

Wardha-Kamptee Basin

The Pranhita basin and its northerly extension upto Kamptee in Central India, represents a distinct tectono-sedimentary province of the Gondwana sedimentation, despite its physical continuity with the Pranhita-Godavari basin. This basin belt is segmented into three subparallel troughs-Wardha trough, Bander trough and Umrer trough, which bear similar records of sedimentation. In this basin, the Talchir Formation and overlying Barakar sequence are well developed. There is evidence of widespread denudation after the deposition of the Barakar rocks. As a result, the overlying units of Kamthi Formation composed of ferruginous sandstones, red and mottled shales rest over the eroded part of the Barakars with an angular discordance. Consequent upon pre-Kampthi erosion, the records of upper units of Barakar Formation have also been obliterated. This basinal area thus documents a unique evidence of well defined stratigraphic hiatus at the top of the Lower Permian sequence. There is a reported occurrence of a skull of Labyrinthodont-*Brachyops Laticeps* and *Concostrachans* of Lower Triassic affinity. Based on the lithologic affinity and the palaeontological evidence, it is surmised that the Kamptee sequence of Wardha Valley represents the upper member of Kamthi Formation of the Godavari Valley. In other words, this denotes a major break in sedimentation and erosion (Upper Permian) during which Barren Measures and lower and middle units of Kamthi were deposited elsewhere.

Satpura Basin

This province encompasses the Gondwana basin along the drainage of Pench, Kanhan and Tawa rivers. The nothern limit of this basin belt is defined by Narmada lineament while its western extension is not precisely known due to the cover of Deccan Traps. The Permian succession of this basin is denoted by Talchir, Barakar, Motur and Bijori Formations. The Barakar Formation is characterised by dominance of sandstones with a few coal seams. It is succeeded by Motur Formation which is composed of red and variegated shales and ferruginous sandstones. This unit is generally considered to be homotaxial with the Barren Measures of the type area. The Bijori Formation overlying the Motur Formation comprises shales which are often carbonaceous, this coal seams, micaceous sandstones and siltstones. This formation has yielded a labyrinthodont-*Gondwanosaurus bijoriensis* of Upper Permian affinity. Based on available palaeontological evidence this formation is considered to be broadly homotaxial with the Raniganj Formation. The Bijori Formation is, in turn, overlain by Pachmarhi Formation which is characterised by thick units of coarse pebbly sandstone and red siltstones. This formation has yielded the typical Lower Triassic Concostrachans *Estheriella*. (GHOSH, personal communication). The Pachmarhi Formation is conformably overlain by Denwa Formation which is characterised by a sequence of red and variegated shales and brownish ferruginous sandstones. This has been assigned a Middle Triassic age based on the find of a reptilian bone of a Parotosaur (CHATTERJEE and Roy CHOWDHURY, 1974). The Denwa clays are succeeded by Bagra conglomerates which contain pebbles of granite, quartzite and also of Vindhyan rocks. There is a well defined hiatus at the top of the Bagra conglomerates and the sedimentation commenced again in the Lower Cretaceous period when the feldspathic sandstones and white clays of Jabalpur beds were deposited. The nature of sedimentation in the Satpura, Proves beyond doubt, that the locli of sedimentation shifted progressively towards north in this sedimentary province.

Coastal Gondwana Troughs

These basins are disposed mainly in the east coast and locally in the west coast in Cutch area. This includes the troughs in Cauvery, Palar, Godavari-Krishna and Athgarh along the east coast. Some of these basins, as Palar and Athgarh, bear undoubted evidence of Talchir glaciation but no younger Permian and Triassic sediments have been preserved in these coastal troughs. These were the milieu of fluvial and near shore paralic sedimentation in early Cretaceous period. The Lower Cretaceous sediments show an interplay of fluvial, lagoonal and paralic environment depending upon the oscillation of the marine strand lines. The tectonic history and mode of sediment infilling in these troughs would be discussed in length while analysing the evidences of the rifting of Gondwanic India.

HIMALAYAN GONDWANA PROVINCE

The Gondwanas in the Himalayan belt occur in two distinct tectonostratigraphic domains. It occurs as a distinct linear belt in the foothill belts of the Eastern Himalayas and also as isolated tectonic windows in Rangit Valley in Sikkim and Kuruchu Valley in Bhutan. The rocks of Gondwanic affinity have also been identified in the Tethyan domain of the Himalayas. In the foothill belt of the Eastern Himalayas, the Gondwanas occur as a discontinuous belt in Darjeeling and Jalpaiguri between the Jaldhaka and Chamurchi in Bhutan and as a persistent lithotectonic unit in Kameng, Subansiri and Siang districts. The basal unit of the Gondwanas in this belt is defined by Rangit pebble slate (ACHARYYA, 1971). This facies, in fact, shows a complete lateral gradation from pebbly mudstone to layered argillite containing dispersed clasts. In Subansiri and Siang districts, marine fossils like *Conularia, Productus, Spirifer* etc. have been recorded from the black shale immediately overlying this pebble bed. These units are overlain by a thick sequence of greyish white to brownish yellow sandstones, carbonaceous shales, grey shales and lenses of coal. The lithological association of this facies, as well as the floral remains show close similarity with those of Damuda rocks of Peninsular India.

Concomitant with the deposition of these Gondwana sediments, spasmodic volcanism took place in this Foot Himalayan belt of Arunachal Pradesh. The volcanic paroxysm reached its peak in the Siang district. The volcanism is known as Abor volcanism (Fig. 4). This com-

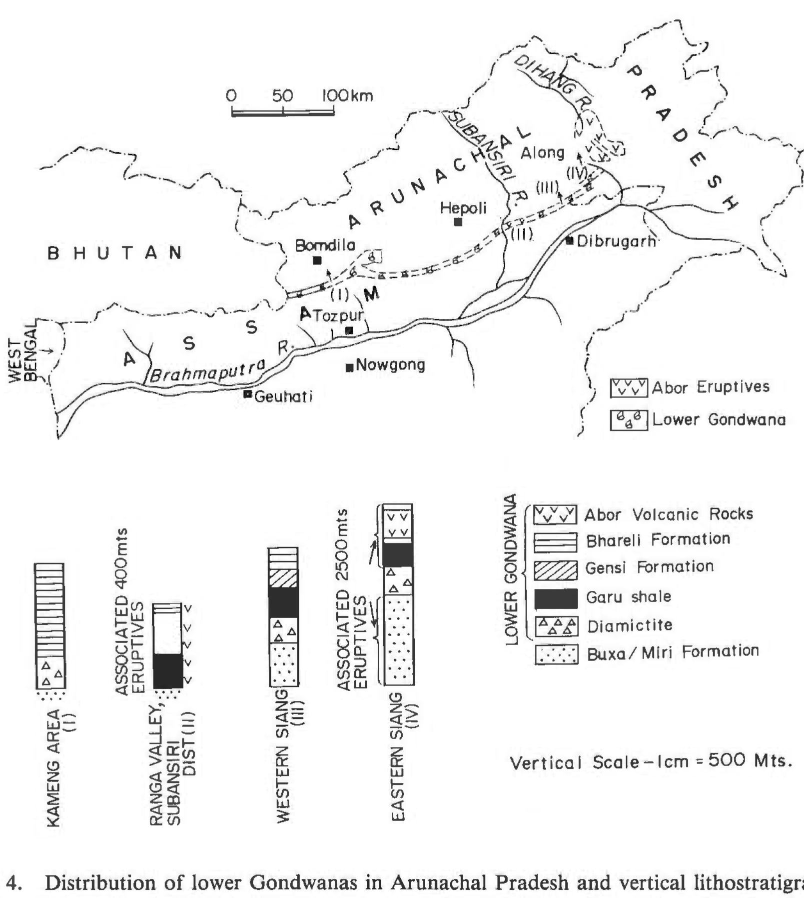

Fig. 4. Distribution of lower Gondwanas in Arunachal Pradesh and vertical lithostratigraphic organisation of lower Gondwana Group.

prises a thick sequence of basaltic to andesitic aa-type lavas and agglomerates. A few black shales associated with the Abor volcanics have yielded sporomorphs of lower Gondwana affinity. This volcanic suite associated with the Lower Gondwanas has often come in Juxtaposition with the younger volcanic rocks of undoubted Tertiary age along tectonised contact. This has introduced an element of uncertainty in assigning the proper chronostratigraphic status of the Abor Volcanics.

In the inner tectonic belt of Sikkim, the Rangit pebble slate is well exposed. Marine Permo-Carboniferous fossils are found within this pebble bed in the Rangit Valley window, on the basis of which, its correlation with the Lachi Series of Tethyan sequence of Sikkim is suggested (SAHNI and SRIVASTAVA, 1956) and the idea of Gondwanic influence in the Tethyan domain of Sikkim followed (GANSSER, 1964). This pebble slate is succeeded by Damuda rocks containing floral assemblage dominated by Glossopteris. These Damuda rocks have also been reported in western Bhutan (ACHARYYA, 1979). The Gondwana pebble slate with coal bearing Damudas is also known from the Lower Himalayas of Nepal but its stratigraphy and structural relation with the associated rocks are not clearly understood.

In the Kumaon and Garhwal Himalayas, the Blaini Formation is considered to be the equivalent of Rangit pebble slate. In the Garhwal Himalayas, the boulder slate sequence of the lower Bijni unit has yielded a rich marine fauna of Bryozoa and Brachiopoda which is comparable with the Subansiri fauna of Arunachal Pradesh (ACHARYYA *et al.*, 1979). This points to the Gondwanic influence in Lesser Himalayan domain of Western Himalayas.

The most ideal development of Gondwanas in the Tethyan domain is known from the Kashmir Himalayas. The Permian Gondwana sequence of Kashmir includes the Agglomeratic slate and the overlying Gangamopteris beds. The Gangamopteris bed is characterised by a vertebrate fauna *Archaegosaurus, Actinodon* and *Chelydosaurus* and the plant fossils showing a dominance of Gangamopteris. In the younger beds, the frequency of Gangamopteris diminishes and a number of species of Glossopteris appear (NAKAZAWA *et al.*, 1975). The Gondwanas are closely associated with the Panjal volcanics, which are now regarded to be of Sakmarian to Kungurian in age based on the information from intercalated fossiliferous horizons (NAKAZAWA, *et al.*, 1975). In Chamba area of Kashmir, the agglomeratic slates with similar fauna have been reported.

In the Spiti area, conglomeratic horizons have been recorded which are correlated with agglomeratic slates of Kashmir (ACHARYYA and SHAH, 1975). This proves the extension of Gondwanic influence in the Tethyan domain of Spiti.

The Gondwana pebble beds and ssociated facies are reported from the Higher Himalayas of Nepal. Lenticular horizons of conglomerates with coaly beds are reported from Thinichu Formation in the Thakkhota Tethyan domain. In the Tethyan zone of Sikkim, the Lachi Formation defines a conspicuous lithostratigraphic unit. It is correlated with the Blainis of the Lower Himalayas and Talchirs of Peninsular India. The faunal association of the Lachi beds also shows a good correlation with those of Talchir marine beds of Daltonganj and Umaria. Glossopteris is also reported from the northern face of the Everest area (ACHARYYA *et al.*, 1979). It is, therefore, emphasised that floral and faunal similarity exists between the rocks of Gondwanic affinity of Lesser and Tethyan Himalayas with those of essentially continental Gondwanas of Peninsular India.

BROAD STRATIGRAPHIC FRAMEWORK

An analysis of the sedimentary framework of the Gondwana rocks of different Peninsular basins proves beyond doubt that sedimentation manifestly took place at varying rates in space and time (Fig. 5). These basins attained their acme of development during Barakar sedimentation and the basinal areas subsided in response to major epeirogenic impulse in Barakar time. The domain of Gondwana sedimentation in the sedimentary provinces of Damodar, Rewa, Godavari and Satpura continued to have fluvio-lacustrine environment in post Barakar period

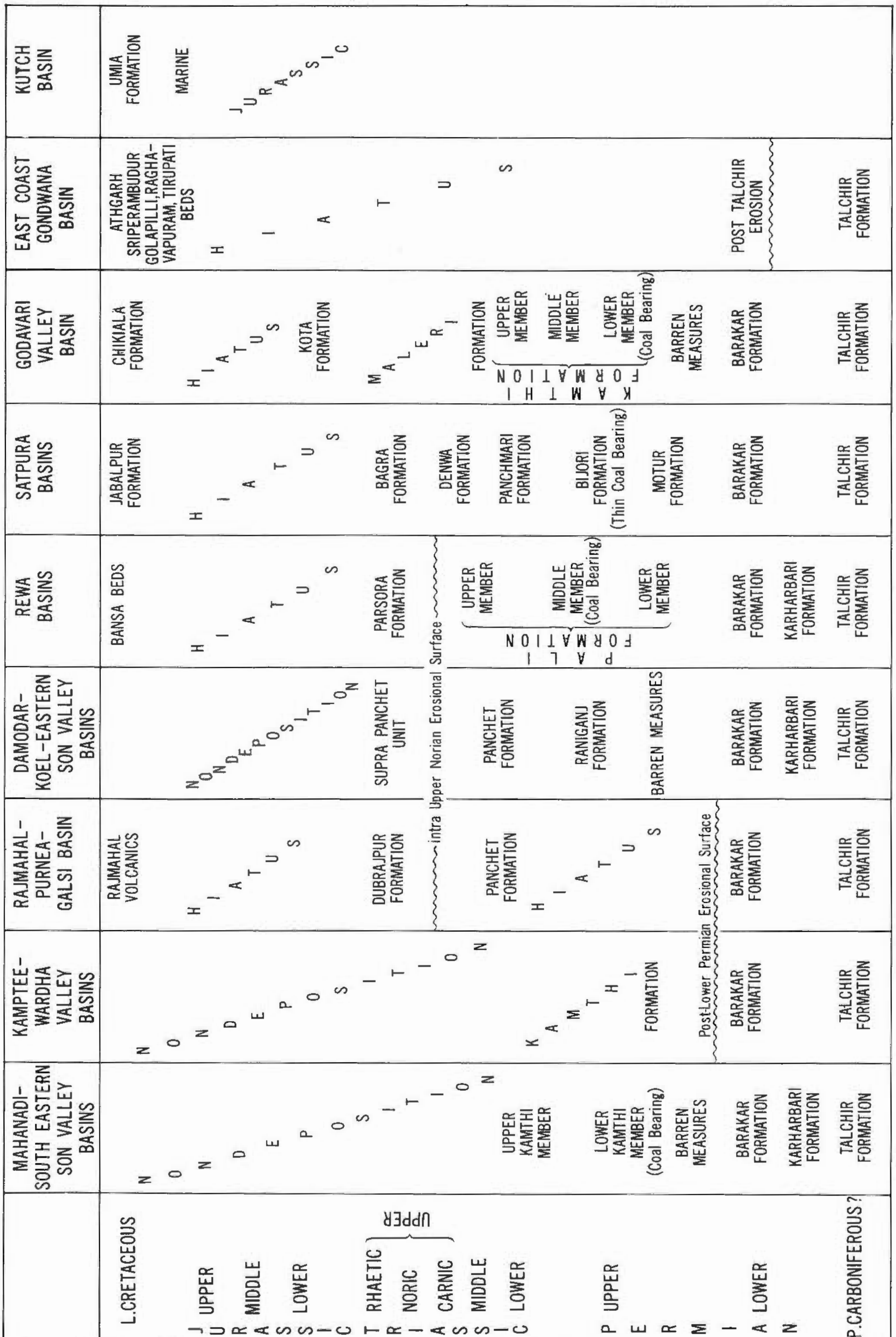

Fig. 5. Correlation of Gondwana Formations of India.

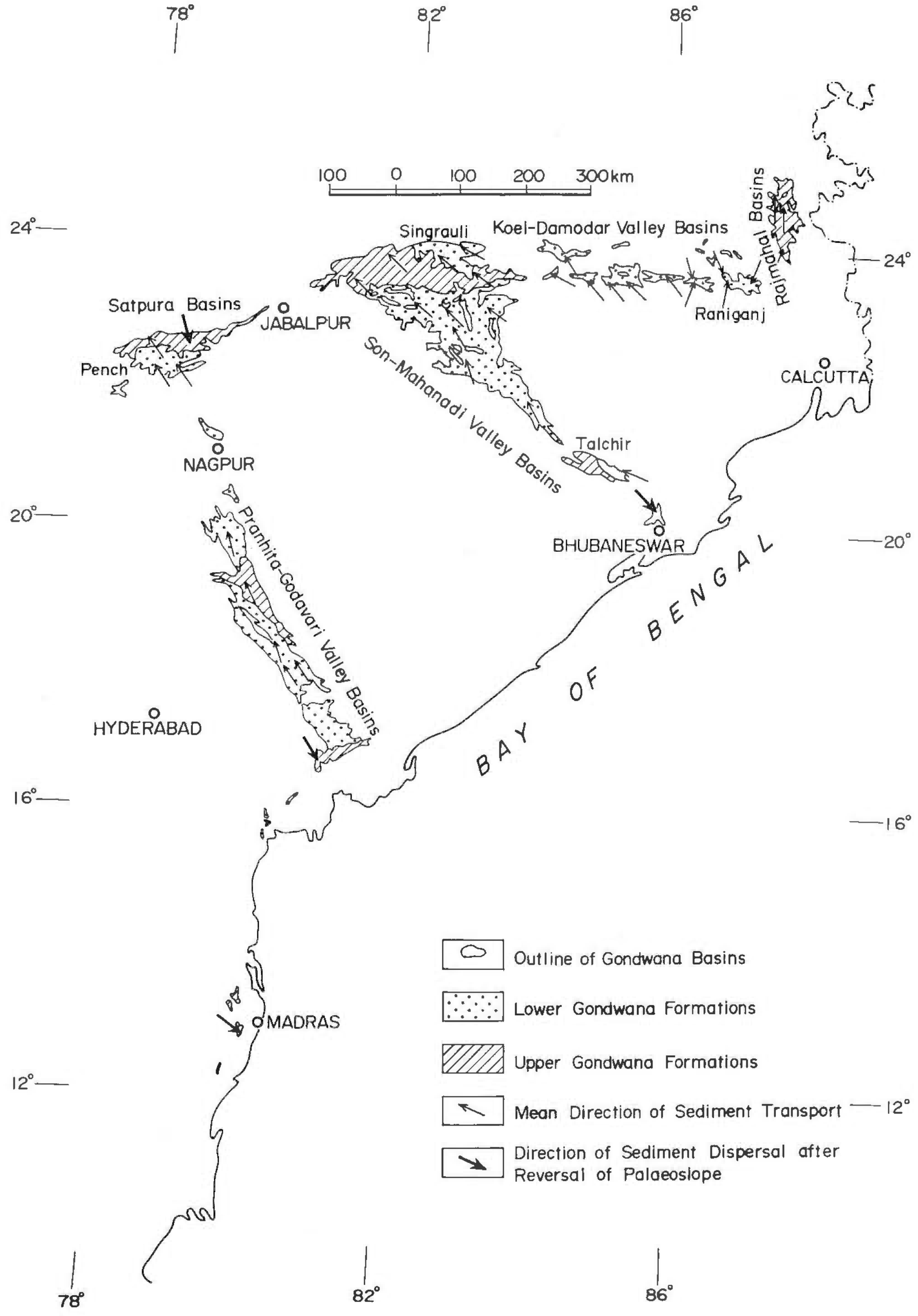

Fig. 6. Pattern of clastic dispersal in Gondwana basins of Peninsular India.

but the sedimentation ceased altogether in Rajmahal master basin, in the subsidiary belt of Damodar valley and in the Pranhita-Wardha basin. This denotes the major stratigraphic hiatus in the terrestrial Gondwana sequence in Lower Permian period. In the Upper Permian time, there is recurrence of coal forming environment in the Damodar, Son-Mahanadi, Godavari and Satpura basins.

Inspite of broad similarity of gross litho-facies, the correlation of Triassic Gondwanas is fraught with uncertainty. The Godavari sedimentary province documents an uninterrupted sequence of sedimentation from earlier Triassic to Rhaetic as evidenced by its rich reptilian fauna. But the succession in other basins denotes a major erosive break in Upper Norian period. The break is precisely dated in the Rewa basin at the base of Parsora Formation because of the available palaeontological information.

The unequivocal evidence of Jurassic Gondwanas is preserved only in a small segment of Godavari Valley. The Kota beds, representing the Jurassic succession, rest over the Maleri Formation with a break of local magnitude at the Triassic-Jurassic boundary. Elsewhere in the Gondwana basins, the Jurassic is denoted as a period of non-deposition and subaerial erosion.

The most fascinating episode of tectonism in the Gondwana basin is denoted in the Early Cretaceous period. the tectonic event in the plate interior was manifested by the formation of coastal troughs, creation of new basins in the heart of Peninsular India, reversal of palaeoslope (Fig. 6) and volcanic paroxysm in well defined segments.

BOUNDARY OF GONDWANIC PLATE OF INDIA

The reconstructions of Gondwanic plate of India have been attempted from the comparisons of regional geology and tectonic evolution, comparisons of fossil flora and fauna, seafloor magnetic anomaly pattern and palaeo-magnetic analysis. The precise outline of Gondwanic India and the interrelation between India and Antarctica, Australian plate have long been a topic of lively discussion. Of the various continental fits, the one proposed by SMITH and HALLAM (1970) received wide acceptance. Later, several modifications have been suggested from time to time within the broad framework of Smith and Hallam's fit. The generally accepted fit places the western margin of India against the eastern margin of Madagascar and eastern Antarctica in juxtaposition with east coast of India. In the fit of Smith and Hallam, the eastern edge of the Indian Plate lies in Assam and is separated from Australia by an oceanic gulf "Sinus Australia". It is now postulated that "Sinus Australia" was occupied by continental block which continues with Indian block in an entity called greater India (VEEVERS *et al.*, 1975, JOHNSON *et al.*, 1976). In other words, according to this fit, the eastern margin of India was partly in juxtaposition with Antarctica and partly with Southwest Australia. In Smith and Hallam's reconstruction, Ceylon has, however, been arbitrarily detached from India though there are valid reasons to believe tht Ceylon was an integral part of Indian plate. MITRA *et al.* (1979) have proposed that if Enderbyland is placed further south of Madras in the Indo-Antarctic fit, Ceylon can be suitably accommodated within the Indian Plate. In this fit the Godavari Valley graben is found to be in juxtaposition with Amery basin of Antarctica.

The crux of the problem of defining the extent of Gondwanic India lies in the precise delineation of the northern limit of Gondwanic plate. There has been suggestions that the northern limit of the Indian Plate is defined by Indus-Tsangpo suture (GANSSER, 1966). This suture is defined by an ophiolitic belt extending from Manasarowar, northwestwards along the Upper Indus, Kargil to Dras. Following Gansser's idea, DEWEY and BIRD (1970) regard the Indus suture line as the relic of a closed ocean that lay between Gondwanic India and Asia. There has been, however, other suggestions of a Greater India in Gondwanaland and the Tibetan Plateau is considered now to be a part of Gondwanic India (CRAWFORD, 1974). It has, further been suggested that the northern plate boundary was beyond Tibet on the northern side of Tarim basin and along the Tienshan. This idea received support from geophysical survey and it has been postulated that the northern boundary of greater India is marked by Kun Lun-Astin Tagh-Nan Shan mountain front. This shape of greater India places the Tethyan margin west of Australia (VEEVERS *et al.*, 1975). Hari NARAIN and KAILA (1976) based on seismotectonics and deep seismic soundings also considered that the northern boundary of the Indian plate extended beyond Tibet and coincides with the southern margin of Tienshan-Nan Shang mobile belt.

The concept of greater Gondwanic India with Tibet within its tectonic block no doubt resolves the problem arising out of intertonguing of strata containing Gondwana and Tethyan biota. It is opined that both faunal zone and correlative litho-facies of Gondwanic affinity extend into Sinkiang-Ulgiur region, Szechwan in China and even upto Kuznets basin (MEYERHOFF and MEYERHOFF, 1976). This include the *Lystrosaurus* fauna similar to the one found from Panchet Formation in India, Trans-Antarctic mountain in Antarctica and from South Africa. It is, however, to be borne in mind that Lower Gondwana *Glossopteris* flora as well as *Lystrosaurus* are also reported from U.S.S.R. On the score of this evidence, the Gondwanic margin is to be extended even beyond the Kun Lun-Astin Tagh suture which is incompatible with palaeomagnetic data. It is, therefore, to be examined whether that Lystrosaurus fauna from the different places document a history of parallel evolution of reptiles.

FRAGMENTATION AND DISPERSION OF INDIAN GONDWANA PLATE

There are divergent views about the period of separation of Indian Plate from the other segments of Gondwanaland. It has been suggested that India separated from Antarctica-Australia segment in Albian-Aptian times (SCLATER and FISHER, 1974). JOHNSON *et al.* however dates the period of inception of seafloor spreading between India and Antarctica at 130 million years. Evidences for this date come from sequence of magnetic anomalies, basement depth of the ocean floor at D.S.D.P. sites. This reconstruction implies that a triangular land locked sea, some 3000 km long and 300 km wide, opened between India and Antarctica at 110 to 120 million years (Aptian-Hoteterivian) and the eastern margin of Greater India cleared the Wallaby Plateau at about 100 million years (Albian). MARKL (1974) and LARSON (1977) have dated the period of separation of India from Antarctica-Australia at 127 million years.

Though there is no significant discrepancy of dates in regard to the period of separation of India from Antarctica-Australian plate there is some ambiguity about the period when India separated from the Western Gondwanaland. COLBERT (1981), based on the distribution of Mesozoic Tetrapods, postulated that India may have been connected to Africa until Late Cretaceous time after which it may have rifted at a rapid rate. NORTON and SCLATER (1979) have also dated the period of separation between India and Madagascar as Late Cretaceous (80–90 million years). This event is accompanied by outpour of lavas along Madagascar east coast. It is also postulated that seafloor spreading after India's separation from Madagascar was very high upto 13 cm./year.

It is further observed on critical analysis of sedimentologic and tectonic history of the Palaeozoic-Mesozoic Burma-Malayan mobile belt, that it extends to Western Yunnan and South-Central Tibet (ACHARYYA, 1978). This mobile belt, in all probability, was located to the north of Gondwanic margin, as the Indo-Burman, Indonesian orogenic belt is tied up with a different development history. Malaya has occupied a latitude of about 150°N since Palaeozoic time (MCELHINNY *et al.*, 1974).

The Chinese geologists after the recent revision survey in Tibet claim that the Himalaya is the result of Indian Plate coming in collision with Asian Plate along the Yalu-Tsangpo-Gurchu deep fault in which numerous ultrabasic bodies are mixed up with the flysch sediment. This zone appears to mark the tectonic suture between two plates. This suture extends to Pomi and then southwards through Chaou to the Wulung river valley of Burma (KUO Wen

Kuei, 1978). Evidently the ophiolite complexes along the Indus-Tsangpo suture represent intrusion-extrusion of mantle material that took place along the continental margin. The question, however, has not yet been resolved whether the ophiolite complex represents oceanic crust that has been obducted on to a continental margin or they took place under conditions of tensions along the margin of Gondwanic India (STONELEY, 1975). The proponents of Greater India model have not yet satisfactorily resolved the implications of the ophiolites of Indus suture in their tectonic modelling. It is, therefore, reasonable to assume that the Gondwanic India with its sedimentological and palaeontological entity extended northwards upto Indus-Tsangpo suture and the Himalayan front is the Tethys-facing margin of this Gondwanic continent (Fig. 7).

The palaeomagnetic information further suggests that the relative drift of Africa, India and Madagascar occurred in late Cretaceous-early Tertiary period and may have been associated with the effusion of Deccan Traps (VILAS and VALENCIO, 1979).

In the context of the fragmentation and dispersion of the Gondwanic India, it is worthwhile to study the geologic events within the plate interior which have significant bearing on dating the fragmentation history of this continent. The manifestation of the crustal extension in Gondwanic plate interior can be analysed in relation to the evolution of marginal basins along the coast, volcanic paroxysm along well defined zones and fault movements vis-a-vis creation of new basins of deposition.

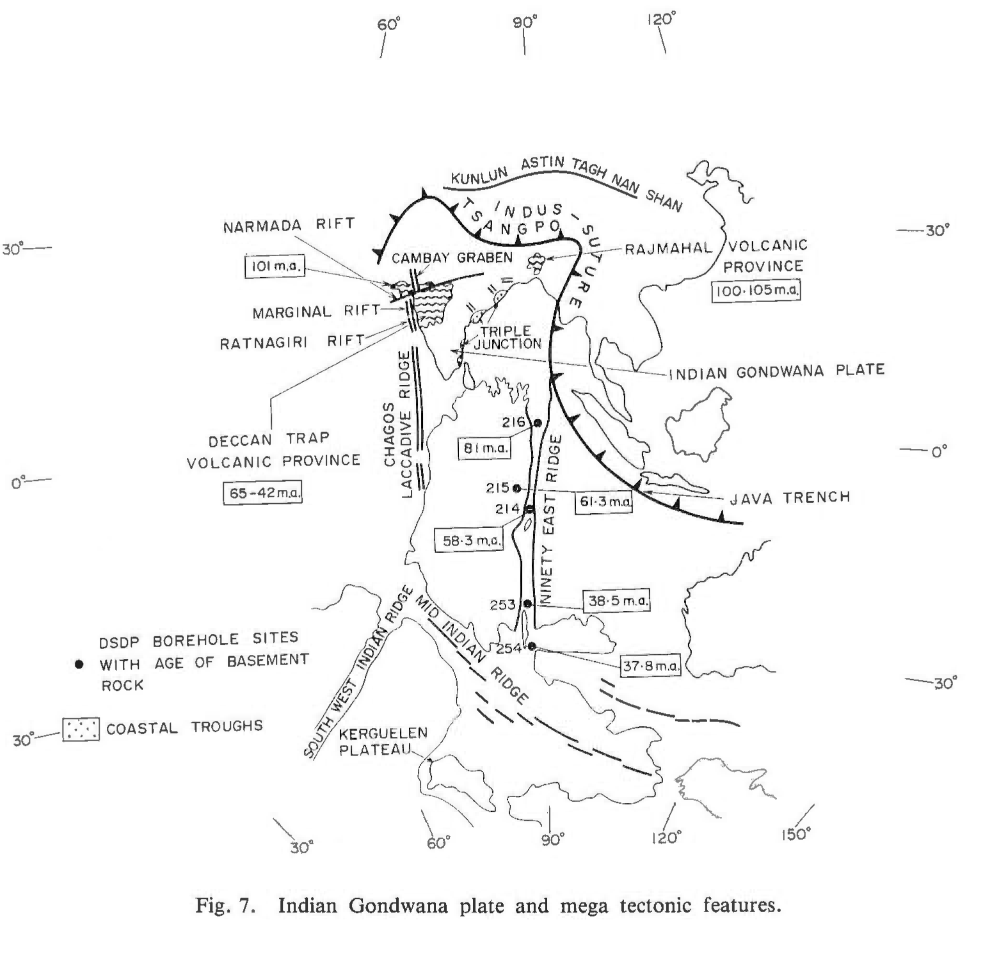

Fig. 7. Indian Gondwana plate and mega tectonic features.

GONDWANA BASINS OF THE EAST COAST

The east coast of India shows evolution of several troughs which have significant bearing with the fragmentation of Gondwana continent. These include the Cauvery trough, Palar basin around Madras, Godavari-Krishna basins along the delta of Godavari-Krishna rivers, Athgarh basin near Bhubaneswar.

The Cauvery basin covers an area of 25,000 sq km on land and the basins extends into the off-shore areas. The oldest sediments resting over the Precambrian basement include Upper Gondwana Sivaganga Formation which comprises paralic shales and argillaceous sandstones of Aptian to early Albian age.

The Palar basin located to the north of Cauvery basin covers an onshore area of 4000 sq km and extends into the sea. This basin experienced block faulting along NE–SW trending basement faults which probably originated at the beginning of Cretaceous period. The Gondwanas of this trough comprise two distinct groups of rocks separated by a pronounced hiatus. The lower Gondwanas are represented by Talchir Formation which comprise glacial and periglacial sequence up to a maximum thickness of 280 m. The Talchir sequence is overlain after a pronounced erosional unconformity by the Sriperumbudur Formation of Lower Cretaceous age. The overlying Satyavedu Formation is represented by arenaceous facies and has been assigned Aptian age (SHASTRI *et al.*, 1973). The Gondwana beds are covered by Palaeogene and other younger sediments.

The Godavari-Krishna trough forms a late Gondwana NE–SW trending trough paralleling the east coast. Structurally it is formed of three depressions which have a pile of 2–4 km thick strata. Godavari depression shows the development of late Permian-Early Triassic Chintalapudi Sandstone which succeeded by Golapilli Sandstone after a stratigraphic hiatus. It is further overlain by Reghavapuram Shale and Tirupati Sandstone. The Golapilli Formation has been assigned Late Jurassic to Early Cretaceous age while the Raghavapuram shales indicate a Neocomian age. The lithological and faunal association of these Gondwana sediments show that these sediments accumulated on a piedmont plain in a marginal basin. The rocks and fossils of Raghavapuram shales show lagoonal deposition in an embayment close to the sea. The Tirupati Sandstone points to a late stage of bay infilling.

The other important coastal Gondwana trough is defined by the Athgarh basin in Orissa. It comprises a few identifiable structural depressions with intervening basement ridges paralleling the east coast. The upper Gondwana sediments in this trough include Athgarh sandstone which on the basis of floral assemblage is considered to be of late Jurassic-Early Cretaceous age.

The tectonic styles of the coastal Gondwana basins and the nature of the lithic fill demonstrate that they correspond to rifted marginal basins with asymmetric cross section. They have a landward faulted margin and gentler slope towards the sea. The lithic fill of these basins shows admixture of fluvial, marine and paralic sediments. Such rifted basins along the continental margin elsewhere are often found to be terminated along their length by transform faults (WILSON and WILLIAMS, 1979). In case of Godavari-Krishna trough and Cauvery basin, prominent shear zones have been found along the margins of this trough transverse to the Indian coast line.

CREATION OF NEW BASINS ALONG NARMADA LINEAMENT

The most spectacular episode of crustal movement in late Gondwana period is witnessed along the Narmada lineament in Central India. This zone defines a prominent gravity low with subsidence history at least since Lower Cretaceous period. As a result of the tectonic movement, this linear belt became a new locale of late Gondwana sedimentation. The Jabalpur basin near Jabalpur, the Idar basin, bearing Ahmednagar sandstone of Cretaceous age, the

Nimar basin in Lower Narmada valley and the deposition of Wadhan sandstones at Kathiawar are manifestations of this late Gondwana crustal movement and accompanying change in palaeogeography.

LATE GONDWANA AND POST GONDWANA VOLCANISM IN PENINSULAR INDIA

Intracontinental Gondwana rifts provide unique opportunity to relate the rift tectonics to episodes of volcanic activity. The Gondwanic plate of India shows manifestation of volcanism both in the eastern and western segments (Fig. 8). The Rajmahal flood basalts of Eastern India have a wide spread from Galsi area close to the eastern part of Raniganj Coal Fields across the Rajmahal Hills in North Bihar to Bangladesh. In all probability, the Sylhet Traps of the Khasi Hills is a continuation of the Rajmahal volcanics to the east. The rich upper Gondwana flora associated with the Rajmahal volcanics shows Upper Jurassic-Lower Cretaceous

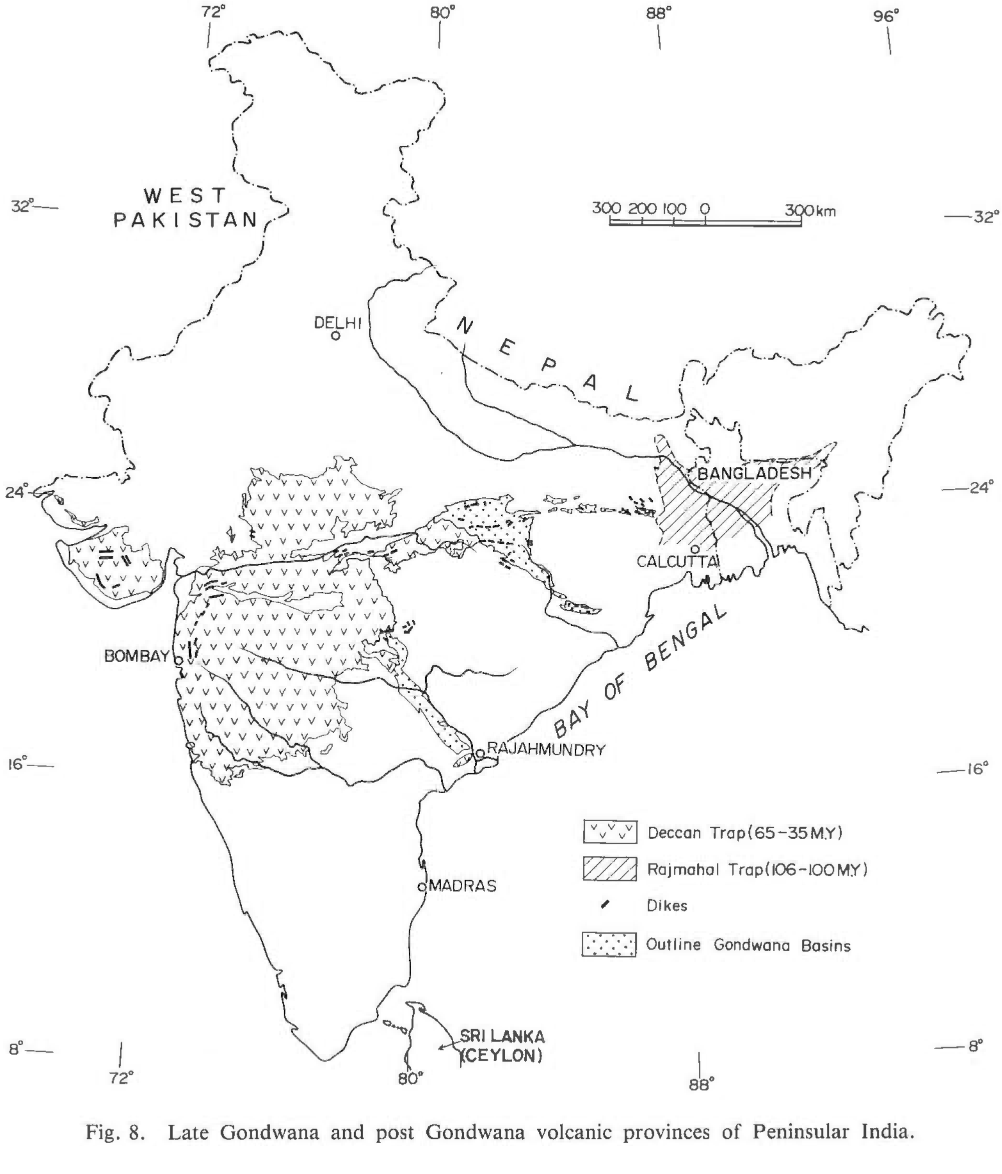

Fig. 8. Late Gondwana and post Gondwana volcanic provinces of Peninsular India.

affinity. McDOUGAL and McELHINNY (1970) report concordant ages of 100 to 105 Ma for the Rajmahal volcanics.

The spatial and temporal relationship of the Rajmahal-Sylhet volcanics with the evolutionary history of the east coast Gondwana troughs prove beyond doubt that the volcanic paroxysm in Rajmahal area in eastern India is an outcome of the crustal extension during the initial phase of rifting of Gondwanic India. SCLATER and FISHER (1974) regard that the outpour of this volcanics appeared to be genetically related to the initial phase of separation of India from Australia-Antarctica during Albian-Aptian times. DUNCAN (1978) further suggests that the Rajmahal traps are the earliest manifestation of volcanic activity that later produced the Ninetyeast Ridge. These traps are considered to result from the passage of India northwards over the hotspot. As the Indian plate moved to the north, its path was supposed to be braced by the Ninetyeast Ridge. There are, however, different views on the involvement of the Kerguelen hotspot as a source of material for Rajmahal activity (MAHONEY, *et al.* under preparation).

The major centres of volcanic eruption were in the western segment of India covering 6,000,000 sq km. The Deccan volcanic province is predominantly constituted of basalts that are associated in the coastal belt of Maharashtra with acid and intermediate differentiates. Dolerite dykes occur as swarms in the Albag-Panvel and Dudiapada areas and intrusions of carbonatites and alkaline rocks are known in the Amba Dongar area (POWAR, 1981). The important structural elements of this Deccan volcanic province include the Narmada-Tapti lineament, west coastal faults and the N–S trending Cambay graben and its extension on Western India shelf. The basalts are known as far south as in Kerala-Lakhshadweep graben. The Deccan Trap flow has a low dip towards south and east but exhibits monoclinal flexure along the Western Ghats close to the coast line.

An analysis of the structural fabric of the Deccan volcanic province shows that the various mega-tectonic features are the sub-crustal basin marginal faults, the shoulders of the rift and junction of the two NNW–SSE trending and ENE–WSW trending basement blocks juxtaposed against each other (RAMANATHAN, 1981).

As the episode of the Deccan volcanism has significant bearing with the rifting of the western margin of Gondwanic India, the age and duration of the Deccan volcanism has considerable significance in dating the history of fragmentation. A recent synthesis of radiometric age data of the Deccan volcanics shows that the earliest manifestation of Deccan volcanism in Western India is coeval with the Rajmahal volcanics (around 100 million years) (ALEXANDER, 1981). The earliest Deccan flows in Sourashtra is dated as 101 ± 3 million years. There are two other major volcanic episodes in the Deccan Trap eruptive history - the major one being during 65–60 million years and other during 50–42 million years. It is, therefore, assumed that volcanism covered a fairly long time and the earliest flows of Kutch-Kathiawar have erupted from the end of Aptian. The recent find of *Dinosaurian* fossils in the intertrappean beds around Ada village of Andhra Pradesh corroborates the idea of the Deccan volcanism commencing before the close of Cretaceous period. The major episode of Deccan Trap activity, however, remained confined to Palaeocene (65–60 million years) period. Low intensity volcanism, continued even upto Oligocene period. From this synthesis of the age data of Deccan Trap, it is further observed that the volcanics of the western part are decidedly older than the flows from northeastern and eastern part.

CONCLUSION

From the foregoing account, it is evident that

(1) the initial phase of rifting and ocean floor spreading along the eastern margin of Gondwanic India commenced about 100 million years ago. Certain segments of the east coast yielded to tensional stress resulting in the formation of the coastal basins open to the sea. These fault bounded troughs in Cauvery, Palar, Godavari-Krishna and Athgarh were the milieu of

fluvial and near shore paralic sedimentation. The marine transgression of Albian period in these coastal troughs marks the beginning of continental separation with the opening up of the juvenile Indian Ocean. It is, therefore, obvious that the initiation of the fragmentation of Gondwanic India along the east coast commenced in Albian period and not in earlier times as postulated by certain workers.

(2) The ocean opening probably began with continental rupture and there is an evolutionary sequence from uplift, rifting and uplift-generated triple junction formation to continental break up. The Godavari-Krishna troughs, for example, represent the rifted arms formed during continental fragmentation while the main Godavari Gondwana graben behaved as a failed arm. Similar rejuvenation of Athgarh graben is postulated with a triple junction near Cuttack.

(3) The basinal evolution of the east coast and contemporaneous magmatism in Rajmahal and Sylhet in Eastern India needs to be studied in the geodynamic framework of plate tectonics. The present thinking corroborates the idea of the evolution of Ninety-east Ridge and the migration of India over a hot spot during its northward journey. The age determination of the rocks drilled from sites close to the Ninety-east Ridge, however, suggests the northward increase in age of basaltic rocks. In other words, the basement ages increase gradually to the north. As the northward extension of the Ninety-east Ridge is covered by Bay of Bengal Alluvial fan, its continuation into continental India is not definite. DUNCAN (1978) has suggested that Rajmahal volcanics which erupted in Eastern India was the earliest manifestation of volcanic activity that produced the Ninety-east Ridge. The palaeomagnetic data from D.S.D.P. sites along the Ninety-east Ridge and from the Rajmahal troughs also point more or less to the same palaeolatitudes in the range of 48° to 53°S. Further geochemical studies are, however, needed to confirm whether the Rajmahal volcanics resulted from the northward migration of India over a hot spot, the subsequent trace of which was marked by the Ninety-east Ridge.

(4) There is some ground for controversy about the period when India separated from Madagascar. Palaeomagnetic and palaeontological evidences broadly suggest that India left Madagascar in the late Cretaceous (80–90 million years) period. But comparative study of the Gondwana geology of Madagascar and that of Cutch basin in western India shows that the marine Jurassic of Cutch is more or less homotaxial with the Marine Bathonian and Portlandian sequence which overlies the Isalo Group in Madagascar. Both basins display a community of faunal character and might have opened marine communication during the Late Jurassic period. During this period, the juvenile Arabian Sea came into being permitting marine inundation of the west coast of India as well as northern Madagascar.

(5) The Cambay graben which is considered to be a manifestation of the distention in the crust during the fragmentation of the Gondwanic India bears record of Mesozoic sedimentation and as such had evolved in Late Jurassic to Early Cretaceous period. Further the presence of extensive marine Bagh beds and Lameta beds over the North Indian basins point to inundation of the Cratonic interior by open sea from the west which existed at least in middle Cretaceous period. The stratigraphic records of Barmer area in Rajasthan also rule out the possibility of marine transgression in the heart of India in the Cretaceous period from the northwestern shelf.

(6) The oldest Deccan volcanics along Cutch and Saurashtra are dated as 105–100 million years and this phase of volcanic activity is coeval with the extrusion of Rajmahal Traps. It is, therefore, obvious that this outpour of basaltic lava flows denoted the accompanying distension in the crust during the fragmentation of western segment of Gondwanaland.

In the Western Indian Ocean, the Chagos-Laccadive Ridge parallels the Ninety-east Ridge and has more or less a similar evolutionary history. It is of further interest to note that the Deccan volcanic pile lies at the northern end of the trace of Chagos-Laccadive Ridge and thus this ridge can be related to volcanism issuing from a major transform fault between the Indian and African Plate, in Early Cretaceous to Oligocene time. Based on this analysis of tectonic framework, it is envisaged that the northward journey of India Plate commenced in Early Cretaceous period and its path is traced by Ninety-east Ridge on the east and Chagos-Laccadive Ridge on the west.

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Geological Survey of Japan Report, No. 263, 1984, p. 27.

The Last 200 Million Years in Eastern Asia: Yanshanian Subduction and Post—Yanshanian Extension

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ABSTRACT

The pre-Yanshanian (pre-200 Ma) geology of Asia can be interpreted as an unique record of numerous small plates, some of which were separate rifted blocks as early as 1,500 Ma. The north-south agglomeration of these blocks to form the bulk of modern Asia began in the west during the Carboniferous (Hercynian events) and climaxed in the east during the Late Triassic (Indosinian events). In the eastern part of the continent, four major east-trending sutures (Red River, Qin Ling, Yan Shan, and Mongol-Okhotsk) bound three major blocks (respectively, South China, North China-Korea, and Manchuria-Bureya).

The Yanshanian geology in eastern Asia, particularly the widespread belts of calc-alkaline igneous rocks, can be interpreted as resulting from magmatism superposed above major peripheral subduction zones that dipped northwestward under South China and westward under North China-Korea and Central Mongolia from 200 to 100 Ma, and westward under North China-Korea (fronted by Southwest Honshu) and Manchuria-Bureya from 100 to 50 Ma. Some subduction also took place from 200 to 100 Ma, parallel to the Qin Ling, Yan Shan, and Mongol-Okhotsk sutures, as all finally closed. Hydrocarbon-rich basins formed as the result of major epeirogenic subsidence on western margins of the oldest continental nuclei farthest from the eastern subduction zones. Rates of subsidence and subduction appear correlative; areas of magmatic arcs and volumes of sedimentary basins reflects subduction rates; both reach a maximum in the Late Jurassic and Early Cretaceous.

The post-Yanshanian (since 50 Ma) geology in eastern Asia can be interpreted as resulting from northeast-southwest crustal extension in the region between the Siberian craton and the continental margin from Primorye to Taiwan, contemporaneously with collisions between Asia and the Okhotsk block in the northeast, the India block in the southwest, and the Philippine arc in the southeast. The extension is evidenced by hydrocarbon-rich Tertiary graben, by voluminous Late Tertiary alkalic basalt volcanism localized along former plate sutures, and by historically recorded, scattered, intraplate, shallow seismicity.

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Was There a North New Guinea Plate?

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ABSTRACT

On the basis of geological and geophysical evidence from marginal basins and subduction zones of early Tertiary age in the southwestern Pacific region, I propose that there was another plate in the southwest Pacific during this period. This plate, which contained northern part of New Guinea and was separated from the Pacific plate at the north by a ridge-transform fault system, was moving to the south with respect to hot-spots, subducting beneath the northern margin of Australia. The West Philippine, Coral Sea, and southern New Hebrides Basins probably formed by back-arc spreading due to the southward subduction of this plate. The abrupt change of the Pacific plate motion at 43 Ma could have resulted from the subduction of the ridge system between the Pacific and hypothesized plates beneath those marginal basins.

INTRODUCTION

Almost all the marginal basins in the western Pacific formed during the Cenozoic (e.g., KARIG, 1971; WATTS *et al.*, 1977). Many of these Cenozoic marginal basins formed since the Oligocene, that is, after the change of the Pacific plate motion with respect to hot-spots from north-northwest to west-northwest at 43 Ma (CLAGUE and JARRARD 1973; JACKSON *et al.*, 1975). However, in the southwest Pacific, there are a few older marginal basins of early Tertiary age, such as the West Philippine, Coral Sea and southern New Hebrides Basins, which formed before the change of the Pacific plate motion at 43 Ma. It seems difficult to explain the origin of these older marginal basins by back-arc spreading in the western Pacific region. This is because during the early Tertiary untill 43 Ma, the Pacific plate was moving to the north with respect to hot-spots (e.g., CLAGUE and JARRARD, 1973) and, in contrast, Australia was almost stationary with respect to Antarctica (CANDE and MUTTER, 1982), that is, to hot-spots (DUNCAN, 1980). Thus the relative motion between the Pacific and Australian plates was diverging during this period. Entrapment of these marginal basins is one idea to explain their origin, as UYEDA and BEN-AVRAHAM (1972) and HILDE *et al.* (1977) proposed for the origin of the West Philippine Basin. However, along the northern Palau-Kyushu Ridge of the Philippine Sea, subduction from the northeast had initiated at least by 48 Ma (see SENO and MARUYAMA, 1984) and at the west of the northern Palau-Kyushu Ridge, there are the Daito and Oki-Daito Ridges which were probably active island arcs during the late Cretaceous (e.g., MIZUNO *et al.*, 1977). Therefore we cannot simply apply the idea of entrapment of an ocean floor or transformation of a transform fault in to a subduction zone to form the Bonin arc. It also seems difficult to apply an entrapment origin to the Coral Sea and southern New Hebrides Basin because there is evidence of island arc type volcanism at their northern margin during the period of their formation (JOHNSON, 1979; ANDREWS *et al.*, 1975), as will be shown in a later section.

The cause of the sudden change of the Pacific plate motion with respect to hot-spots at 43 Ma is another enigma in the tectonic evolution of the Pacific region. Some significant changes in plate driving force system around the Pacific plate, e.g., a change of the consuming or accreting boundary distribution, must have occurred at this time. Until present no reasonable mechanism has been proposed for the change of the plate driving force system. For example, HILDE *et al.* (1977) suggested that ridge subduction in the north and, partly, in the south Pacific was related to the change of the Pacific plate motion. However, the causal relation between the two in their paper is not easily understood.

The purpose of this paper is to present one possible simple model for the tectonic evolution of the western Pacific region since the early Tertiary which incorporates the formation of those early Tertiary marginal basins as back-arc basins. By examining geological and geophysical data of this region, I conclude that a new plate existed during the early Tertiary in the southwest Pacific. This plate, containing the northern half of New Guinea and separated from the Pacific plate by a ridge-transform fault system, would have been moving to the south and subducting beneath Australia. The origin of the West Philippine, Coral Sea and southern New Hebrides Basins is attributed to back-arc spreading due to the subduction of this plate along the northern margin of Australia in this paper. By introducing this plate, it becomes possible to explain the abrupt change of the Pacific plate motion at 43 Ma by the annihilation of the ridge push force at the south of the Pacific plate caused by subduction of the system beneath those marginal basins.

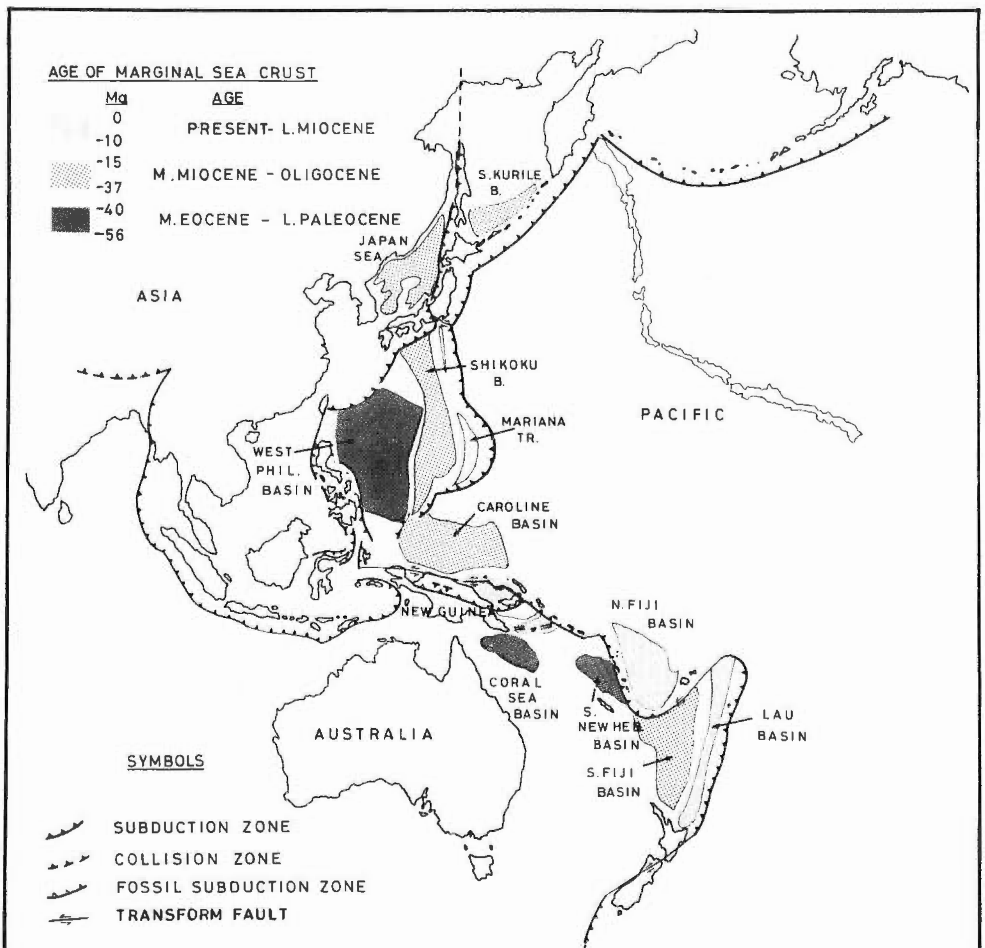

Fig. 1. Distribution of marginal basins and subduction zones in the western Pacific. Marginal basins are categorized into three groups according to the age of their formation.

MARGINAL BASINS OF EARLY TERTIARY AGE IN THE WESTERN PACIFIC

Figure 1 shows the distribution of marginal basins and subduction zones in the western Pacific. Marginal basins which are located landward in the Philippine-Indonesian region are not shown to avoid complexity. Marginal basins of Mesozoic age are also not shown in this figure. Cenozoic marginal basins are classified into three categories according to the age of their formation: late Paleocene-middle Eocene, Oligocene-middle Miocene, and late Miocene-Present. It can be seen that most of the marginal basins in the western Pacific are younger than Eocene. However, from the Philippine Sea through New Hebrides, the West Philippine, Coral Sea and southern New Hebrides Basins are the oldest marginal basins of late Paleocene to middle Eocene age.

Younger marginal basins have back-arc spreading origin (e.g., KARIG, 1971) except for some basins, such as the Caroline Basin, the origin of which has not been elucidated yet. It is noted that the direction of magnetic anomaly lineations of these younger basins are roughly normal to the convergence direction of the oceanic plate at each subduction zone. This supports the idea that these basins formed by the process related to subduction. It is interesting to note that the oldest marginal basins have roughly east-west magnetic anomaly lineations, as will be shown in later sections. This leads us to an idea that if these basins were formed by back-arc spreading, there must have been subduction of an oceanic plate from the north. On the other hand, it is difficult for the Pacific plate to have been subducting beneath the Australian continental margin during the early Tertiary because the relative motion between the Pacific and Australian plates during this period was diverging as stated in the former section. Thus one idea that another plate existed to the south of the Pacific plate comes up. This idea was already described in SENO and MARUYAMA (1984) in a primitive form. I am here attempting to collect geological and geophysical evidence from the southwestern Pacific region to show that the formation of those early Tertiary marginal basins were related to subduction.

Between the Philippine Sea and the Coral Sea along the northern margin of Australia, New Guinea is a hiatus of older marginal basins. However, we can also find evidence of a new plate from this segment of subduction zone. In the following subsections I will look into detail the geological and geophysical data in each region.

The West Philippine Basin

SENO and MARUYAMA (1984) reconstructed the Philippine Sea back to 48 Ma using various geophysical and geological data available in the basin. Figure 2 shows their reconstruction at 48 Ma. One of the most important features in this reconstruction is that the subduction along the northern part of the Palau-Kyushu Ridge (proto-Izu-Bonin arc) started by this time. This is supported by the island arc type volcanic rocks of 48 Ma age which have been found along the northern Palau-Kyushu Ridge and Bonin islands (see SENO and MARUYAMA, 1984). Note that at 48 Ma, the Pacific plate was moving north-northwest with respect to hot-spots (CLAGUE and JARRARD, 1973). Because the northern part of the Palau-Kyushu Ridge had a northwest trend at this time (Fig. 2), the Pacific plate was moving apart from the trench. This would make it difficult for the Pacific plate to subduct along the northern part of the Palau-Kyushu Ridge. It would be formally possible to cause convergence between the Pacific plate and the West Philippine Basin if the West Philippine Basin was moving faster to the north and overriding the Pacific plate (see a possible velocity diagram at the upper right of Fig. 2). However, this seems physically unplausible because much energy requires in order to make the Pacific plate to subduct into the upper mantle beneath the West Philippine Basin. This conclusion does not depend on model of the Philippine Sea reconstruction unless the Philippine Sea Basin rotated significantly in a counterclockwise direction since its formation

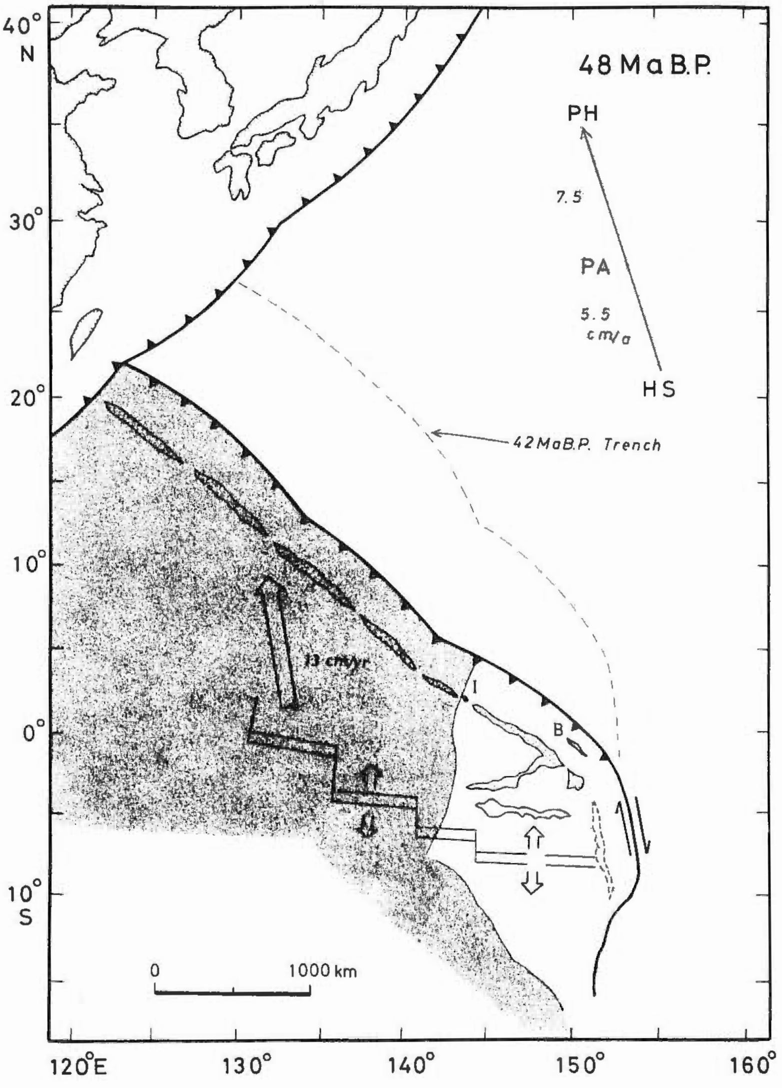

Fig. 2. Reconstruction of the Philippine Sea at 48 Ma (after SENO and MARUYAMA, 1983). Shaded area is part subducted since 48 Ma The West Philippine Basin was currently opening. I and B denote Izu and Bonin islands, respectively. In the upper right is shown the velocity vector diagram between the Philippine Sea, Pacific and hot-spots.

and the trend of the northern Palau-Kyushu Ridge was in a northeast direction at 48 Ma. The counterclockwise rotation of the Philippine Sea since its formation is not consistent with the paleomagnetic data of the Bonin-Mariana islands (see SENO and MARUYAMA, 1984).

We can avoid the above difficulty by postulating another plate between the Pacific plate and the West Philippine Basin subducting beneath the northern Palau-Kyushu Ridge, as SENO and MARUYAMA (1984) suggested.

New Guinea

Tectonic history of New Guinea is characterized by the collision episode along the medial

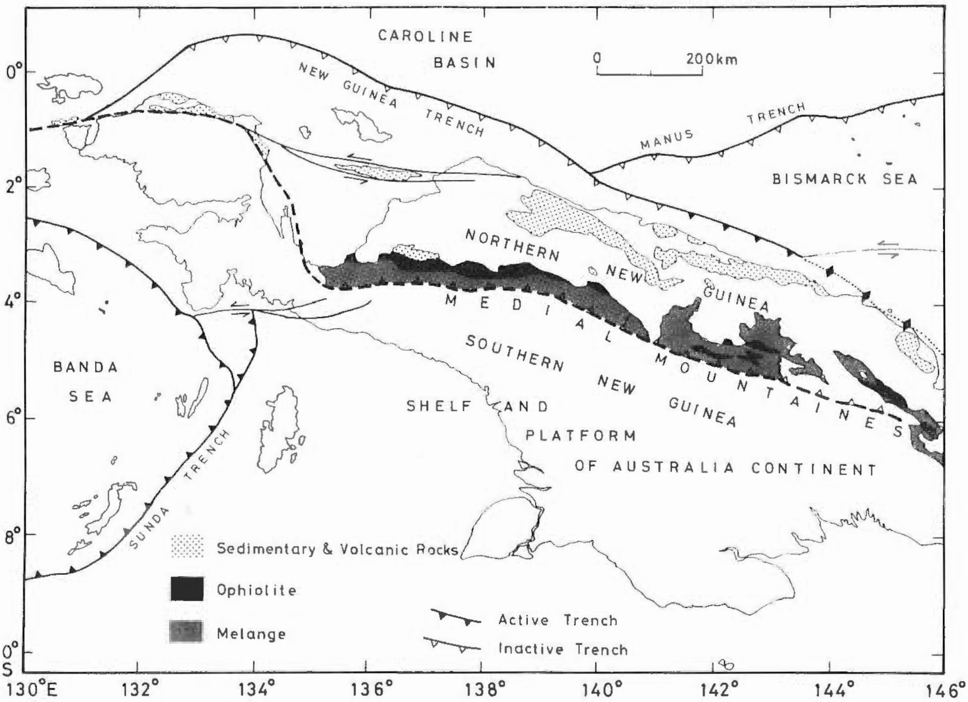

Fig. 3. Paleogene rocks in New Guinea (modified from HAMILTON, 1979). The boundary between Paleozoic southern New Guinea and Paleogene northern New Guinea is indicated by the chain line. Paleogene rocks partly include late Cretaceous rocks.

mountains. Paleogene rocks in New Guinea are shown in Fig. 3 (after HAMILTON, 1979). Southern New Guinea south of the medial mountains is a continuation of the continental mass of Australia. The upper Paleozoic igneous terrain of eastern Australia continues northward to medial southeastern New Guinea and the middle Paleozoic orogenic complex is exposed in northern Vogelkop in western New Guinea; between them Paleozoic rocks are sediments in shelf and platform facies (HAMILTON, 1979). The medial mountains is a suture zone where the northern New Guinea paleo-island arc is opposed to the continental shelf of southern New Guinea, forming a foreland basin in south of the medial mountains. A belt of the Late Cretaceous to Paleogene subduction melange and ophiolite complex of 50 km width runs the length of the medial mountains (Fig. 3). The disposition of the melange complex and island arc type volcanic rocks indicates northward subduction of an ocean floor which once existed north of southern New Guinea (HAMILTON, 1979).

This northward subduction beneath northern New Guinea during the early Tertiary suggests another plate having been existed in the south Pacific. During 70 to 43 Ma, the relative motion between Pacific and Australia was diverging as was stated in the former section. This diverging relative motion between the Pacific and Australian plates and the convergence between northern New Guinea and Australia implies that northern New Guinea could not be part of the Pacific plate, which provides another piece of evidence for a new plate in the south Pacific.

The Coral Sea Basin

The Coral Sea Basin is one of marginal basins of early Tertiary age in the southwest Pacific. Located off northeastern Australia, the basin is bounded on the north by the Papuan Peninsula and the Louisiade Archipelago (Fig. 4). The magnetic anomalies of this basin was studied

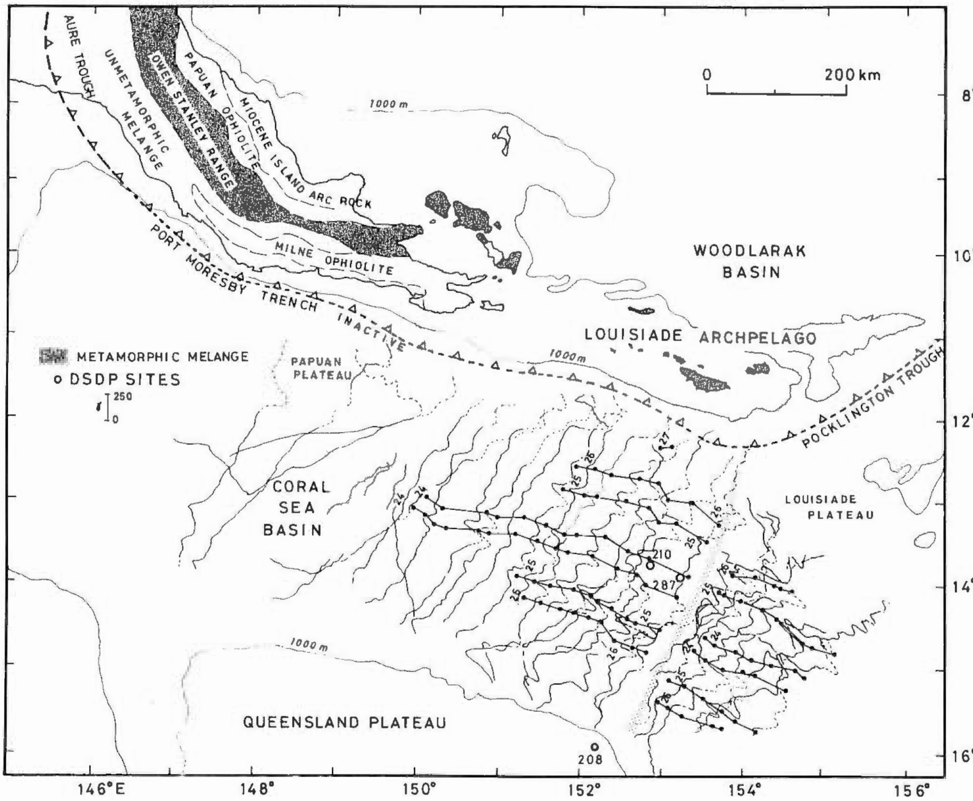

Fig. 4. Magnetic anomalies in the Coral Sea Basin and geological provinces in the Papuan peninsula and Louisiade archipelago (after WEISSEL and WATTS, 1979; HAMILTON, 1979; DAVIES and SMITH, 1971). Positive anomalies are solid lines, negative anomalies are broken lines. Heavy lines indicate magnetic lineations identified by WEISSEL and WATTS (1979). Stippled region indicates the inferred fracture zone which dextrally offsets the magnetic lineations by about 50 km (WEISSEL and WATTS, 1979). Metamorphic melange belt (Owen Stanley Range of Paleogene-late Cretaceous age) is shaded.

by WEISSEL and WATTS (1979). They identified a sequence of anomalies 26 through 24 repeated about an extinct spreading axis in a N70°W direction (Fig. 4). These anomalies correspond to 58 to 53 Ma according to the new geomagnetic reversal time scale (COX, 1983). Drilling results from DSDP Sites 210 and 287 near the center of the basin indicate that the oceanic crust at these sites is at least early Eocene in age (BURNS *et al.*, 1973; ANDREWS *et al.*, 1975) which is consistent with the magnetic anomaly identification by WEISSEL and WATTS (1979).

If the Coral Sea Basin formed by back-arc spreading, there must have been subduction of an oceanic plate from the north beneath this basin at least during the late Paleocene to early Eocene. By the same reasoning as in the former subsections, this oceanic plate could not be the Pacific plate but another plate. Although the present knowledge on the geology of the Papuan Peninsula - Louisiade Archipelago north of the basin does not allow us a unique interpretation of it, we can find a possible candidate for a north-facing paleo-island arc north of the basin as shown below.

From the Papuan Peninsula through the Louisiade Archipelago, there are zones of ophiolite, metamorphic and unmetamorphic melange belts lying along the elongation of the peninsula (Fig. 4). The metamorphic melange belt is called the Owen Stanley Range. The graphite-quartz-feldspar-mica schists are most common metamorphic rocks, although mafic metamorphic rocks become more abundant to the southeast; thus a quartzose sedimentary assemblage was present before metamorphism (DAVIES and SMITH, 1971; HAMILTON, 1979). The age of sedimentation is believed to be mostly late Cretaceous through Paleogene (HAMILTON, 1979). The silicic character of the metamorphic rocks suggests that they belong to a fragment of the Mesozoic Australian continental crust and sediments derived therefrom, which were rifted from Australia when the Coral Sea opened (e.g., DAVIES and SMITH, 1971). In this case, southward subduction has to be invoked along the Owen Stanley Range (e.g., ROD, 1974).

Alternatively JOHNSON (1979) and HAMILTON (1979) proposed that the metamorphic melange belt indicates northward subduction of the ocean floor which once existed north of the Australian continent. They believed that the Papuan Ophiolite is the basement of an south-facing island arc, obducted to the melange belt. KARIG (1972) proposed a similar scenario.

If the Owen Stanley Range formed as a subduction melange of a south-facing island arc, one important difficulty arises. The origin of the thick (10–20 km) silicic sediments of this range cannot be explained easily because the Papuan ultramafic belt to the north does not contain much island arc type or continental type silicic rocks. Only a small amount of tonalites and associated andesites are extruded in the ultramafic belt (DAVIES and SMITH, 1971). Furthermore, the opening of the Coral Sea cannot be explained in a straightforward manner by the northward subduction; in that case the Coral Sea would be part of a normal ocean basin.

JOHNSON (1979) described that late Cretaceous-early Eocene rocks of the unmetamorphic melange belt that grades into the Owen Stanley Range to the north contain a significant volcanic component with intermediate and silicic composition. This suggests the occurrence of island arc type volcanism near or within the unmetamorphic melange belt. According to HAMILTON (1979), other rocks of the unmetamorphic melange belt are described as follows. Between 147° and 148°E, upper Cretaceous through upper Eocene deep-water argillite, shale, siltstone, chert and limestone are disrupted chaotically and are intercalated with shallow-water Paleocene and Eocene strata and with large and small masses of gabbro, diabase and basalt. East of 148°E, the studied mafic rocks are of low-potassium oceanic tholeiite type. Intercalated fossiliferous strata are of late Cretaceous and Eocene ages. Middle Eocene ridge type tholeiitic basalt is exposed in the southeastern part of the peninsula, called the Milne ophiolite (Fig. 4). It should be noted that the volcanic and deep-water sedimentary rocks of the unmetamorphic melange belt have almost the same age as the Coral Sea Basin. It suggests that they were most probably scraped off from the Coral Sea Basin and mixed with the terrigenous rocks south of the Owen Stanley Range when the basin started to subduct along the Port Moresby Trench.

Based on the above geology of the Papuan peninsula, I believe that the Owen Stanley Range was formed by southward subduction of an oceanic plate during the early Tertiary in front of the Australian continent, as may geologists suggested. Because of this southward subduction, volcanism occurred at the south of the Owen Stanley Range and the Coral Sea opened as a back-arc basin and rifted the silicic metamorphic melange belt from Australia. Later, associated with the northward subduction of the northward extension of the Coral Sea along the Port Moresby Trench, island arc type volcanic rocks were mixed with the rocks of the back-arc basin. The time of the initiation of this later subduction would be upper Oligocene to lower Miocene when the Aure Trough started to deposit clastic sediments and explosive volcanism occurred at both sides of the peninsula (DAVIES and SMITH, 1971). This northward subduction along the Port Moresby Trench continued until the late Miocene or Pliocene (HAMILTON, 1979).

The above interpretation of the Owen Stanley Range in Papuan Peninsula implies that it has a quite different tectonic history from the melange belt along the medial mountains in the mainland of New Guinea. The former is the lifted margin of the Australian continent and the latter is the margin of the south-facing paleo-island arc which collided with southern

New Guinea. On the contrary, HAMILTON (1979) regarded them having the same origin and postulated a delayed collision to the east and further southward shifting of the Papuan Peninsula over the Coral Sea. The marked decrease of the Paleogene island arc type volcanic rocks north of the Owen Stanley Range does suggest that it is not a simple continuation of the mainland of New Guinea which has a large mass of Paleogene volcanic rocks. However, more detailed investigations of the melanges including age determination for both terrigenous and oceanic materials are necessary to allow us to determine the subduction polarity during the Paleogene and the tectonic history of eastern Papua.

The Southern New Hebrides Basin

The southern part of the New Hebrides Basin is bounded by the Entrecasteaux Ridge on the north, on the east by the presently active New Hebrides island arc, and on the west by the platform containing the Loyalty Island Ridge and New Caledonia (Fig. 5). The magnetic anomaly lineations of this basin were studied by WEISSEL *et al.* (1982). They identified magnetic lineations in a northeast-southwest direction (Fig. 5). Their tentative correlation of these anomalies with anomalies 18–23 corresponds to 52 to 42 Ma age according to the geomagnetic reversal time scale (COX, 1983). DSDP Site 286, which is located at the northeastern margin of the basin, penetrated the igneous basement below vitric sandstones and slitstones of mid-Eocene age (ANDREWS *et al.*, 1975). The drilling results provide a minimum age for the oceanic crust at this site, which is consistent with the magnetic anomaly identification by WEISSEL *et al.* (1982).

If the southern New Hebrides Basin formed as a back-arc basin, it provides another piece of evidence on the early Tertiary subduction of an oceanic plate from the north beneath the northeastern margin of Australia. Although the existence of a paleo-island arc during the early Tertiary north of the southern New Hebrides Basin is not confirmed directly, rapid accumulation of sediments containing andesitic detritus at DSDP Site 286 occurred during middle and late Eocene time, suggesting to ANDREWS *et al.* (1975) that island arc type volcanism occurred in proximity to the basin during its early stages of formation. WEISSEL *et al.* (1982) suggested that the Entrecasteaux Ridge could be the northern half of a block rifted apart and subsequently isolated by the seafloor spreading in the southern New Hebrides Basin. On the other hand, LANDMESSER *et al.* (1975) cited the East Rennel Island Ridge and the Rennel Island Ridge as a possible candidate for the island arc related to the opening of the southern New Hebrides Basin.

The region between the Coral Sea Basin and the New Hebrides Basin is characterized by the complex bathymetry, comprising numerous ridges and troughs, although most of these features appear to be of Eocene age (LANDMESSER *et al.*, 1975). The ridges have been interpreted as either submerged continental crusts, old spreading centers, or island arcs, and the troughs as either fracture zones which connect spreading centers or trenches (LANDMESSER *et al.*, 1975; HAMILTON, 1979). Their tectonic relationship to the opening of the Coral Sea Basin and the New Hebrides Basin is still only poorly known.

RECONSTRUCTION OF THE WESTERN PACIFIC AT 48 MA

In the former section, from all segments along the northern margin of Australia, I collected evidence for the existence of another plate in the southwest Pacific during the early Tertiary. This does not necessarily mean a single plate having existed, but the case that many small plates existed in the southwest Pacific is also possible. However, postulating a single plate makes the tectonic situation of the western Pacific much simpler; thus I introduce a new single plate south of the Pacific plate and call this plate the North New Guinea plate because this plate contained northern New Guinea. I postulate that this plate was subducting beneath the West Philippine, Coral Sea and southern New Hebrides Basins at least during the period

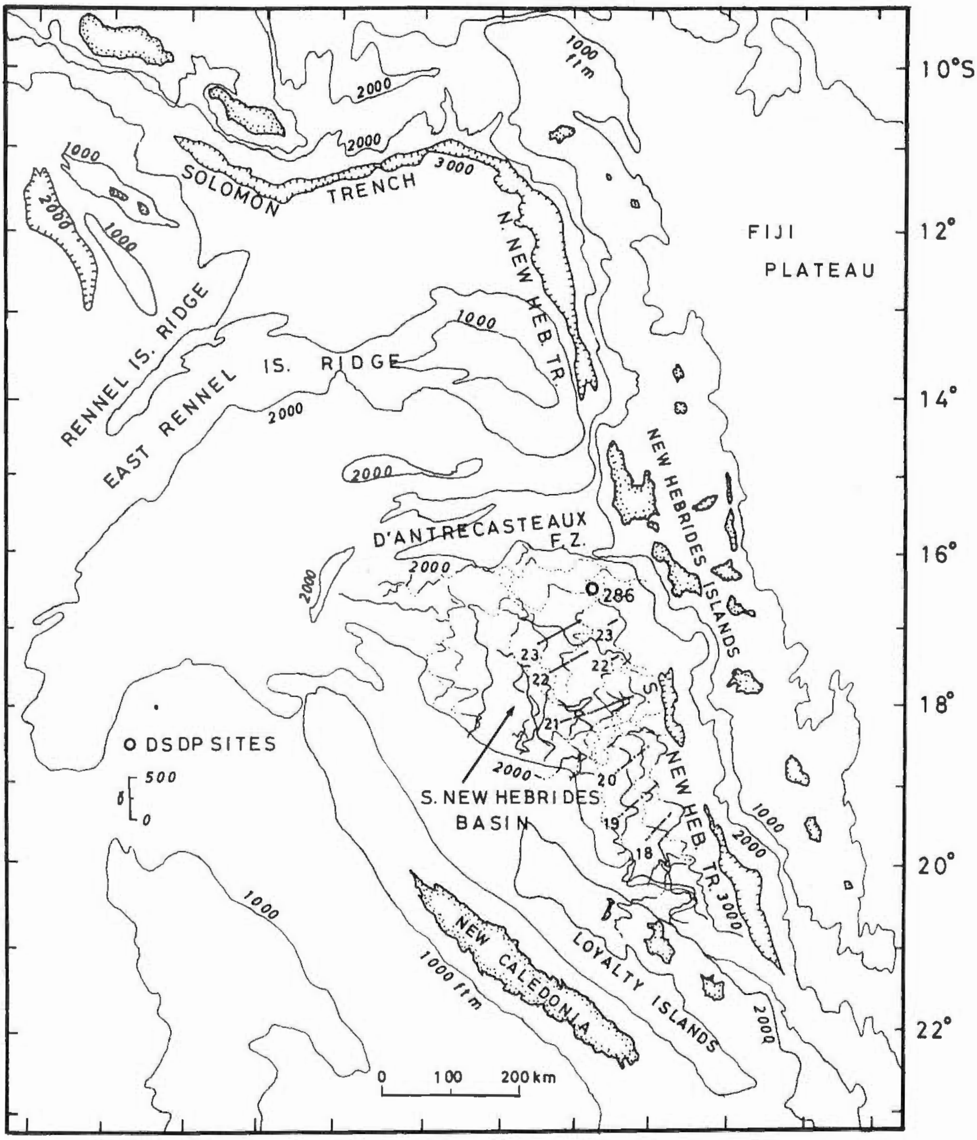

Fig. 5. Magnetic anomalies along ship's track in the southern New Hebrides Basin (after WEISSEL *et al.*, 1982) and major tectonic features around the basin. Positive anomalies are solid lines, negative anomalies are broken lines. Magnetic lineations are denoted by the heavy broken line. Bathymetry is in fathoms.

of their formation, that is, during the late Paleocene through middle Eocene. The northward motion of the Pacific plate and the southward subduction of the North New Guinea plate beneath the Australian continental margin lead us to an obvious conclusion that these two plates were separated by a rigde-transform fault system which probably had a trend roughly in an east-west direction. In this section I reconstruct the western Pacific at 48 Ma based on the North New Guinea plate hypothesis.

Figure 6 shows the reconstruction. Australia and the southern New Guinea were rotated

Fig. 6. Reconstruction of the western Pacific at 48 Ma Eurasia, North America, and Pacific are rotated back with respect to hot-spots using ENGEBRETSON *et al.*'s (1981) finite rotations. Antarctica was fixed; Australia is rotated with respect to Antarctica using the rotation by WEISSEL *et al.* (1977) and CANDE and MUTTER (1982). For the position of northern New Guinea, see text. EP, ST, HS, MP and OJ denote Emperor Seamount Chain, Shatsky Rise, Hess Rise, Mid-Pacific Mountains, and Ontong-Java Plateau, respectively.

to Antarctica using the pole and rotation by WEISSEL *et al.* (1977). I used the revised magnetic anomaly identification by CANDE and MUTTER (1982) to correct the rotation angle of WEISSEL *et al.* (1977) up to 48 Ma. The Eurasian, North and South American and Pacific plates were rotated with respect to hot-spots using the rotation poles and angles by ENGEBRETSON *et al.* (1981). The northern half of New Guinea were reconstructed as follows. First it was rotated back to 25 Ma with Australia because it has been with Australia after the collision at about 25 Ma. From 25 through 43 Ma, it was rotated back with the Pacific plate. There is no strong evidence for this and the reason of this rotation will be described in the next section. From 43 through 48 Ma, it was translated to the north more or less arbitrarily along with the hypothesized southward motion of the North New Guinea plate during this period. The reconstruction of the Philippine Sea is from SENO and MARUYAMA (1984). The marginal basins younger than the Eocene (Fig. 1) are all closed.

The reconstructed position of northern New Guinea and the Coral Sea poses a problem; northward subduction occurred along the southern margin of northern New Guinea and simultaneously southward subduction occurred along the northern margin of the Coral Sea Basin. Because northern New Guinea and the Coral Sea Basins are located in a similar longitude in Fig. 6, the North New Guinea plate is difficult to subduct beneath the Coral Sea Basin.

To avoid this difficulty, I postulated another small plate, subducting southward beneath the Coral Sea Basin, south of northern New Guinea as shown in Figure 6. We can avoid this ad-hoc postulate if the North New Guinea plate was moving southwestward with respect to the hot-spots. This might be better concordant with the paleomagnetic evidence of a counterclockwise rotation of northern New Guinea since Cretaceous (GREEN and PITT, 1966). In that case the trend of the Bonin-Mariana arc became normal to the convergence direction.

The eastern half of the southern New Hebrides Basin in Figure 6, which has been subducted beneath the north Fiji Basin, was attached to the western portion visible at present. The amount of extention of this basin to the east is not determined uniquely. If the Pacific plate is rotated back to 15 Ma the when arc polarity reversal probably occurred along the Solomon - New Hebrides arc (KARIG and MAMMERICKX, 1978; DUNKLEY, 1983) and the north Fiji Basin is closed, a much larger area will appear at the east of the present New Hebrides Basin. I suggest that in this large area back-arc basins of Oligocene - mid Miocene age existed, which would have now been consumed beneath the north Fiji Basin and the adjacent Pacific plate.

On the basis of the above reconstruction of the continents and plate boundaries, the configuration of the North New Guinea plate is drawn in Figure 6; the position of the ridge-transform fault system is more or less arbitrary. However, as will be discussed in the next section, if the ridge subduction south of the Pacific plate was the cause of the Pacific plate motion change at 43 Ma, the ridges cannot be placed much further to the north. Some submarine features in the Pacific Ocean were also reconstructed in Figure 6; they are the Emperor Seamount Chain, Shatsky and Hess Rises, mid-Pacific mountains, and Ontong-Java Plateau.

DISCUSSION

By introducing the North New Guinea plate, some enigmas in the evolution of the western Pacific can be solved. First, the abrupt change of the Pacific plate motion around 43 Ma can be explained simply by the subduction of the ridge system south of the Pacific plate beneath the northern Australian margin if we assume that it occurred around 43 Ma. Major driving forces of plates are the gravitational pull of the slab and the ridge push force (FORSYTH and UYEDA, 1975; HAGER, 1978; CHAPPLE and TULLIS, 1979; CARLSON *et al.*, 1983). If the ridge system disappeared south of the Pacific plate, it is expected that the Pacific plate motion changed. Actually GORDON *et al.* (1978) showed that the present motion and the motion at 65 Ma of the Pacific plate can be calculated by the plate boundary geometries at these times proposed by HILDE *et al.* (1977). The geometry of the plate boundary around the Pacific plate at 65 Ma of HILDE *et al.* (1977) is almost similar to that shown in Figure 6 except for the existence of subduction zones along the northern margin of Australia, it is expected that the geometry shown in Figure 6 will also produce the north-northwestward motion of the Pacific plate. Recently, YAMANO and UYEDA (1983) demonstrated that the geometry in Figure 6 and extinction of the ridge system south of the Pacific plate can produce the change of the Pacific plate motion as represented by the Emperor-Hawaiian bend, by postulating the ridge push force as large as the slab pull force.

In order to cause the ridge subduction to occur, the southward component of the absolute motion of the North New Guinea plate should be larger than the half spreading rate at the ridge system south of the Pacific plate. This does not seem unrealistic provided that the ridge subduction actually has been occurring beneath western North America since the middle Tertiary (ATWATER 1970).

After the change of the Pacific plate motion, some segments of the plate boundary of the western Pacific region would have turned into subduction zones as proposed by HILDE *et al.* (1977); they are the southern part of the Palau-Kyushu Ridge (proto-Mariana arc), and Tonga-Kermadec arcs. The Solomon-New Hebrides arcs might have initiated before this change of motion because the basement of these island arcs has late Mesozoic age (COLEMAN, 1970).

These older island arcs also might be originated by the subduction of the North New Guinea plate beneath the northeastern margin of Australia.

Most part of the North New Guinea plate would have subducted beneath the marginal basins along the northern margin of Australia; however, the segment which contained northern New Guinea could not have subducted because the arc polarity was reversed in this segment. I speculate that the segment of the North New Guinea plate which contained northern New Guinea was captured by the Pacific plate at this time and continued travelling with the Pacific plate until it collided with southern New Guinea in the early Miocene. The reconstruction of the paleo-position of northern New Guinea shown in Figure 6 is based on this idea. The subduction along the southern coast of northern New Guinea continued even after it was captured by the Pacific plate because the relative motion between the Pacific and Australian plates had a convergent component since 43 Ma. This might have resulted in back-arc spreading north of northern New Guinea and formed the Caroline Basins during the Oligocene. Part of the Caroline Basins was possibly consumed beneath northern New Guinea or beneath the Pacific plate by subduction since the early Miocene collision of northern New Guinea with southern New Guinea.

Forearc or near trench volcanism would have occurred along some subduction zones associated with the ridge subduction and succeeding initiation of subduction of a very young hot plate. Boninites of middle Eocene-early Oligocene age along the Bonin-Mariana arc (e.g., SHIRAKI and KURODA, 1977; MEIJER, 1980; BLOOMER, 1983) and northeastern Papua (DALLWITZ 1968) might be associated with the subduction of the ridge system and very young plates. If this is the case, it may not be necessary to assume a large amount of tectonic erosion, as BLOOMER (1983) did, to explain the island arc type volcanism beneath the Bonin-Mariana inner trench slope. However, more direct evidence of the ridge subduction around 43 Ma is necessary to substantiate the idea.

Implications of the North New Guinea plate hypothesis to the tectonic evolution of the southeastern Pacific region is not in the scope of the present paper. However, it is possible that the fragments of the North New Guinea plate existed also in the southeast Pacific; the Aluk plate (WEISSEL *et al.*, 1977; CANDE *et al.*, 1982) might be a possible candidate.

CONCLUSIONS

On the basis of geological and geophysical data from the western Pacific, I conclude that the North New Guinea plate existed in the southwestern Pacific during the early Tertiary. The ridge-transform fault system separated this plate from the Pacific plate. The expected ridge subduction beneath the northern margin of Australia would have resulted in the abrupt change of the Pacific plate motion at 43 Ma Northern New Guinea possibly migrated with the Pacific plate since 43 Ma. and collided with southern New Guinea in the early Miocene. The subduction along the south-facing Northern New Guinea arc during the Oligocene would have formed the Caroline Basins as a back-arc basin.

Although for the evidence of the new plate to be found from all the segments along the northern margin of Australia is too fortuitous to consider that it is a mere coincidence, much more data are needed to substantiate this hypothesis. The melanges accreted since the middle Eocene along the Japan-Bonin-Mariana arc might be able to provide data regarding the age of the oceanic lithosphere which has been subducted and might be helpful to discriminate whether a young plate produced by the North New Guinea-Pacific ridge existed eastward of these arcs.

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Fundamental Framework of Arcs in the NW Pacific Rim

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ABSTRACT

There is a fundamental framework which characterize an arc. It consists of trench, forearc basement high and volcanic chain. Backarc basin is also one of them in the Western Pacific. Arc geomorphology is variable both spatially and in geological time. There are variable features even within a single arc.

A possible mechanism for arc volcanism and spreading of the backarc basin is suggested. This is related to the formation of the subduction complex at the trench. They are caused by the convection current under the arc formed by the frictional heating along the upper surface of the subducted oceanic plate. The characteristic feature is that since they are caused by similar mechanism, they are incompatible. In other words, when arc volcanism is active, backarc spreading is dormant and accretionary wedge is formed at the trench. When arc volcanism is less active, spreading occurs in the backarc and subduction erosion occurs at the trench. It is known that the stress conditions affects the formation of the fundamental elements of the arc. One possibility is that the alternative activities may be caused by the change of the stress condition of the arc whether it is highly compressed or not.

Fan spreading is suggested as a mechanism for the formation of backarc basin related to the arc activity although there may be mid-oceanic rift type spreading apart from the control of the arc formation in some of them.

INTRODUCTION

Arc is a characteristic feature in the convergent margins and is essentially formed by the subduction of the oceanic plate. Studies on arcs have been advanced by offshore surveys in many regions of the circum-Pacific arcs associated with the development of the plate tectonics concept since middle of the 1960s. New models for modern arc have been presented as a result of more recent surveys, especially by multichannel seismic data and by Deep Sea Drilling Project (DSDP) in the convergent margins.

Japanese and its neighbouring islands consist of sereral arcs. They are the Kuril, the Tohoku (NE Japan), the Seinan (SW) Japan, the Ryukyu, the Bonin (Ogasawara) and the Mariana Arcs (Fig. 1). There are a few paleo-arcs in the same area. They are the Hidaka, the Seinan Japan and the Daito Paleo-arcs. The Seinan Japan Arc and Paleo-arc overlap in Southwest Japan where the latter had been active during Cretaceous to Early Paleogene.

There are some arcs which do not have any backarc basins as are seen in the arcs of the eastern Pacific Rim. There are some double arcs, not only backarc basin but also an additional (secondary) arc in the inner side of the convergent margin with an additional backarc basin as are seen in the situations of the Bonin and the Seinan Japan and the Ryukyu Arcs, and the Mariana and the Philippine Arcs.

In these arcs, there are several fundamental elements which constitute the arc, although some of them are discontinuous (HONZA, 1981). They are trench, forearc basement high and volcanic chain. Backarc basin (marginal sea) is also one of the fundamental elements in the western Pacific Rim (Fig. 2).

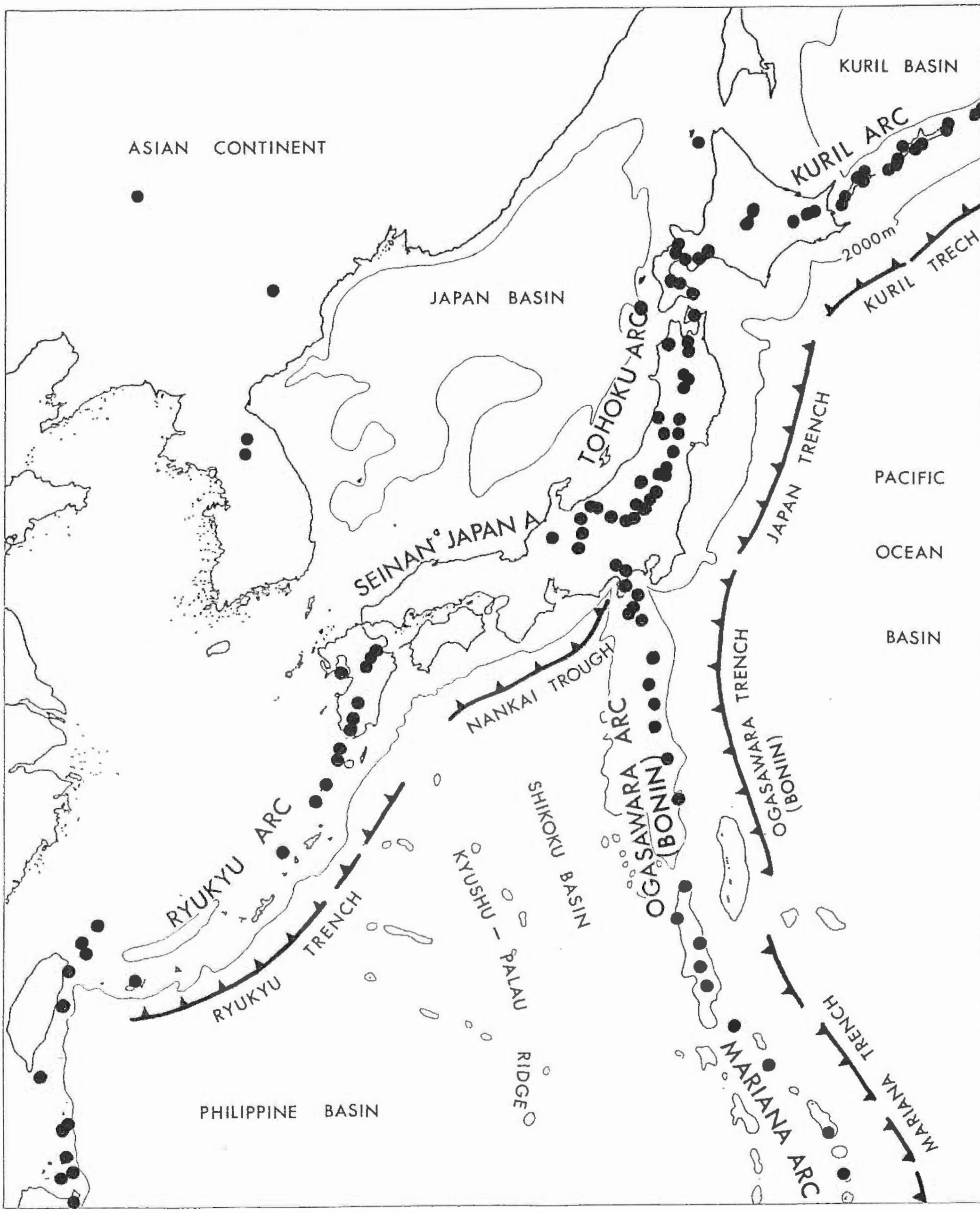

Fig. 1. Arcs in the NW Pacific Rim. Holocene volcanoes are shown in closed circles (HONZA, 1983).

There are some models to distinguish arcs by the geomorphological conditions. Some of them are based on the forearc phenomena (DICKINSON, 1973, KARIG and SHARMAN, 1975,; SEELY *et al.*, 1979; HONZA, 1981) and some of them are based on the existence of a backarc basin (UYEDA and KANAMORI, 1979).

With the accumulation and development of arc data at sea, onshore geology is also re-

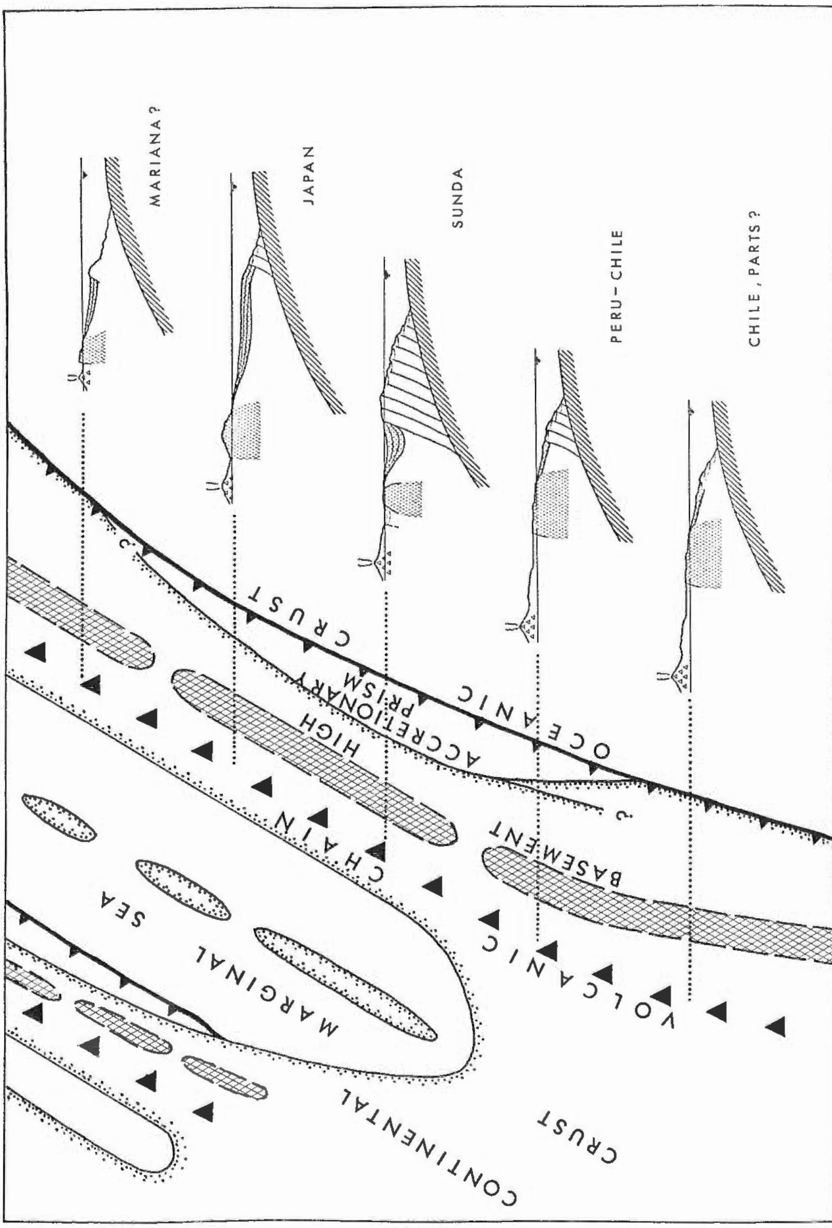

Fig. 2. Arc geomorphology based on the fundamental elements which constitute arc. Some of these elements are discontinuous and variable.

examined in order to establish the paleo-geomorphology on the basis of modern arc concept. This work is also reflected in understanding the tectonics of the modern arc. This suggests that the works both offshore and onshore influence each other in advancing the understanding of arc.

This is an attempt to present some fundamental frameworks of the arc systems on the basis of offshore works in the northwestern Pacific Rim.

GEOMORPHOLOGY OF ARCS

Zonal arrangement parallel to the arc was first postulated in the Tohoku and the Seinan Japan Arcs on the basis of onshore studies in which the arc was documented to be a feature associated with subduction of oceanic lithoshere at the convergent margin (MATSUDA and UYEDA, 1970; SUGIMURA and UYEDA, 1973).

Several different morphological terms have been used for arcs. The term arc is here applied to the area between the backarc basin and the outer edge of the oceanic trench associated with that arc (SEELY, 1979; HONZA, 1981). Some characteristic features are observed in the arcs. There are steep slopes in the landward side of the trench. A gentle high is commonly observed in the outer margin of the slope transit to the oceanic basin. There is a nick-point or break in the landward side of the slope which is referred to as trench slope break or ridge. The term inner trench slope is used here for the deeper part of the slope from the break to the trench on which benches may occur. The terms outer trench slope is used for the oceanward slope of the trench and trench swell, instead of outer arch or outer rise, for the outer morphologic bridge oceanward of the trench (Fig. 3).

In the forearc area, a basement high between the volcanic chain and the trench consists of mountains onshore or a submarine high overlain by modern slope sediments. Volcanic chain consists of a ridge or a chain of highs in the inner side of the basement high.

From the geomorphology of the forearcs, three types can be distinguished, the first consists of a slope underlain by continental crust and others with slope partly underlain by an accretionary wedge. Forearcs of the former type can be categorized as consumption or subduction erosion. The latters consist of one type dominantly underlain by a continental crust which is categorized as continental forearcs and the other dominantly underlain by an accretionary wedge and categorized as accretionary forearcs in which the subduction complex extends upward to the trench slope break (Fig. 4). Common features associated with all of the forearcs are the active volcanic chain, the basement high and the trench, even there discontinuities may exist in some of the features in them. Basins filled with sediments to varying extent

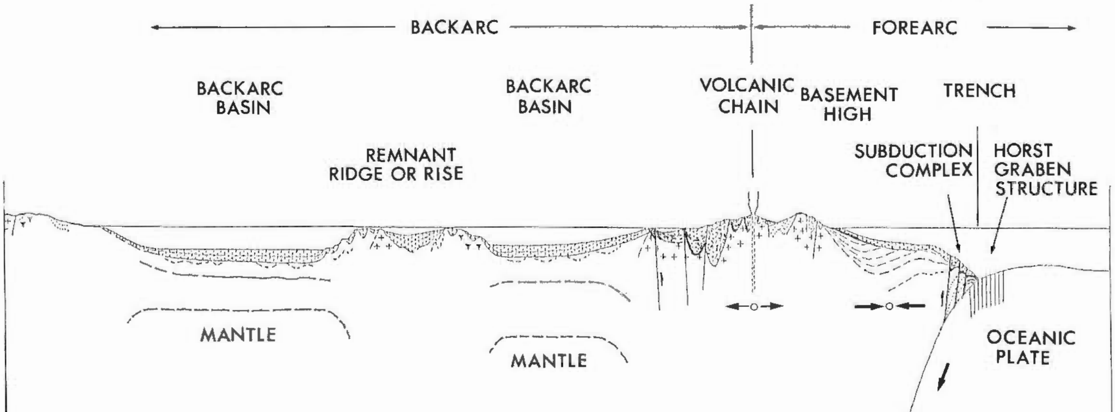

Fig. 3. Arc geomorphology illustrated in a diagrammatic profile in the Tohoku Arc.

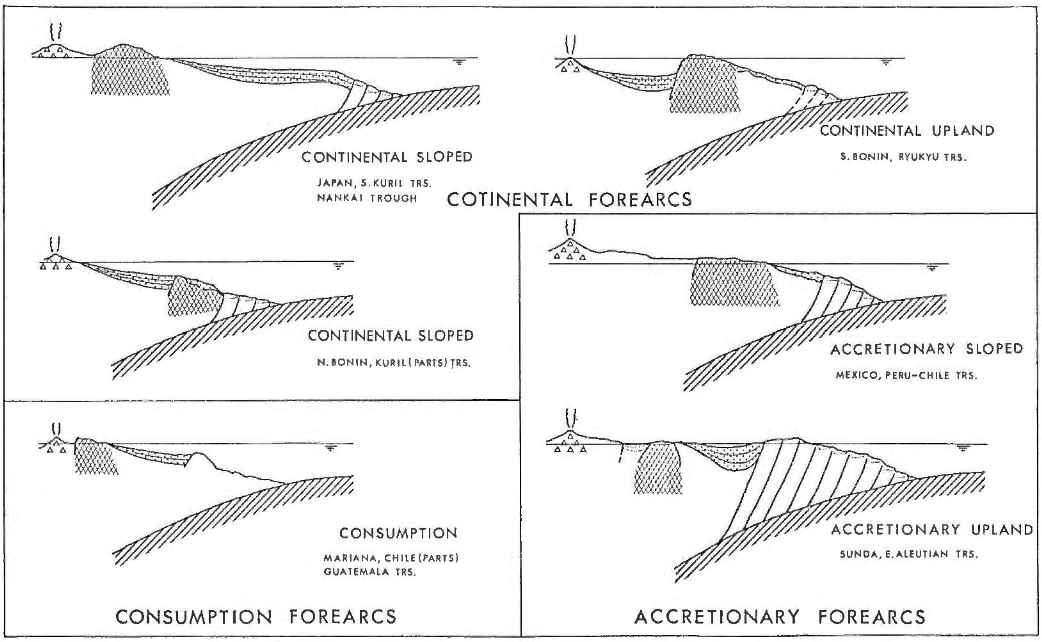

Fig. 4. Models of modern forearcs. Fundamental framework of the forearc is similar in all cases, except in the model for consumption. Open triangle: volcanics, dotted layers: modern sediments and cross hatches: forearc basement high.

may occur among the volcanic chain, the basement high and the trench. The position of the basement high is variable. There may be a mountain range onshore such as in the Tohoku Arc, Seinan Japan Arc and Peru-Chile Arc or a mid-slope high (trench slope break or outer high) such as in parts of the Bonin Arc, in parts of the Mariana Arc and parts of the Kuril Arc, or an island chain such as in the Ryukyu Arc and in parts of the Bonin and Mariana Arcs.

SUBDUCTION AND ACCRETION AT TRENCH

The concept of accretionary wedges for convergent margins was developed by the interpretation of multi-channel seismic data and by the drilling results of the Deep Sea Drilling Project (DSDP) in the Pacific Rim.

The first, imbricated thrust model for accretionary wedge was proposed on the basis of seismic data in the Sunda and the Middle America Trenches (BECK and LEHNER, 1974; SEELY *et al.*, 1974; KARIG and SHARMAN, 1975).

Subduction Erosion and Continental Sloped Forearc

Recent DSDP drilling works in the convergent margins provided significant information for construction very clear models for accretionary wedges in the Japan Trench (VON HUENE *et al.*, 1982), in the Mariana Trench (HUSSONG *et al.*, 1982), in the Middle America Trench (VON HUENE *et al.*, 1982; WATKINS *et al.*, 1982) and in the Nankai Trough (KARIG *et al.*, 1983). From the results of these drillings, different models were also constructed for the process not only of accretionary wedges, but also of consumption in the subduction zones. The consumption type is postulated for the Mariana Trench.

Different process of arc development is suggested for the Japan Trench, namely subduction erosin in earlier stage which to form accretionary wedge in the latest stage (HONZA, 1981;

VON HUENE *et al.*, 1982). There may be different processes between the north and the south Middle America Trenches. A progressive accretionary wedge is suggested in the northern part (MOORE *et al.*, 1982), while large scale sediment subduction is suggested in the southern part (VON HUENE, *et al.*, 1982).

Sediments in the inner trench slope are deformed by the subduction process of the oceanic plate. Some of the sediments on the outer trench slope are accreted over the trench instead of subducting under the arc and are covered by the terrigenous sediments supplied from the upper part of the inner slope. These sedimentary and structural processes have resulted in a complicated deformation forming a subduction complex at the trench. Studies on tectonic process and on formation mechanism in the subduction zone are needed to clarify these variations both in time and in space.

A model without accretion of the oceanic sediments from the outer side of trench is a type of "subduction erosion". This may be a transition zone on the inner side of the trenches which is characterized by sheared and mixed features on seismic profiles. There may be less compressional stress at the subduction erosion trenches, deducing from no occurrence of accretion.

One possible mechanism to have less compressional stress at trenches is the case when the force is relatively small near the surface of the trenches and is converted to hirozontally high compressional stress in the deeper parts of the subducted slabs. This is suggested in the earthquake solutions along the subducted slabs in the Japan Trench (YOSHII, 1978). In this trench, there is a strike slip vector under the inner trench slope. Horizontal tensional force is observed near the surface of the outer trench slopes. Horst and graben structures occur in the outer trench slope by bending of oceanic plate at trench and horizontal tensional force is formed on the upper surface of the bended plate.

The other possibility is to have less compressional stress at the trench, such as gravitational pull caused by a heavy plate under the arc. In this case, the subduction angle may be steep enough to pull the upper parts of the oceanic plate and asthenosphere. Some problems, however, remain in this case, namely features commonly observed in the forearcs some of which are interpreted to be caused by the horizontal compressional stress over the forearc area. For example, there are ultramafic cones in the inner trench slope of the subduction erosion forearc of the Mariana Trench (HONZA and KAGAMI, 1975; HUSSONG and FRYER, 1983) and of the Bonin Trench (B. TAYLOR, *personal commun.*). Serpentinite cones in the forearc slope may be dehydrated material mixed with the oceanic basement and uplifted by the horizontal compressional stress beneath the slope.

It is thus necessary to clarify the stress field of the subduction erosion trench in detail.

Accretion at trenches is essentially formed by the thrust and overthrust movements. There are high and low angle thrust and overthrust faults in the accretionary wedges.

Relatively high angle thrust faults are observed in the Japan Trench. The Late Cenozoic and underlying Upper Cretaceous sediments (continental basement) show an abrupt change in the lower part of the inner trench slope. The stratified Late Cenozoic sediments (forearc sediments) and an unconformity between the underlying Upper Cretaceous sequence on the continental slope cannot be observed in the lower part of the inner trench slope (Fig. 5). Vague discontinuous horizontal reflectors are observed among the dominant reflectors dipping landward. These reflectors may suggest sheared faults which caused deformation of the horizontal layers. The oceanic basement which can be traced from the outer trench slope under the trench to the subduction complex is cut by several large thrust faults. There is uncertainty in the area between the continental basement and the subduction complex where no thrust faults are recognizable in the profile. However the layers are deformed along the contact zone between the continental basement and the subduction complex.

The thrust faults which occur in both the subduction complex and the underthrusted oceanic basement suggest that there is no displacement along the bottom of the accretionary wedge.

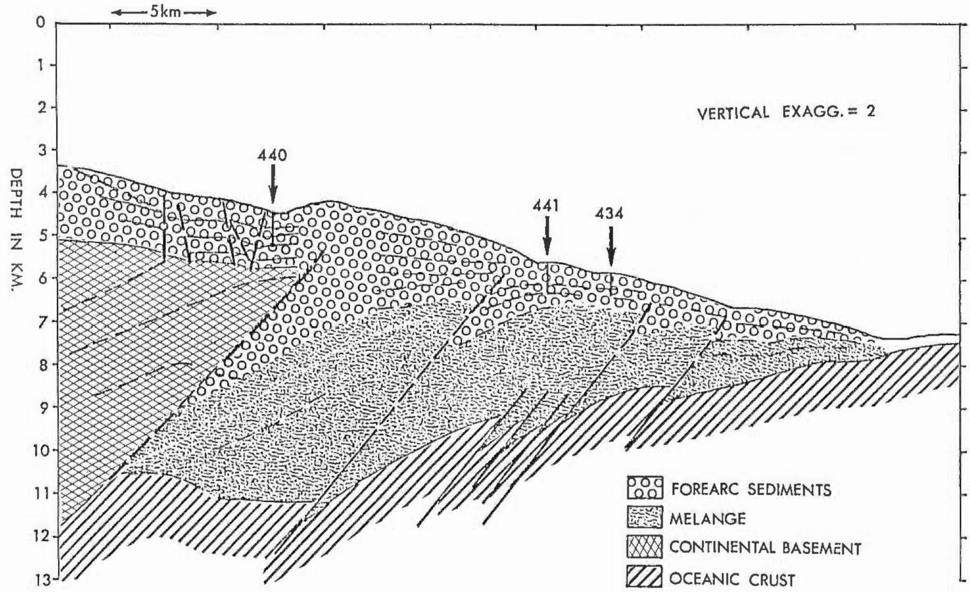

Fig. 5. Diagrammatic structural interpretation of a multi-channel seismic profile in the Japan Trench (HONZA, 1981).

An unit presumed to be a melange which constitute the accretionarty wedge is fixed upon the oceanic basement on the inner trench slope and there may be no consumption of the melange under the arc in this area. It is inferred from this fact that there may be a retreat of the trench axis toward the ocean side by the development of the accretionary wedge.

Accretion in the Nankai Trough

A few cases of accretion are distinguished in the Nankai Trough (HONZA and MURAKAMI, in press). One is associated rather higher angle imbricated thrust faults. Here, some of these thrust faults may have developed through the subducted basement as is observed in the Japan Trench. This process may contribute to the underplating of oceanic basement in the accretionary wedge. Rather lower angle imbricated thrust faults are dominant in the second group. They change to overthrust faults near the surface and the decollements in the deeper parts. The third is a mixture of the both high and low angle thrust or overthrust faults. Accreted sediments are blocked in units of high and low angle thrust faults. Layered sediments which overlie the hemipelagic seiments in the Shikoku Basin consist of turbidites (KINOSHITA *et al.*, 1975; KARIG *et al.*, 1983). Thick turbidites may offer a favorable condition for offscraping and underplating by accretion (COWAN and SILLING, 1978; MOORE *et al.*, 1982).

Accretionary wedges in the eastern part of the Nankai Trough have variable profiles. The angle of landward dipping reflectors change remarkably. It is inferred from these profiles that the angle of significant thrust or overthrust faults are controlled by both subduction angle and morphology of subducted basement. If there are topographic highs, the thrust faults on them are complicated and form many high angle thrust faults on both sides of the highs. On a smooth basement, relatively uniform imbricated thrust faults with relatively long segments are formed (Fig. 6).

Imbricated thrust faults are discontinuous with wavy patterns. In many cases of landward imbricated units, layers near the surface are overthrusted and have depressions where some amount of terrigenous sediments are ponded approximately 10 km from the bottom of the inner trench slope. This overthrusted feature is concordant with an offscraping model initially

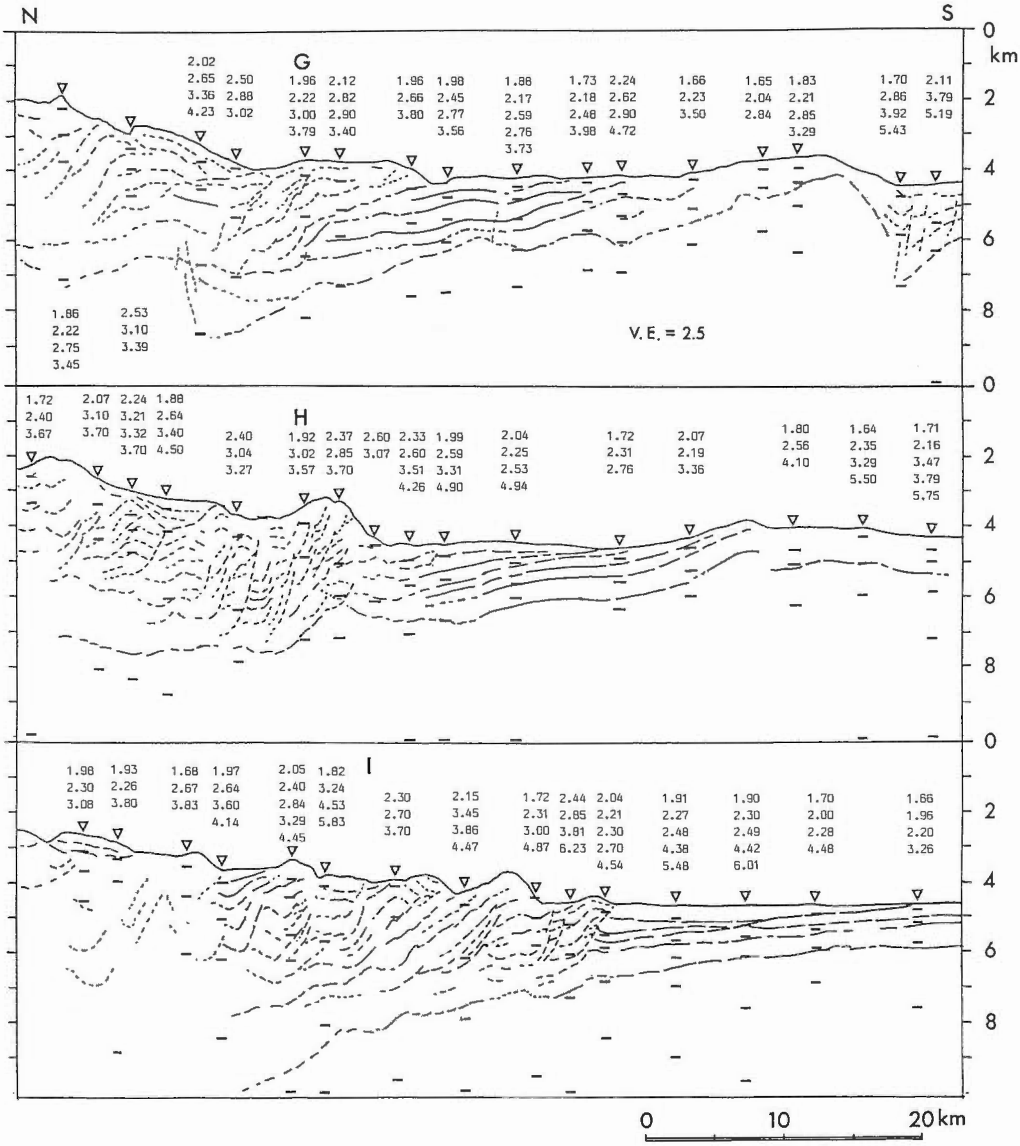

Fig. 6. Interpreted profiles of migrated depth sections in the Nankai Trough off Kill Peninsula, east to west in decending order. (HONZA and MURAKAMI, in press).

documented by SEELY *et al.* (1974). Apparently offscraped units have a uniform total thickness throughout the accretionary wedge, except for a few initial units near the trough.

Underplating by decollements tends to increase in thickness landward by increase of number of decollements. Total increase of thickness of accretionary wedges on the decending subducted basement under arc is supplied by increase of underplating. Offscraping is approximately of the same thickness throughout the lower and upper slope of accretion (Fig. 7). Thrust faults are discontinuous and show wavy patterns with a few to several kilometers long. Within an unit, internal velocity tends to increase downward. There is a high velocity layer even in the initial unit near the trough.

Landward thickening of underplating may be different from the underplating process noted

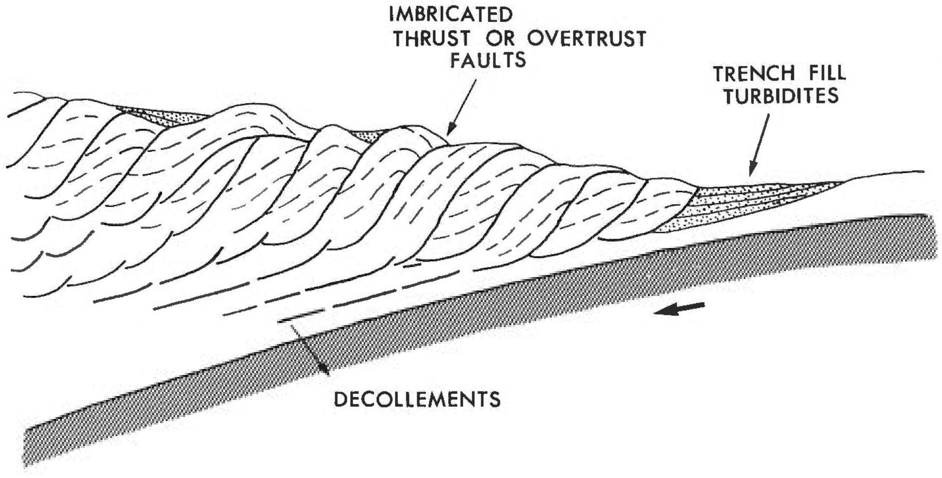

Fig. 7. A model of acction in the Nankai Trough. Imbricated offscraping by thrusts and overthrusts are dominant in the upper horizon and underplating by decollements are dominant in the lower horizon (HONZA and MURAKAMI, in press).

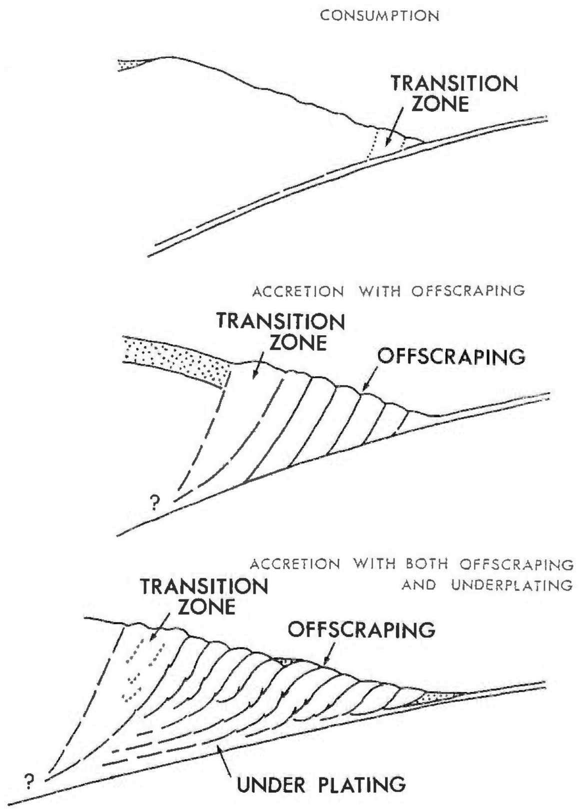

Fig. 8. Forearc models on basis of formation mechanism in the convergent margin. Consumption or subduction erosion is associated with subduction of oceanic and continental materials. Some of accretion are only associated with offscraping and some of that with both offscraping and underplating.

in the Middle America Trench (WATKINS *et al.*, 1981; MOORE *et al.*, 1982). Subduction erosion process noted in the south of the Middle America Trench (VON HUENE *et al.*, 1982) may have the same feature as the underplating process in the Nankai Trough, neverthless there is an additional thickening of underplating by the generation of decollements changed from imbricated thrust faults of the upper horizon in the Nankai Trough. This may be originated by the fundamental difference which controls not only the forearc but also the whole arc (HONZA, 1983). There is less possibility of this difference coming from sediment composition and thickness at the trench.

From these results in the convergent margins of both sides of the Pacific Ocean, some types of the trench system can be distinguished. The first is subduction erosion or consumption at the trench. The second is association with imbricated thrust faults and the third is association with both imbricated thrust faults and underplated decollements (Fig. 8).

In most of the seismic reflection data in the forearcs, there is a less reflective area in the landward side between the continental mass and the trench or the accretionary wedge. This is a transition zone between them and suggests some deformation of both continental and oceanic material by subduction. The material transition zone may consist of sediments deposited before the start of accretion or earlist accreted sediments (WATKING *et al.*, 1981).

FOREARC BASEMENT HIGH

Arcs are commonly associated with forearc basement high which is one of the fundamental elements constituting the arc (HONZA, 1981). The basement highs consist of rocks older than the development of the arc, and is located between the trench and the volcanic chain. The Kitakami and the Abukuma mountains form the forearc basement highs in the Tohoku Arc. Some of the highs constitute the island chain, such as in the Ryukyu and the Bonin Arcs. A long narrow forearc basement high is developed in the Chile Arc. Here the high consists of Pre-Cambrian and Paleozoic formation.

In some areas, forearc basement high cannot be seen, but highs exist in the mid-slope. The Ogasawara Islands form the forearc basement high in the southern Bonin Arc while there is a high in the mid-slope area on the northern extension of the Ogasawara Islands. The northern high consists of a trench slope break of the Bonin Trench and do not show highly uplifted feature as in the southern arc (Fig. 9).

Some of these highs are interpreted to have formed by the horizontal compressional stress as an extension of the stress field over the trench. However, most of them are free from the effect of the subduction complex and is located at some distances inside from it. This fact suggests that the forearc basement high was originated by the deeper tectonics of the arc.

ARC VOLCANISM

Arc volcanism occurs in a chain or in a zone along arcs, some hundreds of kilometers landward of the trenches. This feature of arc volcanism is noted as an indication of a possible control of subduction of an oceanic plate under the arc. However, the mechanism of the heat rising to the surface from the deeper part under the arc to produce the arc volcanism is not yet satisfactorily explained.

The chain distribution of the arc volcanoes is commonly observed in most of the arcs of the circum-Pacific Rim, except for some arcs in which a zonal distribution is observed. A zonal distribution of modern arc magma is well known in the Tohoku and the northern Ogasawara Arcs in which three main volcanic rock series of tholeiitic, calc-alkali and alkalic series are recognized. The zonal distribution is also observed in Kamchatska, parts of the Philippines, Mexico and a part of the Chilean Arcs.

The difference between a chain and a zonal distribution in modern arc volcanism seems

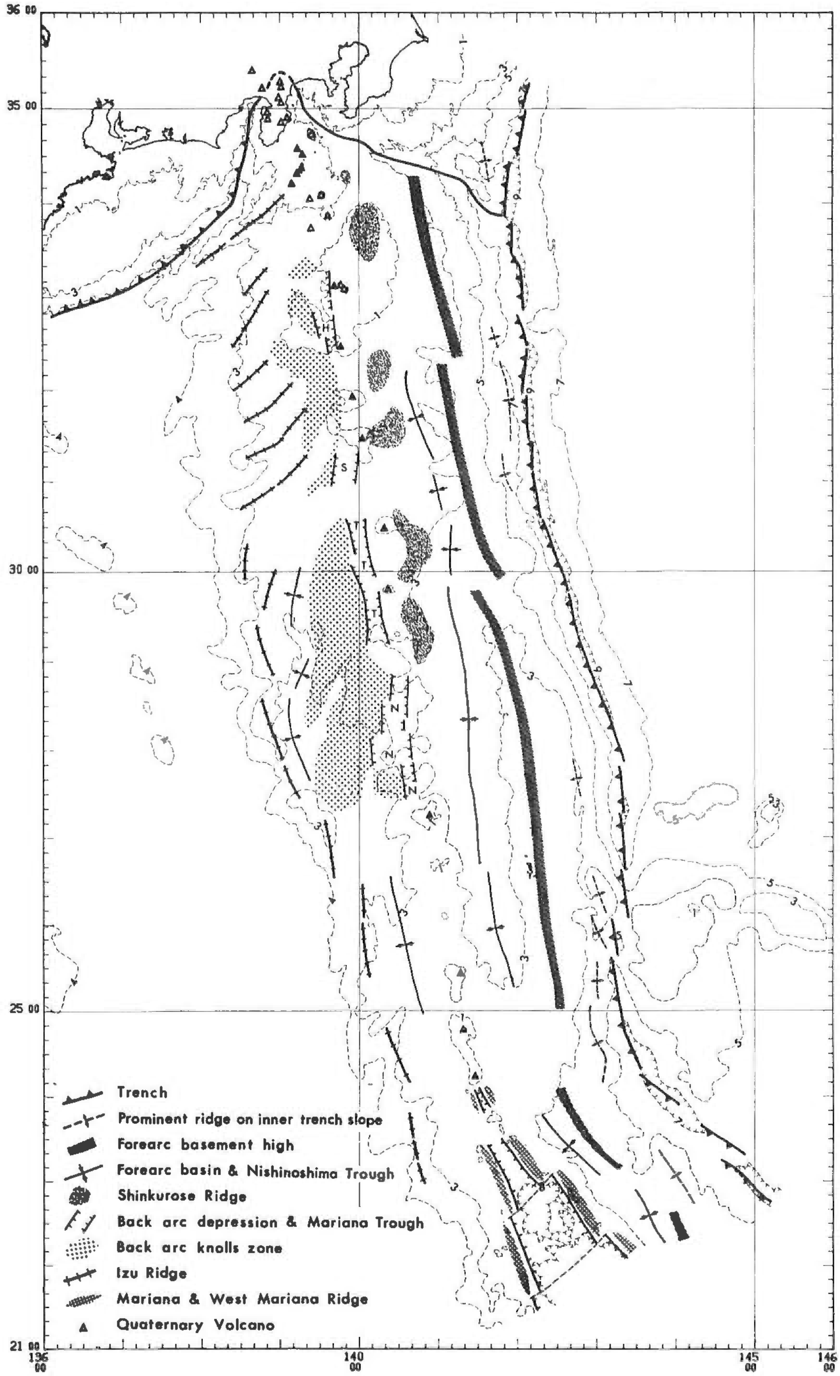

Fig. 9. Geological structure of the Bonin Arc and the northern Mariana Arc. En echelon arrangement of the forearc basement highs is noticed in the Bonin Arc (HONZA and TAMAKI, in press).

to be related to the difference in geometric scale of the arcs. At least, as a surfacial phenomenon, relatively wide arcs have a zonal distribution while narrow arcs have a chain volcanism. This fact seems to imply that arc volcanism occurs essentially as a chain eruption and is variable to zonal distribution by the enlargement of geometric scale of the arc bodies. Some exceptions may appear at the junction of arcs where some complex tectonics may develop as suggested in the Mexican Arc.

Activity of arc volcanism is not uniform during its history. Radiometric age determinations on the Tohoku, the Seinan Japan and the Bonin Arcs (KANEOKA *et al.*, 1970; TANAKA and NOZAWA eds., 1977; TSUCHI ed., 1979) show histories of arc intermittent volcanism (Fig. 10).

Some uncertainties remain regarding the beginning of volcanism in the Tohoku Arc in which stratigraphic and biological studies support late Oligocene, but earlier ages up to early Oligocene were obtained by absolute age determinations for several samples. The beginning of the activity of the Tohoku Arc is also suggested in the forearc area where young sedimentary basins were formed since late Oligocene (HONZA, 1981; VON HUENE, LANGSETH, *et al.*, 1980).

Apparently, volcanic activity occurred continuously in the Tohoku Arc since late Oligocene, although the intensity of volcanism were variable. Evidences show the occurrence of intense volcanism in early Miocene, gradually decreasing until late early Miocene, weak volcanism during middle Miocene and gradually increasing again in late Miocene (ISSHIKI, 1977).

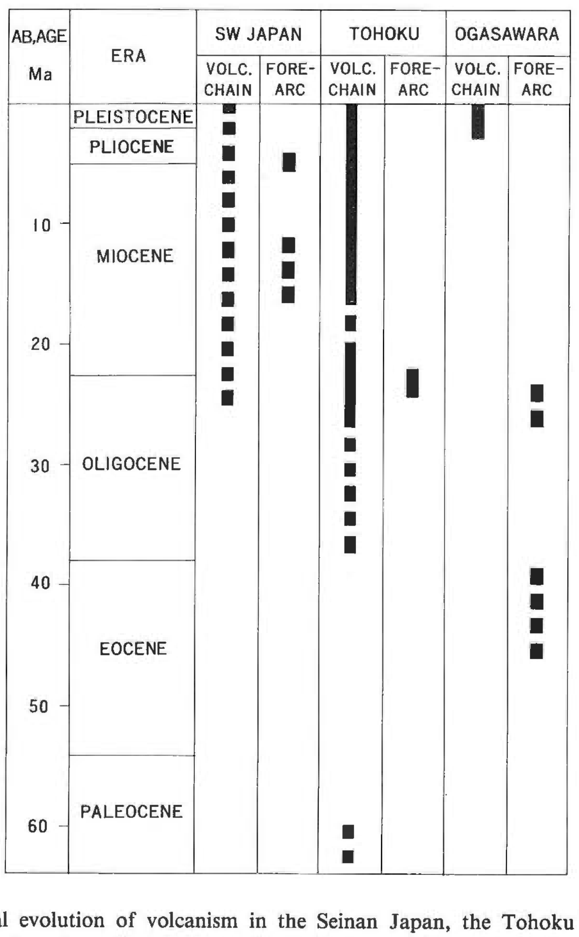

Fig. 10. Historical evolution of volcanism in the Seinan Japan, the Tohoku and the Bonin Arcs based on the radio metric age determinations without any consideration on intensity of volcanism. (HONZA, 1983).

Volcanic history is not clear in the Seinan Japan Arc, because of sparse age data. However, a continuous eruption was taking place apparently during its development and a unique volcanism occurred in the Setouchi forearc area during middle Miocene (TSUCHI ed., 1979).

Volcanism of the Bonin and the mariana Arcs was intermittent since middle Eocene, although the data obtained are only from the islands which occupy small areas on the ridge (Table 1). There probably were three stages of volcanism in the Bonin and Mariana Arcs, the first

Table 1. Stratigraphy of the Bonin and the Mariana Arcs (Shikoku Basin from KARIG and INGLE, *et al.*, 1975. DEVRIES and KOBAYASHI, *et al.*, 1980 and WATTS and WEISSEL, 1974. Ogasawara Arc from KUNO, 1968, MIYASHIRO, 1974, KANEOKA *et al.*, 1970, HANZAWA, 1947, IWASAKI and AOSHIMA, 1970, MATSUMARU, 1974, and UJIIE and MATSUMARU, 1977. Mariana Arc from LADD, 1966).

	SHIKOKU BASIN	SHICHITO RIDGE	OGASAWARA RIDGE	MARIANA RIDGE
Quaternary	hemipelagic sediments and turbidites	volcanic rocks		Mariana Limestone
Pliocene				
Miocene	volcano-clastics			Alifan Ls. Bonya Ls.
Oligocene			Minamizaki F. volcanoclastics	Umatac Formation Alutom Formation
Eocene			Sekimon F. Okimura F. Yusan F.	
Paleocene				
References	DSDP results (Karig, Ingle et al., 1975; deVries Klein, Kobayashi, et al., 1980); Watts and Weissel, 1974.	Kuno, 1968; Miyashiro, 1974; Kaneoka et al., 1970.	Hanzawa, 1947; Iwasaki and Aoshima, 1970; Matsumaru, 1974; Ujiie and Matsumaru, 1977	Ladd, 1966.

from middle to late Eocene, the second during late Oligocene and the last since late Pliocene. Latest Miocene (7 Ma) was suggested by recent age determination of samples from the northern margin of the Mariana Ridge, while in the Bonin Arc, Miocene age has not been obtained from both the Bonin and the Shichito Ridges (HONZA and TAMAKI, in press.).

The last volcanism which formed the volcanic chain of the present Bonin Arc occurred on a different line as compared to that of the earlier two stages which occurred on the Bonin Ridge. The Bonin Ridge is the forearc basement high of the present Bonin Arc. The volcanic chain (Shichito Ridge) is approximately 100 km west of the earlier volcanism (Bonin Ridge) intervened by the Bonin Trough in betweeen.

The Mariana Arc located on the same morphologic line as the Bonin Arc have somewhat different features. There are, from west to east, the West Mariana Ridge, Mariana Trough which is a possible active spreading backarc basin, and Mariana Ridge consisting of both volcanic chain and forearc basement high. Volcanic chain and forearc basement high seem to separate gradually southward until the middle part of the arc (HESS, 1948). Volcanism do not occur to the south of Saipan Island.

Geomorphologic variation is also observed in the Ryukyu Arc where different features are distinguished between the northern and the southern parts. The northern arc has a volcanic chain (Tokara Volcanic Chain) and the backarc basin is not observed clearly, only showing gradual deepening toward the south. The southern arc has no volcanic chain and a few volcanics are found in the narrow faulted depressions along the center of the Okinawa Trough (HONZA, 1977; HERMAN *et al.*, 1978). However, it is not certain whether the volcanics are a part of the present volcanic chain or not.

A small shift of the volcanic chain is also noted in the Tohoku Arc during Neogene, the older volcanic chain was probably located a little to the forearc side as compared with that in Recent (NAKAMURA, 1969).

BACKARC BASIN

Backarc basin is interpreted to be essentially formed by the horizontal tensional force which occurred in the backarc area creating a new oceanic crust. However, the mechanism of the formation of the tensional force is not yet clear. Many backarc basins observed in the western Pacific show a contrast to the system in the eastern Pacific without these basins. The North and the South America Plates are drifting westward which implies the application of horizontal compressional stress to the arcs on the Pacific side. This fact suggests that the movement of the continents play important roles for the formation of the backarc basin. The occurrence of the backarc basins may depend on the balance of stress field between compressional stress in the forearc area and tensional force in the backarc area. Backarc basin may not be formed if the retreat of continent is fast enough. In this case, not consumption but passive margin may be formed. Some of backarc basins occur in the fractured or complexly bounded areas of the plates.

Most of the characteristic features suggest that the stress fields of the arcs are commonly horizontally compressional although there are some regionally horizontal tensional fields. There is a model which indicate that the horizontal tensional force in the backarc area is formed by the process of arc formation, that is the process of subduction under the arc. If this is the case, this force may be too weak to constitute a primary force as compared with the compressional stress of the subducted oceanic plate which prevails over the forearc area. If the continent is to retreat with smaller speed than the subduction, the backarc basin may occur while if the continent is to approach the arc, the backarc basin may not be formed.

Active and inactive backarc basins are distinguished from heat flow regime in the western Pacific (KARIG, 1971). It is noted from heat flow values that the Japan, the Yamato, the Kuril and the Shikoku Basins are inactive while the Okinawa Trough is an active backarc basin.

Spreading of the Japan Sea

No Paleogene sediments are distinguished in the Japan and the Yamato Basins (HILDE and WAGEMAN, 1973, KARIG *et al.*, 1975; HONZA *et al.*, 1977; TAMAKI *et al.*, 1981). The lowermost horizontally layered sediments are estimated to be lower Miocene in the Japan Basin and upper Miocene in the Yamato Basin from the assumption of constant accumulation ratio during Neogene. There is a possibility that the diffracted layers beneath the transparent layers

Fig. 11. A fan spreading mosel for opening of the Japan and the Yamato Basins. Marginal blocks on the opposite side of the pole are in different movements as compared with that in the shorter radius.

in the seismic profiles consists of volcanoclastics which are correlated to the miocene and the late Oligocene volcanism in the inner side of the volcanic chain of the Tohoku Arc. If this is the case, the Japan and the Yamato Basins have approximately the same history as that of the Tohoku Arc. A two stage opening of the Japan Sea is suggested in the paleomagnetic analysis of the volcanic rocks in the Seinan Japan (OTOFUJI and MATSUDA, 1983). Three stages of structural movements are distinguished in the sedimentary units of the Japan Sea. They are in the earliest Miocene or the latest Oligocene, late Miocene and in the earliest Pleistocene. The first is correlated to the formation of the Japan Basin and the second to the Yamato Basin and the third to the formation of the ridges along the northeast margin of the Japan Sea.

From geometric analysis, a fan spreading of the Japan Sea is proposed with assumption of a geometric boundary of the continents and ocean on the basis of reflection data (Fig. 11). This model is also concordant with the paleomagnetic analysis of the igneous rocks in the Seinan Japan (YASUKAWA, 1979; OTOFUJI and MATSUDA, 1983). Also differential fan spreading is proposed from the geometry and magnetic data in the Mariana Trough. It is difficult to have a differential fan spreading in the Japan Sea, for there are no differential block movements of the older terrain in the Seinan Japan where long tectonic blocks are fixed since Paleozoic, at the lastest early Mesozoic.

Geometric rearrangement of the original position of the Japanese Islands to the Asian Continent suggests that there is no space in the Japan Basin for the northern Japan. The Japan and the Yamato Basins are occupied by the Seinan Japan blocks. This and other evidences suggest that the Tohoku and the Hokkaido blocks are different in origin from the Seinan Japan block and probably have drifted to the present position from another place. Neverthless a possible original position could be on the northern extension of the Seinan Japan which is the present Tartary Trough.

The direction of the spreading with a pole in the southern Korea Peninsula poses another problem. This direction is oblique to the direction of the Japan Trench. This suggests that the direction of the spreading is not necessarily controlled by the direction of the subducting trench, but by the drifting direction of the continent.

The final stage of the Japan Sea since the earliest Pleistocene is noted to be in the horizontally compressional field, which is observed as ridges and troughs in the northeast margin of the Japan Sea where thrust faults are the dominant feature (HONZA *et al.*, 1977).

Fan Spreading in Other Backarc Basins

If the backarc basins are formed by the fan spreading caused by the subduction at the trench in front of the arc, there is an inconsistency of geometric reconstruction of the backarc basins as shown in the Mariana Trough and in the Kuril Basin (Fig. 12). The fan spreading model is inconsistent with the magnetic lineation in the Mariana Trough. The marginal feature of the opposite side of the pole in the reconstructed model by the fan spreading is also inconsistent in geometry. This feature may occur as a deformation in the margin when it opened.

Some models are proposed regarding the spreading center of the backarc basin. One is along the immediately inner side of the volcanic chain (KARIG, 1971; WATTZ and WEISSEL, 1975; HONZA, 1981; HONZA and TAMAKI, in press). The other is along the central part of the basin or trough (Sclater *et al.*, 1977; KOBAYASHI and NAKADA, 1970; UYEDA and KANAMORI, 1979). The latter is based on the same mechanism as is seen in the mid-oceanic rift apart from the influence of the subduction.

DISCUSSION

These facts indicate that arc geomorphology is variable both in space and in geological time. There may be variable features in the different parts even within an arc, variable from

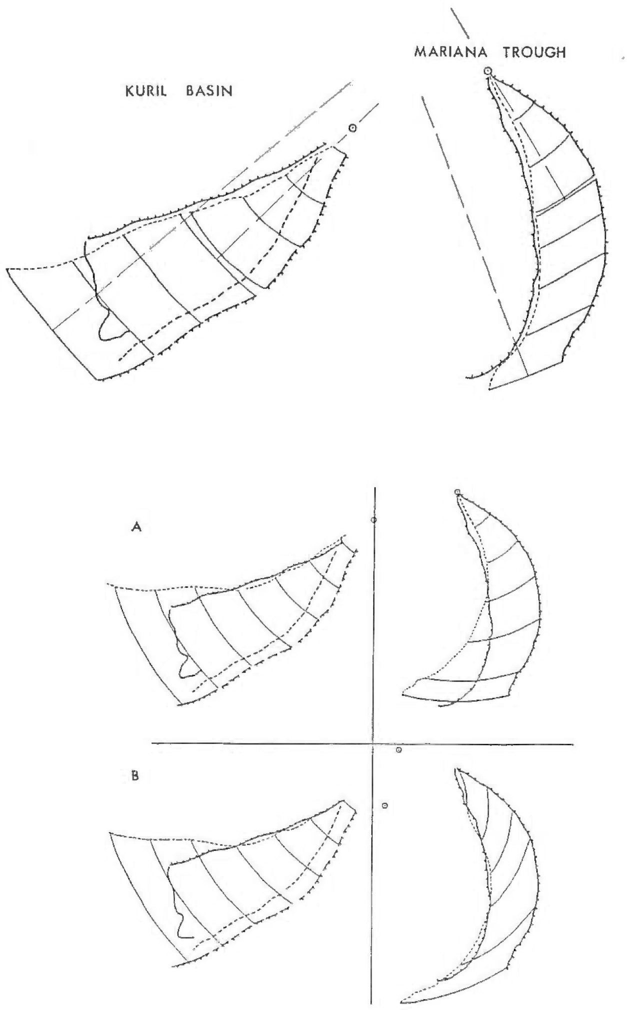

Fig. 12. Opening of the Kuril Basin and the Mariana Trough based on the fan spreading. There are some geometric inconsistensits in the marginal blocks on the opposite side of the pole (A and B). This feature may suggest some restricted length to open in fan shape and parallel spreading in the outer side from the pole.

intense to no volcanism, variable from uplifted forearc basement high having a range of islands to insignificant uplifted high showing only a break bordering the continental slope and inner trench slope, and variable from deep backarc basin to gradual deepening without any basin feature.

There may be the similar temporal change as mentioned above, even in the same place within an arc, as suggested by periods of subduction erosion or accretion at trench, period of intense to no volcanism, periods of uplift or subsidence of forearc basement high and alternating periods of spreading to no spreading of backarc basins.

Certain features are believed to alternate during their evolution. A volcanic ridge during the earlier phase may convert to a different role in the later stage of the arc such as a non-volcanic forearc basement high in the forearc area, resulting in the formation of a new volcanic chain on the inner side of the Bonin Arc (HONZA, 1983; HONZA and TAMAKI, in press).

There may be a certain correlation between arc volcanism and backarc spreading (UYEDA and KANAMORI; 1979; SCOTT and KROENKE, 1980; HONZA, 1983, KARIG, 1983).

Studies on magnetic anomalies in the Shikoku Basin revealed lineations striking northwest, parallel to the volcanic chain of the Bonin Arc. The lineation pattern is identified as a sequence of anomalies 7 (27 Ma) through 5 (10 Ma) between the base of the Kyushu-Palau Ridge and the east margin of the Basin with tentative indentification on the easterñ side on account of rough and complex morphology of the basement (WATTS and WEISSEL, 1975). The other identification is based on a symmetrical anomaly profile with a spreading center along the center of the basin (KOBAYASHI and NAKADA, 1979).

Spreading of the Shikoku Basin, thus appears to have begun in late Oligocene and continued until millde to late Miocence. On the other hand, no volcanism is known on the Bonin Arc from Miocene to early Pliocene (Table 1).

Morphologic variation in the Ryukyu Arc also suggests that there may be a relatively deeper backarc basin when there is no volcanic chain and there may be no deeper backarc basin when modern volcanic chain is active.

These facts from modern geomorphology and historical evolution may be an indication that arc volcanism is incompatible with the spreading of the marginal sea. In other words, arc volcanism and spreading of the backarc basin may take place altenately. Low level volcanism may occur on the volcanic chain while backarc basin is opening and slight spreading may occur on the backarc basin when volcanism is active on the volcanic chain (SCOTT and KROENKE, 1980; HONZA, 1983). A different interpretation is also proposed (KARIG, 1983).

A possible tectonic erosion is also noted in the Japan Trench during the earlier stage of its development. A subduction complex was developed in the lower part of the inner trench slope during the later stage. There might have been a wide shallow sea on the forearc of the Tohoku area before subduction began. A probable evidence is the unconformity developed in most of the forearc area and in the coarser material lying on the unconformity confirmed by drilling of IPOD Leg 57 (VON HUENE, *et al.*, 1980).

These facts suggest that there is an alternate development of subduction complex, one is the transgressive stage where the subduction complex is formed with seaward migration of the trench axis, and the other is the regressive stage tectonic erosion occur with the landward migration of the trench axis.

The Mariana Arc may be in the regressive stage while there may be modern spreading of the Mariana Trough in the backarc side (HUSSONG and UEDA *et al.*, 1982). The Tohoku Arc may be in the transgressive stage while no modern spreading is suggested in the Japan Sea.

It is inferred from these facts that there may be a spreading of the backarc basin while subduction (tectonic) erosion is taking place in the trench, and subduction complex may begin to develop when spreading of the backarc basin ceases (UYEDA and KANAMORI, 1979; HONZA, 1983).

Several models or hypotheses have been proposed for arc volcanism and for backarc spreading. Most of them were discussed independently on arc volcanism and on the origin of the backarc basin. Those models for spreading of the backarc basin are related to the subduction of the oceanic plate and some of them are based on the convection current in the upper mantle formed by the subduction (UYEDA, 1977; KARIG, 1971; TOKSOZ and BIRD, 1977; HONZA, 1978, HONZA 1983).

Low stress or tensional mode in the Mariana type provides a favourable condition for subduction erosion at the trench and for backarc spreading (UYEDA and KANAMORI, 1979). It may also be favourable for weaker volcanism at the volcanic chain, for less frictional heating may occur between the subducted plate and the asthenosphere under the arc, while accretion at trench and active arc volcanism occur under stronger compressional field. Therefore, each

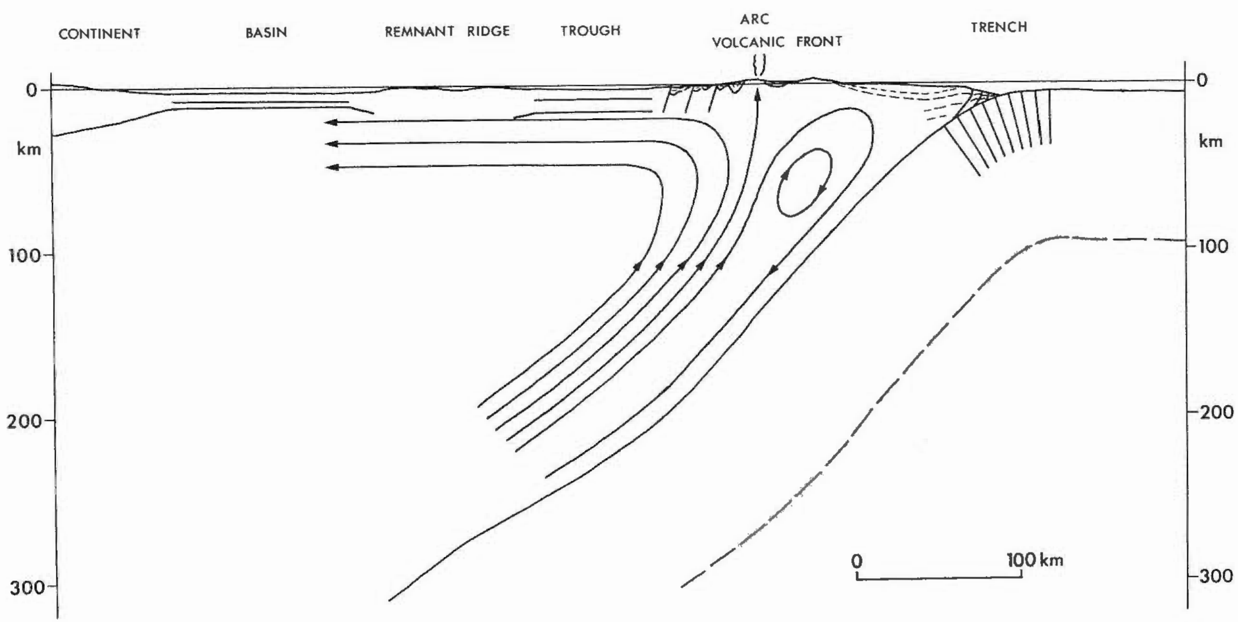

Fig. 13. A convection current model under an arc illustrated in the Tohoku Arc (HONZA, 1978). The model is based on the calculated result by ICHIE (1971) in which frictional heating may occur on the boundary between the subducted oceanic slab and the asthenosphere under the arc.

of the two types underwent quite different processes in forming the arcs.

One possible source of heat energy for arc volcanism is the frictional heating along the upper surface of the subducting oceanic plate which is the same model examined for the origin of backarc spreading (Fig. 14). Upwelling conponent of the convection current could play an role as a source of heat for the arc volcanism, although theoretical distance of the upwelling is toward the backarc than volcanic chain according to the calculated result by ICHIE (1971). In this case, there may be a heat supply whenever subduction occur. The difficulty for this model is the mechanism of deep earthquake which occur at the heated boundary between a subducted slab and the upper mantle under the arc.

In the case without any heat supply from the subducted slab nor the upper mantle under the arc, convection current might occur downward by mechanical drag along the upper surface of the subducted slab followed by horizontal flow toward the arc near the surface on the backarc side (TOKSOZ and BIRD, 1977).

In the case when frictional heating occurred along the upper boundary of the subducted slab, convection current might be welling upward turning to the both sides on the surface with relatively strong flow toward the inner side of the arc (horizontally away from descending plate) and weak counter flow toward the outer side (ICHIE, 1971, HONZA, 1978). Geology of the arc seems to support a compornent of the flow toward the continent in the backarc basin, especially on the double arcs such as seen in the Bonin and the Ryukyu Arcs intervened by the Shikoku Basin (Fig. 14).

Convection current toward the continent implies that the arc drift toward the continent. However, when a continent becomes a barrier to the horizontal component of the current near the surface, the arc may drift seaward adding new material along upwelled sites of the current near the surface. There may be a drift toward the continent when a new subduction occurs along the margin of the continent as is seen on both sides of the Shikoku Basin, and when supply rate of new material along upwelled sites on the surface is not enough to recover the total loss incurred by consumption.

Arc volcanism needs heat sources under an arc. A calculated heat pattern under an arc suggests that temperature is lower along the subducted oceanic slab than in the surrounding asthenosphere which probably is the result of the subduction of cool plate (HASEBE *et al.*, 1970). In this case, it seems difficult to supply heat for arc volcanism from along the subdcted slab.

Quite different mechanism is suggested for mid-ocenic volcanism and for continental volcanism which may be attributed to heat process in deeper mantle than that of the arc area. Even in some of the backarc areas, the same spreading mechanism as is seen in the mid-oceanic rifts apart from the influence of the subduction is estimated in the Lau and Shikoku Basins. There may also be another mechanism to form arc volcanism independent with the formation of backarc basin, although both of then may need heat supply under the arc.

Here forearac and backarc features are joined as a related phenominon to constitute arc. Geomorphologic variations of arcs make it difficult to understand the fundamental frameworks which constitute arcs. Some of them occur within an arc. Further difficulty comes from the variations of geomorphology during geological ages discussed above. Modern arcs are devloping now, in which it is difficult to know the direction of forearc development which phase is taking place transgressive or regressive.

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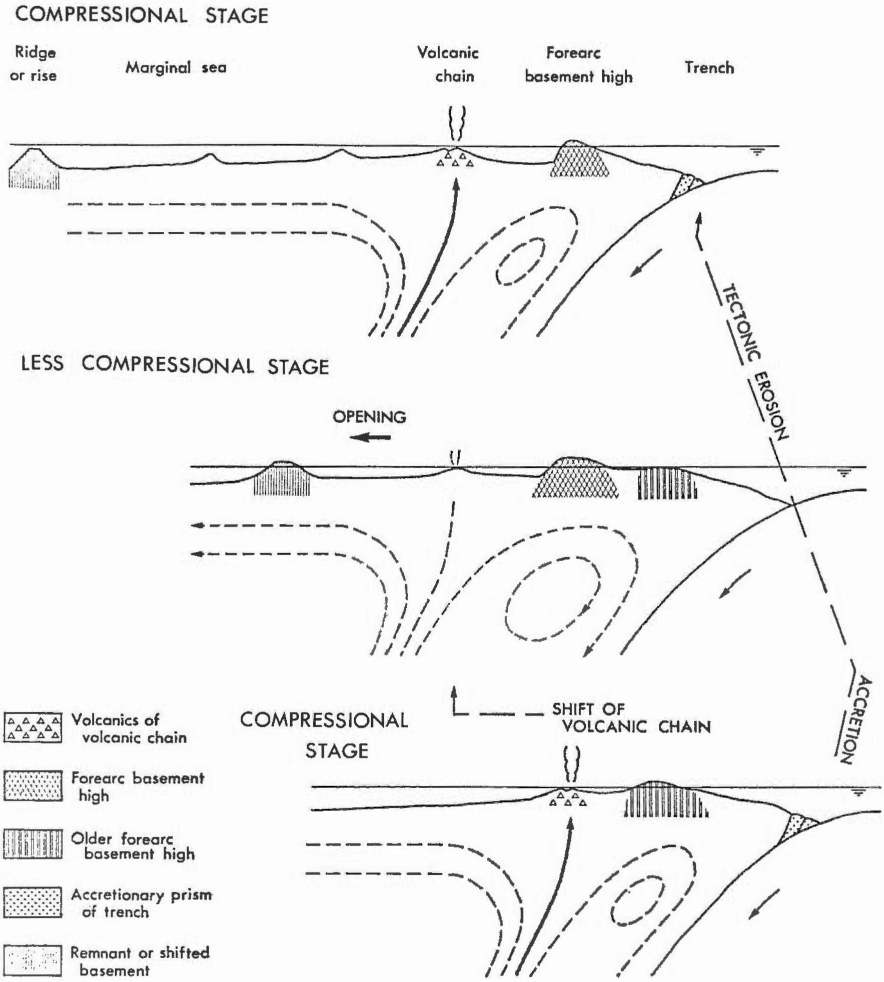

Fig. 14. A model for evolution of fundamental framework of an arc based on a convection current model illuatrated in the Bonin Arc (HONZA, 1981). During compressiond stage slight spreading may occur in the backarc area when the volcanism is active on the volcanic chain associated with the development of subduction complex at the trench. During weak compression stage low level volcanism may occur in the volcanic chain while the backarc basin is opening associated with development of tectonic erosion.

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II. Energy Resources—Geothermal

Chairman H. HASE

1. Geology and Geothermal Resources in Northern Thailand.
2. Geothermal Exploration in Kenya with Special Reference to Eburru Prospect.
3. Philippine Geothermal Resources: An Alternative Indigenous Energy.
4. Geothermal Exploration in Japan.

Geological Survey of Japan Report, No. 263, 1984, p. 69–77

Geology and Geothermal Resources in Northern Thailand

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ABSTRACT

The stratigraphic succession in northern Thailand was summarized from Precambrian to Quaternary including the important igneous activities. In addition, the significances of heat sources, fault structures, origin of thermal water and the general surface discharge features related to the geothermal resources were also discussed.

The Precambrian rocks are mainly composed of gneisses which have high metamorphic grade and complex intrusives history, are compared with adjacent low grade or unmetamorphosed Lower Paleozoic rocks. Arenaceous and calcareous rocks intercalated with some volcanics are recognized to be the Upper Paleozoic sequence.

The Lower Mesozoic rocks are characterized by volcanic rocks with marine sediments whereas the Middle Mesozoic sequence is composed predominantly of continental sediments.

The Tertiary sediments are basically predominant in a large number of basins over the region.

The geothermal fields in Thailand are believed to be associated with igneous activities of possibly Cretaceous to Tertiary ages. Presumably, the probable heat source is contributed from tectonic movements and/or radioactive elements from some granitic batholiths.

The average temperature of thermal water ranges from 60–100°C with some warm springs of 45–60°C and they are classified as sodium-bicarbonate type. Most of the thermal water in northern Thailand are originated from local meteoric water and probably diluted from cold ground water at shallow depth.

INTRODUCTION

Geological map of northern Thailand shown in the Figure 2 was compiled by A. LUMJUAN and S. LOVACHARA SUPAPORN (1981) then edited and modified by S. SUENSILPONG *et al.*, Igneous Research Project, Geological Survey Division, Department of Mineral Resources (DMR). They were compiled from geological map on scale of 1:250,000 which was prepared by the joint mapping and prospecting project between DMR and the German Geological Mission (GGM) during 1965 to 1971 and partly by the Geological Survey Division, DMR (Fig. 1).

Generally, in the western regions, thick complete sequences of the Precambrian to Jurassic and some Tertiary sediments are observed, while in the eastern regions the known sediments are only of the Silurian-Devonian to the Cretaceous and possibly Tertiary ages (BUNOPAS, 1976). The successions of the Precambrian to Tertiary sediments were correlated by GGM (1972) as shown in Figure 3.

There are 64 hot springs distributed throughout the country, but most of them (42 hot springs) are concentrated in northern Thailand (Fig. 4). In general, their manifestations existed in the provinces of Chiang Rai, Mae Hong Son, Chiang Mai, Lam Phun, Lampang, Prae and Sukhothai.

Preliminary geothermal reconnaissance was done in northern Thailand by Chiang Mai University (CMU) in 1976 and Kingston Reynolds Thom and Alladice Limited (KRTA) of New Zealand in 1977. Their reports indicated that many hot spring areas could be developed for geothermal power generation and for agricultural application. In 1978–1983, a working group consisting of personnel from Electricity Generating Authority of Thailand (EGAT), Department of Mineral

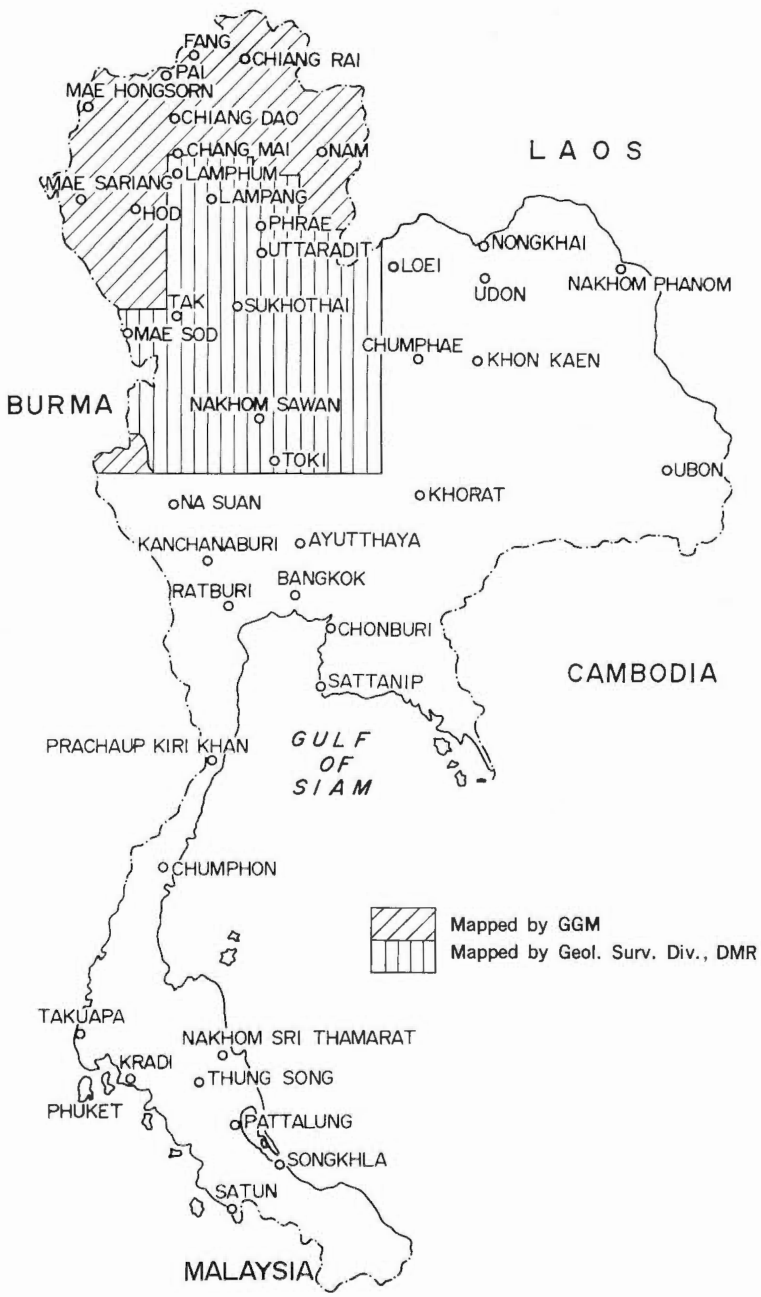

Fig. 1. Geological Index Map of Thailand.

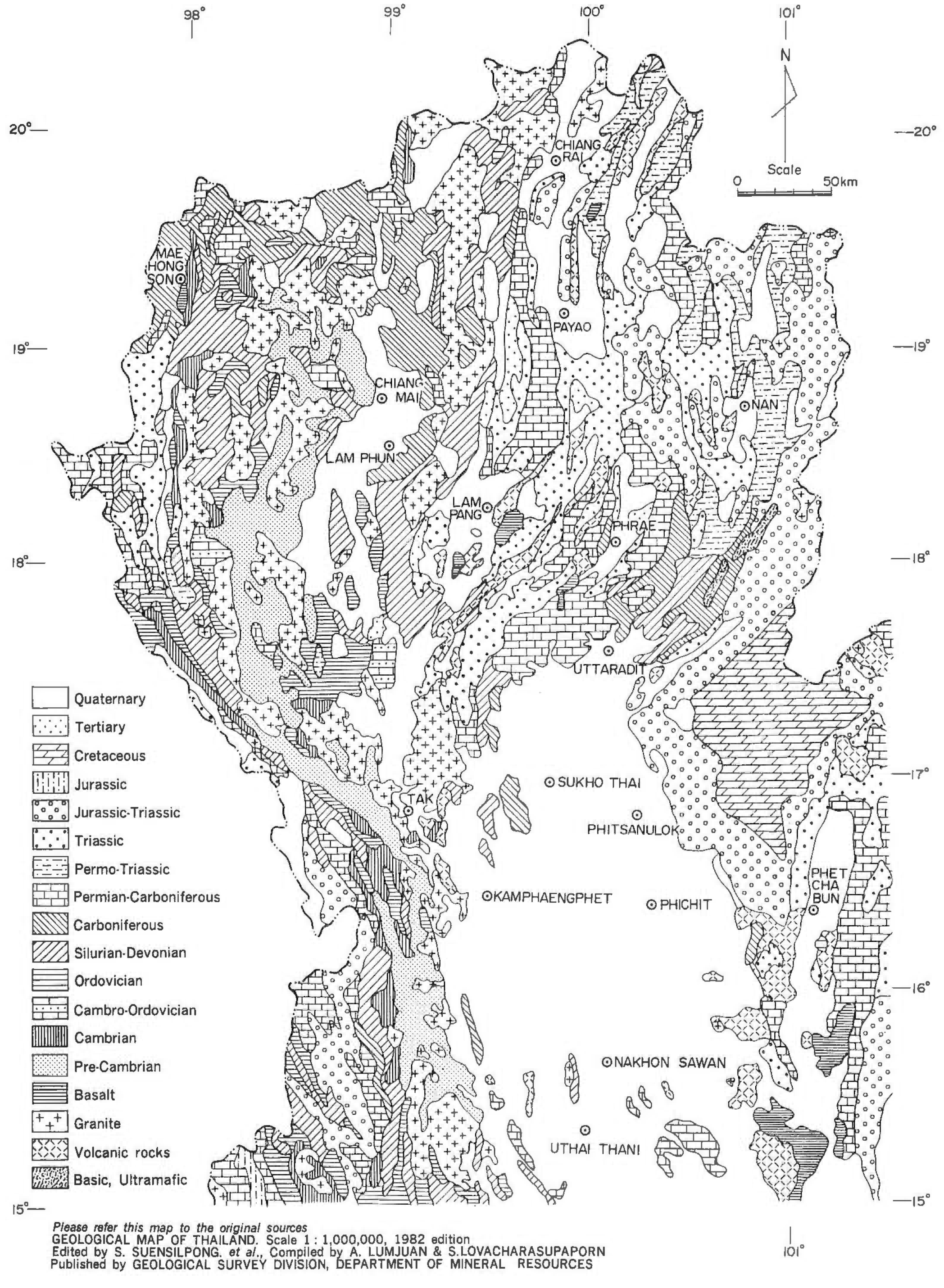

Fig. 2. Geological map of Thailand covering northern provinces (modified by the Igneous Research Project, Geological Survey Division).

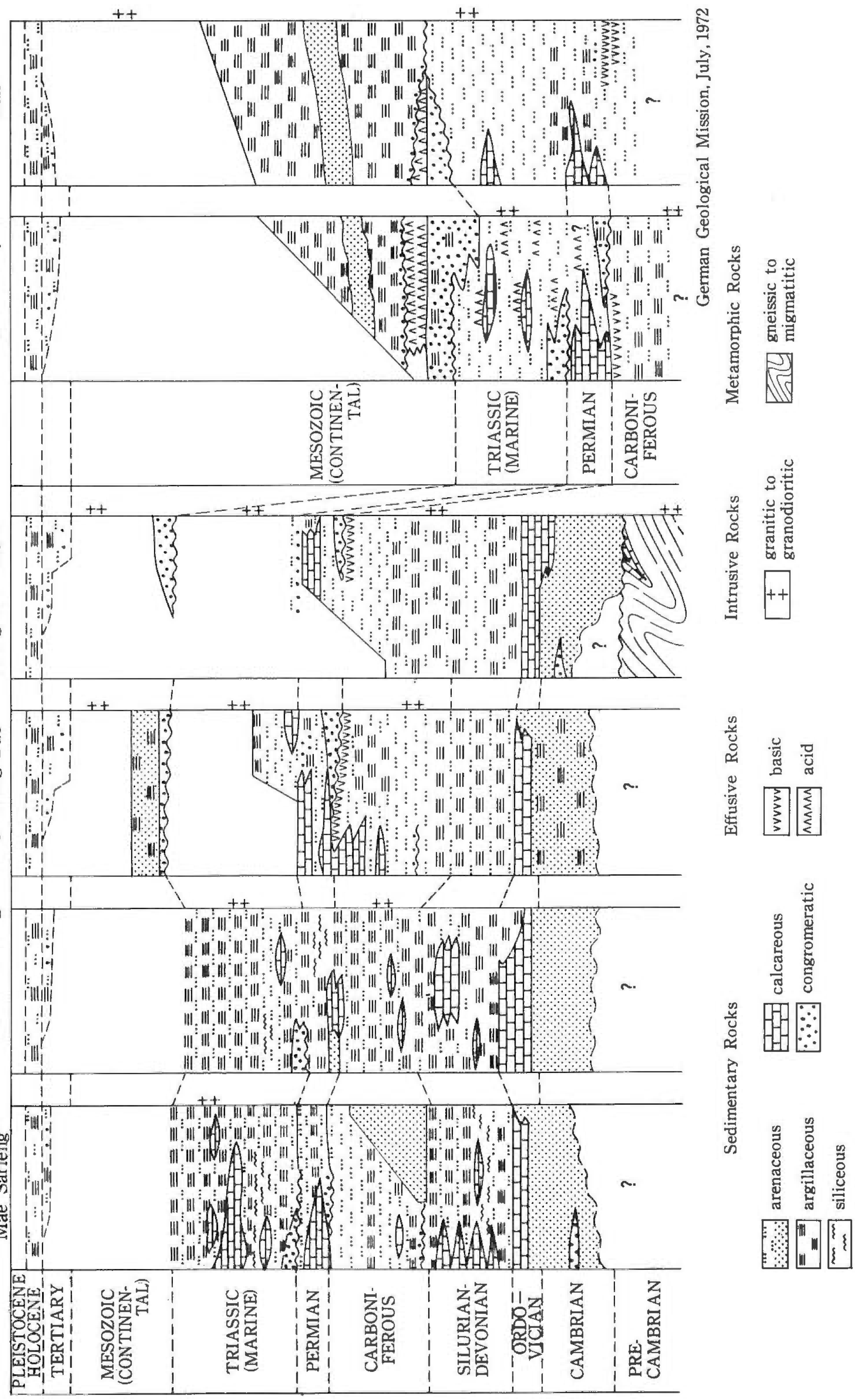

Fig. 3. Generalized Stratigraphic Columns of Northern Thailand.

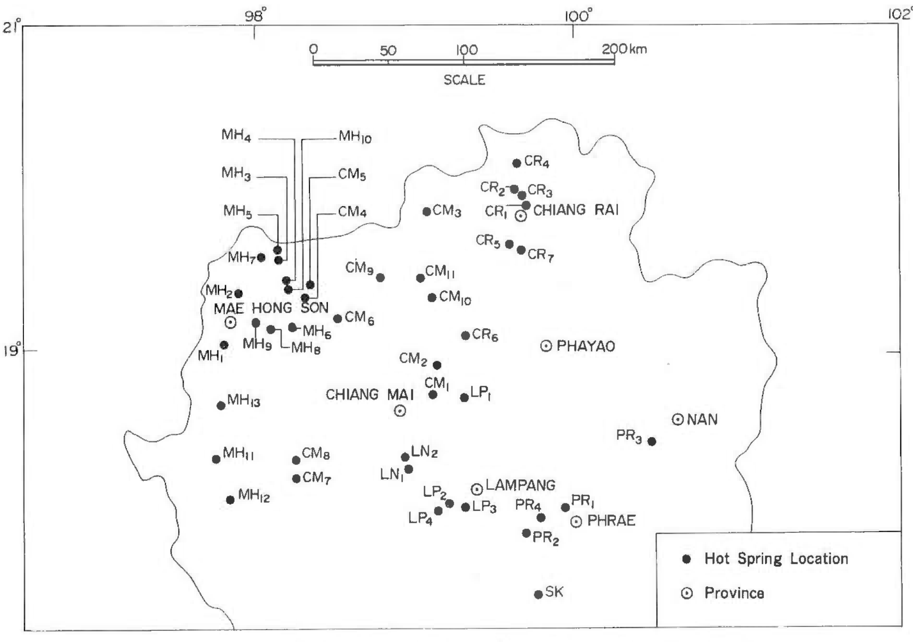

Fig. 4. Distribution of hot springs in northern Thailand.

Resources (DMR) and Chiang Mai University (CMU) was formed for geothermal energy development programme of northern Thailand. Five hot spring areas; Sankamphaeng, Fang, Mae Chaem and Papae in Chiang Mai then Mae Chan in Chiang Rai, are selected for detailed studies. Initial studies to compile basic data, assigned and carried out separately by the three organizations, were completed in early 1980. Three parties of foreign geothermal experts from Japan (Geological Survey of Japan) and the United States (Los Alamos Scientific Laboratory and U.S. Geological Survey) visited the five geothermal sites at different period of time. It is agreed by local and foreign experts that there is a good probability that medium to high temperature geothermal resources are present in Thailand at accessible depth.

GENERAL GEOLOGY

The Precambrian rocks are exposed with N–S trend in the mountains bordering Chiangmai plain to the west and further south to Lan Sang National Park, Tak. The rocks are mainly composed of migmatised paragneisses and include quartzitic schists, biotite schists, calcsilicate schists and marbles (CAMPBELL, 1975; GGM, 1972). They are penentrated by concordant and discordant veins and irregular masses of granodiorite and pegmatite. Apparently, Precambrian gneiss series are unconformably overlain by less metamorphosed or unmetamorphosed Cambrian rocks (GGM, 1972).

East of Mae Hong Son, Mae Sariang and west of Kamphaengphet, the rocks are well bedded quartzite to massive quartzite, often crossbedded with some conglomerate beds, up to 500 m in thickness. These rocks are Cambrian in age and described by BUNOPAS (1976) and they are conformably overlain by Ordovician limestone. The Lower Paleozoic sediments (Cambro-Ordovician) consist of quartzitic rocks with locally increasing amounts of shaly and calcareous intercalations to the upper part. The averge thickness of the Ordivician limestone in the north ranges from 80 to 100 m.

The Silurian-Devonian sediments occur in Mae Hong Son and throughout northern Thailand particularly to the southeast, west of Chiang Mai, Lampang and northeastern Uttaradit. Rocks are sandstone, graywackes, carbonaceous shales, cherts and thin limestones. The thickness of the series does not exeed 500 m (GGM, 1972) and the distribution generally corresponds with that of the Ordovician limestone.

The Carboniferous rocks are characterized by clastic sediments with occasional limestone or chert intercalations. They are mainly exposed to the west of Mae Hong Son, north of Chiang Mai, southeastern Lampang and northeastern Uttaradit. The end of Lower Carboniferous is marked by orogenic movements with magmatic activities (GGM, 1972). The Upper Carboniferous sequence shows both marine and terrestrial facies. Marine sediments are chert, sandstone, shale and conglomerate. Deposition of continental or marine clastic facies is documented by a thick red conglomerate or shale, sandstone and chert. They laterally interfinger with marine Permian-Carboniferous limestone. In many places the uppermost Carboniferous for mation contains basic volcanics (GGM, 1972). MACDONALD and BARR (1978) found that volcanic rocks or basalts have the composition of island arc tholeiites. They suggest that the rocks represent part of a volcanic island arc extruded through oceanic crust. Clastic and marine facies continue into the Permian.

The Permian rocks consist mainly of limestone and minor sandstone and shaly conglomerate, agglomerate and tuff. In the central part of northern Thailand, particularly between Lampang and Nan there develops the most complete Permian succession. The rocks, however, are predominantly clastic and rhylolitic lavas, with some interbedded limestones. In the north of Chiang Mai and northeastern Mae Hong Son, the Permian rocks consist mostly of a thick limestone formation, the Ratburi Limestone. The thickness of the Permian limestone is about 100–150 m.

The Permo-Triassic rocks are predominantly rhyolitic and andesitic lavas distributed in almost north-south direction from east of Chiang Rai to southeastern Lampang.

The Mesozoic in northern Thailand is characterized by a distinct regional and depositional subdivision. The marine Triassic sediments rest unconformably on the Permian sediments to the south of Mae Hong Son and southeast of Mae Sariang (see columns I and II of Fig. 3) and overlie the volcanic sequence in Lampang and Prae areas. In general, the marine Triassic sediments consist of shale and limestone and then change the rock facies into a sandstone-shale sequence, described as resembling Alpine flysch (BUNOPAS, 1976).

The continental sedimentary environment continued well into *Jurassic*. These terrestrial sediments consist of red sandstone, mudstone, shale and a characteristic volcanic member of acid to intermediate composition particularly in the Nan area (Column VI, Fig. 3) and the east of the Uttaradit area, the Sukhothai area and the Phichit area (Fig. 2).

The Cretaceous rocks are exposed in the eastern part of Uttaradit and Thai border. They consist mainly of quartz sandstone and conglomeratic sandstone. In the area surveyed by the GGM, maximum thickness of the continental Mesozoic sediments may reach 1,000 m.

In northern Thailand the Tertiary sediments predominently occur in isolated basins with distinct north-south trend, overlying the regional structure of the older formations. It consists of shales, sandstones, marl beds, fresh water limestone and local accumulation of lignite, oil shale and carbonaceous shale.

Pleistocene terraces and alluvium are developed in basins all over the area, they lie unconformably over the older rocks.

Regarding igneous activities, large areas of Precambrian rocks and also areas adjoining older Paleozoic formation have been affected by high grade regional metamorphism and granitization. In several areas, plutonic activity provided intrusive rocks and they have been dated to be of Middle Carboniferous age (GGM, 1972). After widespread deposition of basic to intermediate volcanics, the tectonic activity started again in the early Upper Carboniferous age.

There are several granite complexes in northern Thailand, they were considered to be of Late Carboniferous, Late Triassic to Early Jurassic, Cretaceous and Tertiary ages. Main batholiths intruded only during the Triassic, perhaps extending into the very earliest Jurassic.

This period of intrusion coincides with the age of andesitic and rhyolitic volcanic activities. BUNOPAS and VELLA (1972) sugested that the age of volcanics in the central part of northern Thailand extended from Late Permian to Early Triassic according to their category of volcanic belts. They also believed that the collision of the Shan-Thai craton with the Indochina craton took place in Early Jurassic time marked by scattered occurrences of ultramafic rock to the east of Nan and northeastern Uttaradit.

The Pleistocene basalt at Lampang have been investigated using palaeomagnetic and dating techniques by BARR *et al.*, (1976). The basalts to the north of Payao, the Prae and the eastern Nakorn Sawan areas are probably of the same age as Lamapng basalt.

GEOTHERMAL RESOURCES

Forty two thermal areas are scattered in northern Thailand. Most of the hot springs occur in low terrain close to streams or rivers, and are predominantly aligned along fault zones (Fig. 4).

The heat sources of these hot springs are not clearly explained. Their occurrences do not lie on the seismic belt and there are no active volcanism in Thailand. The main phenomena indicating heat sources of geothermal fields are believed to be associated with granitic intrusion of possibly Cretaceous-Tertiary age or the rejuvenated younger pluton or late basaltic eruption. Recently, study of radioactive elements such as uranium and thorium from some granitic batholith, shows rather high heat production value, for example, Khun Tan batholith is about 17 KW/km^3 (WATTANAIKORN and RAMINWONG, 1980). This may indicate the influence of radioactive elements upon the appearance of high heat flux in some geothermal areas, for example San Kamphaeng and Fang (Fig. 4 CM_1 and CM_3). The other probable heat source is the contribution of tectonic movement in active belts indicated by microearthquake study in northern Thailand. Nearly all shallow earthquakes with magnitude greater than four are located in Burma, while in northern Thailand most of the magnitudes range from one to three.

Regarding the geological setting of the thermal springs, they occur from various rock types, particularly from sedimentary and granitic rocks. It can be summarized that they are controlled by three major fault systems; the N–S fault at the western margin along Maehongson province close to Thai-Burma border, the two E–W faults at the northern and extremely northern region in the vicinity of Lampang and Chiangmai provinces. In addition, some minor hot spring areas which also have close relationships to faults and fractures are distributed in the central northern Thailand.

Faults and joints control significantly the fluid paths and effective permeability of geothermal reservoirs. In northern Thailand, there is no active faulting of Quaternary period. However most of the major fault structures are strike-slip fault and normal fault which formed in tensional dynamic field. This might indicate an appropriate overall subsurface permeability for the geothermal system in northern Thailand. This is seen clearly in several exploratory wells drilled in San Kamphaeng area where faults and various joint patterns provide preferential passage for fluids at different depths. From many well studies at geothermal fields, it seems that the average permeable horizontal-reservoir has significantly greater potential in terms of geothermal reserve than vertical fracture reservoir.

GIGGENBACH (1977) has studied isotopic compositions of Fang and Pa Par thermal area (CM_4), the isotopic composition of δD and $\delta^{18}O$ between thermal water and water from nearby river are very similar. This suggests that most of the thermal water of hot spring area in northern Thailand originated from local meteoric water.

The surface manifestations at thermal areas in northern Thailand are quite similar. They are predominantly water-dominated bubbling and boiling springs, except Pa Pae which is a geyser type shooting hot water up to 3 meters. Temperatures of thermal areas in northern Thailand range from 60–100°C. Some other warm springs have temperatures of 45–60°C.

The water is usually clear, colourless with some precipitation of grey to white amorphous silica, calcareous matter and algae. The flow rate from each hot pool is generally less than 1 litre/sec, pH ranges from 6.5 to 9.5, the hot water could therefore be classified as sodium-bicarbonate type. Surface hydrothermal alteration does not show wide distribution. Silica sinter, travertine and clay are commonly deposited at the vicinity of thermal springs. Sulphur deposition derived from fumarole or steaming ground is rare. Due to high humidity of tropical climate, the effect of weathering and erosion is substantially greater than that of hydrothermal alteration. Thus it is difficult to differentiate the process of alteration in these areas.

Reservoir temperatures calculated from T_{SiO_2}, T_{Na-K} and $T_{Na-K-Ca}$ reveal that several geothermal areas such as San Kamphaeng, Fang, Pa Pae, Tepanom and Mae Chan (CM_1, CM_3, CM_4, CM_7 and CR_4) exceed geothermometric temperature of 170°C. The different temperature values estimated from various geothermometers indicate dilution or slow rising of the thermal fluid which allow silica to re-equilibrate. The apparent very low chloride content in every thermal spring may not indicate the origin from the deep hot water reservoir, even though chloride by nature is not consumed in water-rock interaction, but this low chloride content should mainly be derived by dilution of cold ground water at shallow depth.

THIENPRASERT and RAKSASKULWONG (1982) suggested that the heat flow values calculated from many water wells in northern Thailand range from 0.4 to 3.06 HFU except the San Kamphaeng geothermal area where it ranges from 3.10 to 7.67 HFU. There are also other geothermal areas of anomalously high geothermal gradient and high heat flow. The cause of high geothermal gradients may be the effect of hydrothermal convection at deeper zones.

CONCLUSION

Geothermal resources of northern Thailand have been systematically investigated since 1978. The application of geological, geochemical and geophysical exploration in many geothermal areas are now being carried on, particularly in areas with higher resource potential such as San Kamphaeng and Fang areas. Several exploratory wells have been drilled in those two areas by the collaboration of the Government of Japan and France respectively. Although the characteristics of occurrence and geological setting of thermal areas in northern Tahiland differ greatly from other geothermal fields in the world, studies have shown the areas to be promising and intensive prospecting is providing guidance for the development and utilization of geothermal resources in the near future.

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Geothermal Exploration in Kenya with Special Reference to Eburru Prospect

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ABSTRACT

The Eburru area is situated about 120 km NW of Nairobi whithin the mid-Rift Valley region. The Eburru geothermal prospect was one of the three geothermal prospects identified by the UNDP geothermal explortion project between 1970 and 1978, the other two being Olkaria and Bogoria. Eburru and Olkaria prospects are about 200 km apart and close to the shores of fresh-water lake of Naivasha.

The geothermal surface exploration of Eburru prospect was started three years ago by a joint team of Japan International Cooperation Agency (JICA) experts and Ministry of Energy (MOE) staff. The team has updated the mapping of the Tertiary/Quaternary volcanics, mapped and sampled the alteration zones and undertook both geochemical and geophysical survey of the prospect.

The results of the exploration work indicate the existence of a N-S fault zone within which exist recent volcanics and phreatic craters. At the top of Eburru Hill, there are major steam emanations and alteration zones closely related to carbon dioxide and mercury geochemical (in soil air and soil) anomalies as well as resistivity anomalies. The alteration zones and geochemical and geophysical anomalies have been observed in the N-S fault zone up to, and beyond, the old Eburru railway station. The results indicate good steam conditions at the top of Eburru Hill and hot water conditions at the base of the hill (about 600 m below) near the Eburru station. Shallow drilling is proposed in 1983 followed by deep drilling work. There is a need to extend the geothermal surface exploration area to the north and south. Meanwhile two 15 MW power stations are in operation at Olkaria Geothermal Field. The average depth of the steam wells is 1000 m.

INTRODCUTION

The geothermal resources in Kenya is concentrated along the Kenya Rift Valley which is a part of the African Great Rift System traversing in the north-south direction from the north of Syria in the Middle East to Mozambique in the southeastern Africa and having a total length of about 7000 km. It forms a major continental, fault-bounded graben and is indeed the world's greatest rift valley.

From the Red Sea Valley, the Rift Valley enters the Gulf of Aqqaba, which forms a part of the Red Sea Rift, before turning southwards into Africa through Ethiopia. The Affar depression is the centre of the triple junction betwen the two opened arms of the Red Sea and the Gulf of Eden, and the failed arm that forms the southern extension of the Rift Valley into Africa. The Rift Valley extends beyond Ethiopia into Kenya, Tanzania and Mozambique as the Eastern Rift Valley while another arm extends northwestwards from Malawi, Tanzania and Uganda/Zaire border up to Uganda/Sudan border. It should be noted that most of Eastern African lakes are found in the Rift Valley. Many of these lakes are salty but a few of them have fresh water. The major exemption is Lake Victoria that lies in the depression between Eastern and Western Rift Valleys.

Fig. 1. Distribution map of the African Great Rift System.

In recent years geothermal energy proved to be a useful source of energy particularly as electrical and heat energy. In a tropical country like Kenya, geothermal energy offers an alternative source of electrical energy as well as industrial heat energy. The existence of this geothermal resource has been well documented by past geological mapping of the Kenyan Rift Valley graben which extends 800 km between Ethiopian and Tanzanian borders and is 40 to 60 km wide. Using the method of analogy, which uses the knowledge and experience gained in a relatively well explored region as a basis for extrapolating limited data to a relatively unknown region it was estimated that the geothermal power potentials in the Kenyan Rift Valley is 1700 MW. It is clear that not all estimated geothermal potential can be exploited from an area because much of it depends on geological condition of a geothermal field concerned.

THE KENYA RIFT VALLEY — GENERAL GEOLOGY & STRUCTURE

The development of the whole Rift Valley system started in late Tertiary with a major doming along the axis followed by major fissure and central volcanic eruptions. This was

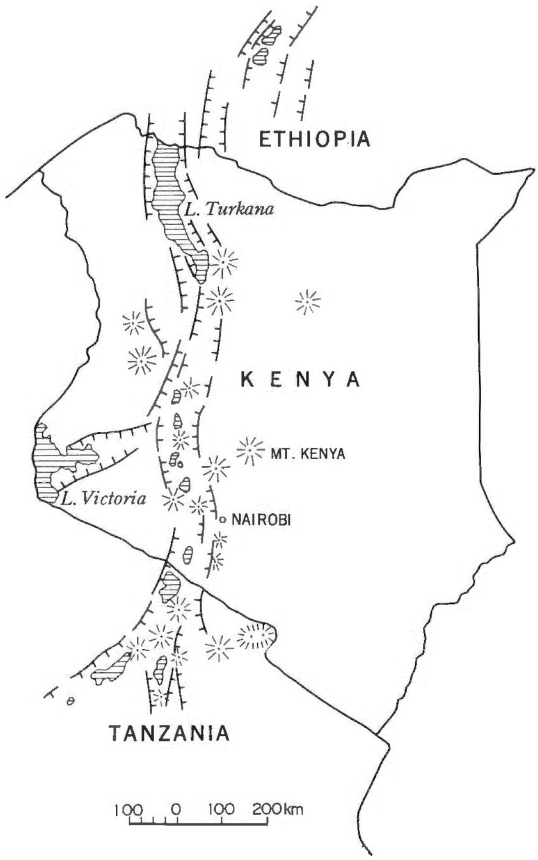

Fig. 2. Distribution of young volcanoes located in the East African Great Rift System from the Kenya Ethiopian border to northern Tanzania.

followed by the dome collapse and further fissure and central volcanic eruptions. These magmatic phases are separated by phases of erosion and sedimentation into the lakes formed in the grabens. These sequence of events are more dynamic in some parts of the Rift Valley resulting in the development of major volcanic domes. The Ethiopian and Kenyan domes form major highlands outside and inside the Rift Valley.

In the saddle between the volcanic domes the basement is exposed as the volcanic cover is negligible. These development of volcanic domes is typical of the Kenyan Rift Valley but a typical of the western Rift Valley. Due to the Quarternary volcanism, manifestations such as fumaroles, steam jets, hot mudpools and hydrothermal rock alterations are seen in many parts of the Kenyan Rift Valley.

The line of calderas and craters in the centre of the Rift Valley indicates the last phases of volcanic activity. This line of calderas and craters is considered, as a result of crustal studies of the Rift Valley, to be formed along the axis of a mantle doming underneath the Rift Valley. The crustal studies undertaken by various researchers in the Rift Valley based on both refraction and reflection seismic studies, indicate that the crust is thinner underneath the Rift Valley. This would lead naturally to a higher thermal gradient along this line of craters and calderas.

Most of the faults bordering the Rift Valley are in N-S direction. While the graben boundary faults of the Rift Valley are N-S direction in general, the floor of the valley has horst

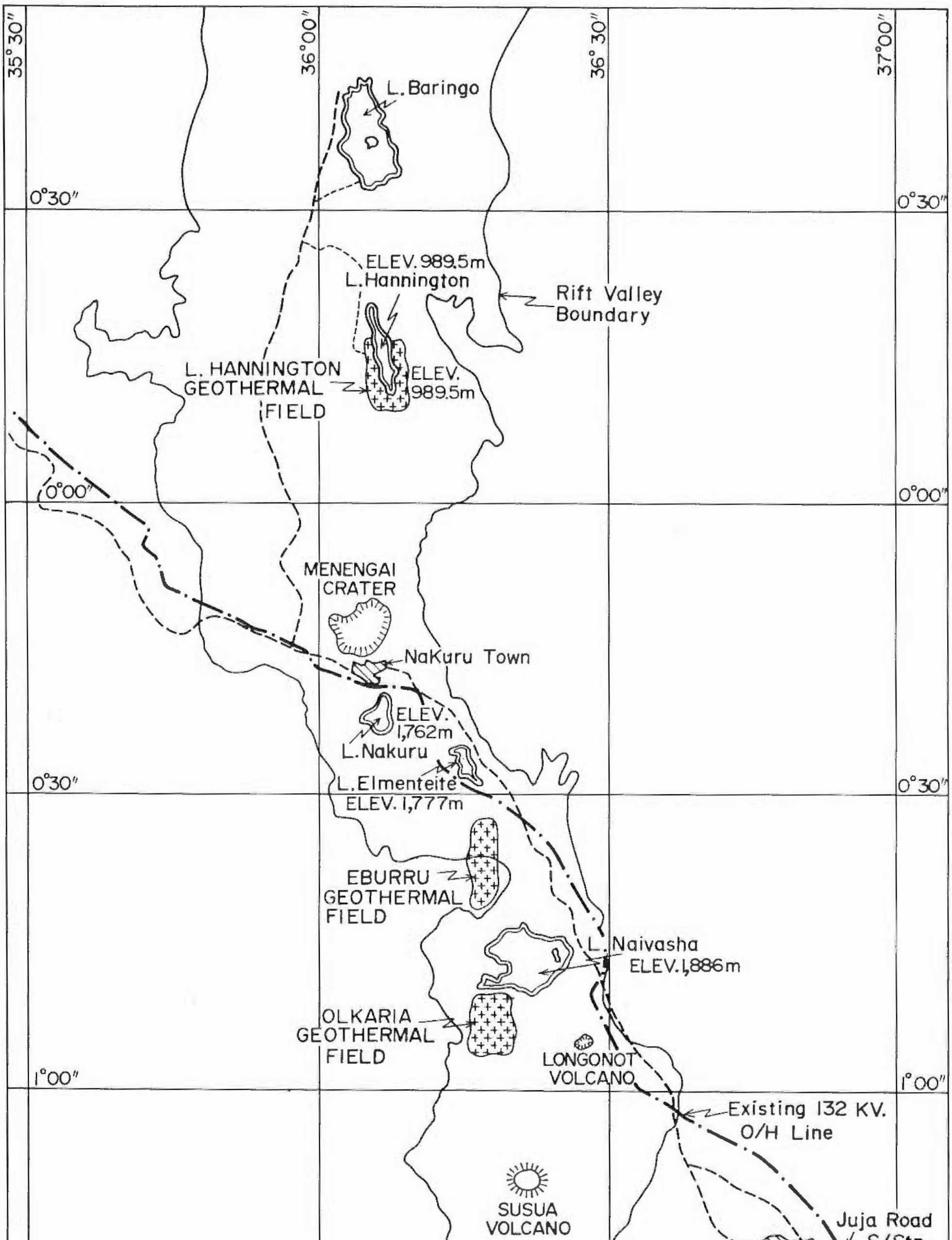

Fig. 3. Location of geothermal areas.

and graben structure due to E-W faults crossing the former.

THE OCCURRENCE OF GEOTHERMAL ACTIVITY ALONG THE KENYA RIFT VALLEY

In the Rift Valley, as already indicated, there are many areas of active geothermal manifestations visible on the surface but only three of these areas have been well surveyed. These are Olkaria, Eburru and Lake Bogoria. Olkaria and Eburru geothermal manifestations are confined mainly to widespread fumaroles and hot ground.

At Eburru, these fumaroles have been used to supply the local population and their animals with water. It is condensed from steam in sloping aluminium pipes and the condensed water is collected into a concrete tank. The steam is also used by farmers as a source of heat for drying pyrethrum flowers. At Lake Bogoria the geothermal activity is demonstrated by steam jets and boiling hot springs centred in the southeast corner of the lake, while on the peninsula it is boiling springs along the southern end of the western lake shore, and scattered warm springs all along major faults.

The presence of hot or warm waters and steam, within a radius of several kilometers around the lake, indicates that the heat flow in the immediate environment is high and that a heat source must exist somewhere in the vicinity of the lake. On the basis of the available data, it is postulated that the waters originate from at least two deep high temperature (140°C to 300°C) sources. (Fig. 3).

THE GEOTHERMAL EXPLORATION AT OLKARIA

Investigations of the geothermal energy potential in the Kenya Rift Valley first began in the period between 1955 and 1959 by drilling two deep boreholes (X-1) and (X-2) at Olkaria which unfortunately failed to discharge steam of economic viability.

When the drilling operations were stopped, the colonial Government, through the Mines and Geological Department, continued further investigations. They included the measurement of near surface temperature and shallow drilling to measure temperature variations of shallow underground. Unfortunately, these efforts were interrupted in 1963 and the whole programme came to a standstill due to shortage of technical staff.

Towards the end of 1970, however, a major geothermal exploration programme was started by the Kenya Government and the United Nations Development Programme (UNDP) under the management of the United Nations Geothermal Exploration Project Manager. This programme, which ended in 1976, covered the surveys of three main geothermal fields in the Kenyan Rift Valley, namely Olkaria, Eburru and Lake Bogoria. Of the three regions, more detailed geological, geochemical, geophysical and hydrogeological investigations were made and the exploratory and production drilling was concentrated at Olkaria.

At the Olkaria Geothermal Field the first 15 MW turbo-generator plant began operation in July 1981 and the next 15 MW in December 1982. The total capacity planned to be developed at Olkaria East Geothermal Field is 45 MW.

THE GEOTHERMAL EXPLORATION AT EBURRU

Following the success of the Olkaria Geothermal Field, the Kenya Government requested the Japanese Government to conduct a geothermal exploration survey in the Kenyan Rift Valley. The request was agreed on and an exploration survey project agreement through Japan International Cooperation Agency (JICA) was signed. The first Japanese Mission came to Kenya in February 1979 and after the mission returned to Japan a second mission led by Dr. Koji Motojima was despatched to work out in cooperation with Ministry of Energy a comprehensive programme to evaluate the geothermal potential along the Kenyan Rift Valley especially the Eburru area. Since then a detailed survey based on geology, geochemistry and geophysics have been carried out at the Eburru prospect by the joint project team.

The location of Eburru Prospect

The Eburru Geothermal prospect lies within the Kenyan Rift Vally between 0° 55′ and 0° 83′ S. latitude and 36° 15′ and 36° 45′ E longitude and about 30 km north of the Olkaria Geothermal Field.

The Eburru prospect is connected to the main Nairobi-Naivasha road by three dry weather roads. These are, Moi South Lake Road which goes around the western side of Lake Naivasha, while the second road follows Moi North Lake Road and the third road is through Gilgil Town following Kiambogo Road (Fig. 3).

Physiography

East-West orientation of the Eburru Ridge is different from most of the structural trend in the Rift Valley. An E-W fault served as the centre of volcanic activity in Quaternary time providing pyroclastics. The present topography of Eburru was formed by these pyroclastics. The top of Eburru Ridge is 2750 m and the floor of the Rift Valley is 1900 m. The last volcanic activity took place in recent time along a N-S zone across the eastern side of Eburru Ridge and produced a number of obsidian cones due to viscous nature of the acid magma. The cones form very prominent features over the eastern face of Eburru Ridge. The 2750 m elevation gives Eburru a very cool climate. The wet season is normally April to May but heavy rains fall also in October to November period. The thick natural forest at the top of the ridge, there live different types of wild animals and birds due to attractive climate. The lower parts of Eburru Ridge are dry like the floor of the Rift Valley.

Vegetation

The vegetation of the eastern Eburru area is characterised by scattered trees and schrubs in contrast with a thick forest on the western side of the ridge. The local people grow maize, potatoes, barley, and pyrethrum. The area is occupied by 150 families with a total population of about 2000 people and the animal population is estimated to be more than 5000 heads.

Geology of Eburru

The Eburru area appears to rest upon a visible basement of Rift Valley trachytes which crop out along series of N-S trending fault scarps in the flat area, south of the town of Gilgil. These may have been flow lavas, extruded from fissures of N-S direction. Two small faulted centres are seen on Cole Estates, east of the Badlands Basalts. These were followed by trachytic volcanism and the trachytes are mostly covered by the Badland Basalts. The related welded tuffs are seen overlying a part of the earlier trachytes. These later trachytes are roughly correlated with the pyroclastics of the N-S trending Waterloo Ridge.

One of the above volcanic centres is thought to have constituted the embryonic Eburru Ridge. From the proto-Eburru centre, a series of trachyte flowed down to the north, south, and east flanks of the mountain. It is overlain by later pumice lapilli tuff. The latest activity was the eruption of the Badland Basalts which more or less filled the space between Eburru Ridge and Lake Elementaita and the extrusion of contemporaneous obsidian domes.

Structure

The main structural framework of the area was established during major faulting activities in earlier time. The main structural characteristics is the narrow but significant fracture system running in N-S direction traversing the eastern side of Eburru Ridge. This weak line provided the access route for underlying deep pockets of magma to reach the surface. However, an

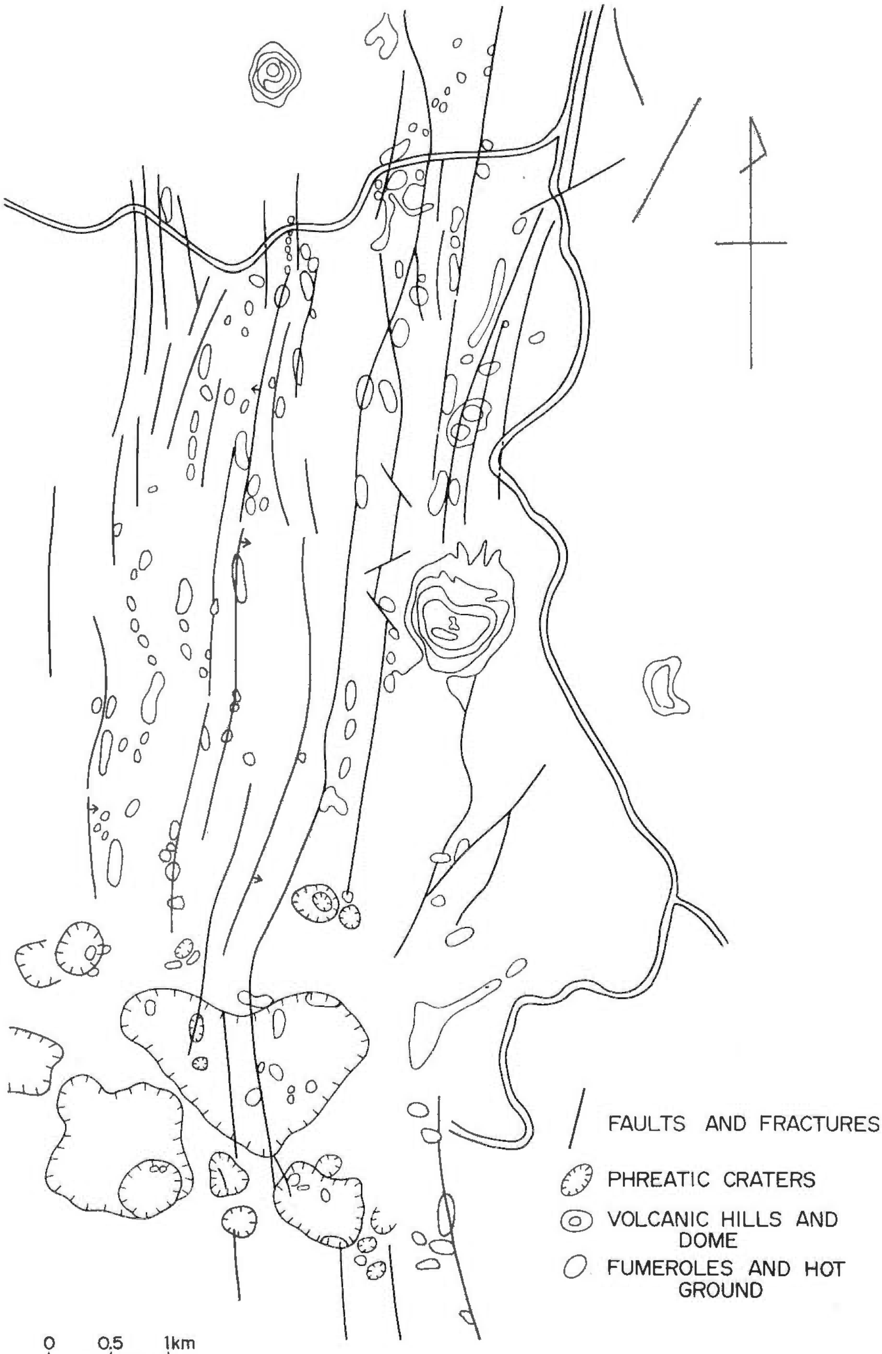

Fig. 4. Structural map of Eburru and distribution of geothermal manifestations.

E-W fracture may possibly extend beneath the Eburru Ridge to the western wall of the Rift. Early stage (1970) of the UNDP geothermal project a survey was carried out using aerial infrared imaging sensor to locate hot spots on the ground. Areal mapping revealed hot spots at the areas of rough terrain and poor access (Fig. 4). The anomalous area shown by the infrared image data corresponds with the zone of intense fracturing with N-S direction.

Geochemical Prospecting at Eburru

The most useful and powerful techniques being used in geothermal surveys is fluid geochemistry.

Some of the geothermal sampling localities show manifestations such as hot springs and fumaroles. From the fluids discharge which is assumed to come from a geothermal reservoir, we can estimate the subsurface temperature. The geothermal fluids differ greatly from field to field and even within a single field. The sampling of geothermal fluids for geochemical analysis is only feasible in water dominated fields. In the case of the steam dominated fields other methods such as gas methods are applied. The Eburru Geothermal Field lacks hot springs and only fumarole discharge is the visible manifestations on the surface. This is probably due to the too low water table level. However the mercury (Hg) and carbon dioxide (CO_2) geochemical methods were used effectively at Eburru.

The two geochemical methods have been used in US, Japan and Eburru and have proved to be very successful since Hg indicates the hot geothermal areas and CO_2 helps to determine the geological structures.

There is clear evidence of an association of unusual amounts of Hg and CO_2 with areas having major geothermal activity. The occurrence of Hg and CO_2 at Eburru is closely related to the hot area detected by the infrared survey, which covers approximately 40 km^2 (Fig. 5 and 6). The relationship of anomalously high Hg areas with high temperature areas has been surveyed by ground temperature measurements in all sampling localities.

Geophysical Prospecting at Eburru

The electrical resistivity sounding was conducted over a total of 163 stations located along, more or less, E-W traverse lines covering an area of approximately 66 square km. The lines, numbering 22 in all were designated "lines A to V"

The soundings were carried out on all those lines except lines N and V. The lines were marked by staked stations placed 50 m apart. The minimum distance between adjacent survey lines was maintained at 400 m and only one set of equipment was used along a given traverse line.

Two sets of electrical resistivity equipment were used. The one set consisted of a powerful IP transmitter, Model 15202 and an accompanying power supply, Model LF-83-B, both of which are manufactured by the Yokohama Electronics Laboratory of Tokyo, Japan, for delivering a square wave current at 0.1 Hz into the ground. The recording system has a filter-amplifier unit and an analogue chart recorder.

The transmitter and power supply were powered by a 2.4 kw gasoline generator. The other set of resistivity equipment consisted of a less powerful but lighter ABEM SAS 300 Terrameter with an accompanying ABEM SAS 200 booster. This type of equipment is the latest model manufactured by the ABEM Company of Sweden and is powered by chargeable gel cells.

The Schlumberger configuration of vertical electrical sounding was employed throughout. In this type of configuration, two "Current" electrodes, usually made of non-polarizable metal stakes for sending a current into the ground, are dug into the ground at two points, placed some distance apart on the survey line. Two "potential" electrodes, usually made of porous pots filled with copper sulphate solution, are placed in contact with the ground symmetrically between the current electrodes also at two points which are placed some distance apart. During the transmission of the current into the ground, the potential difference between the two pots is recorded. The transmitted current is also recorded. The sounding station is that point

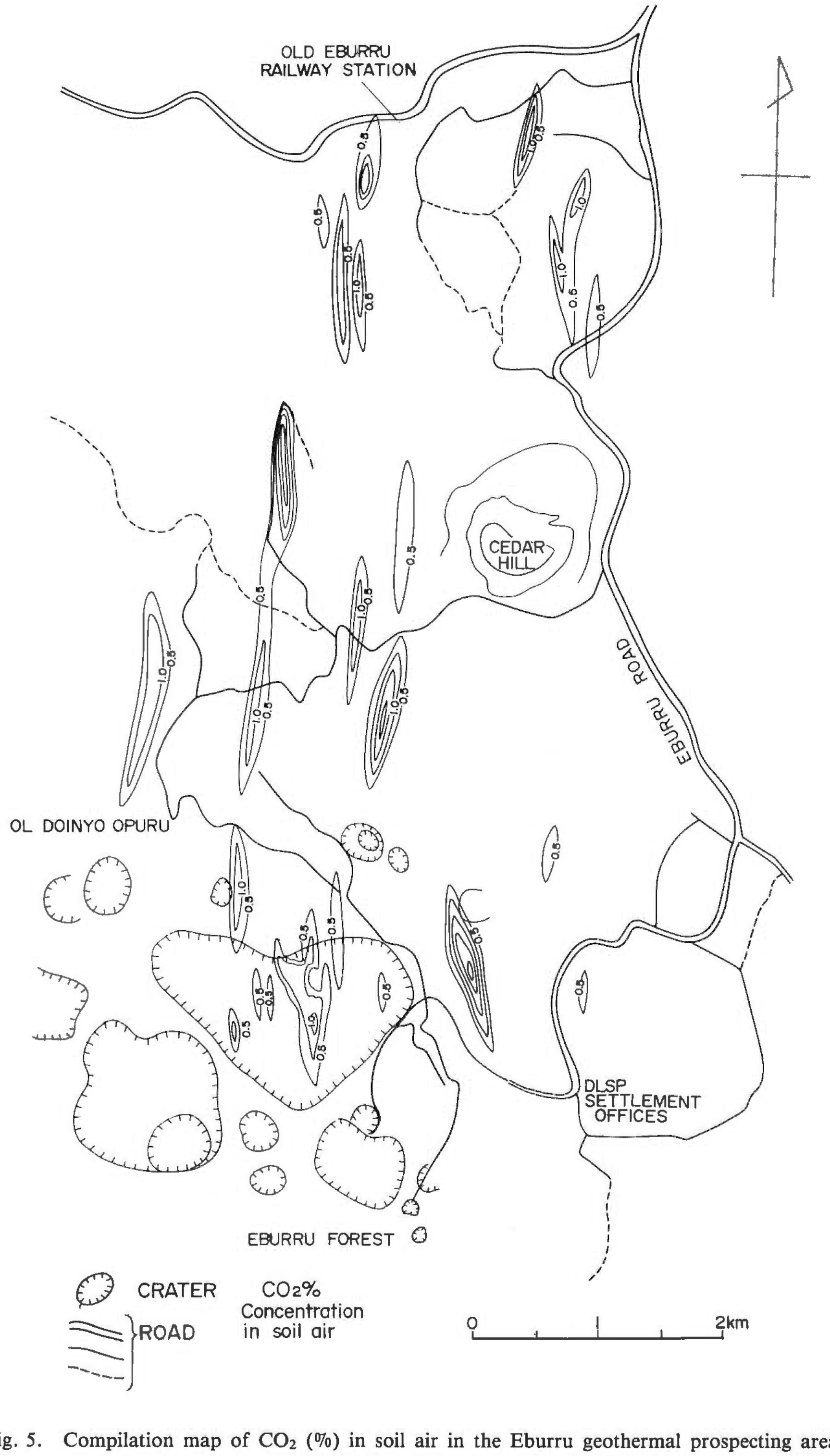

Fig. 5. Compilation map of CO_2 (%) in soil air in the Eburru geothermal prospecting area (1980–82).

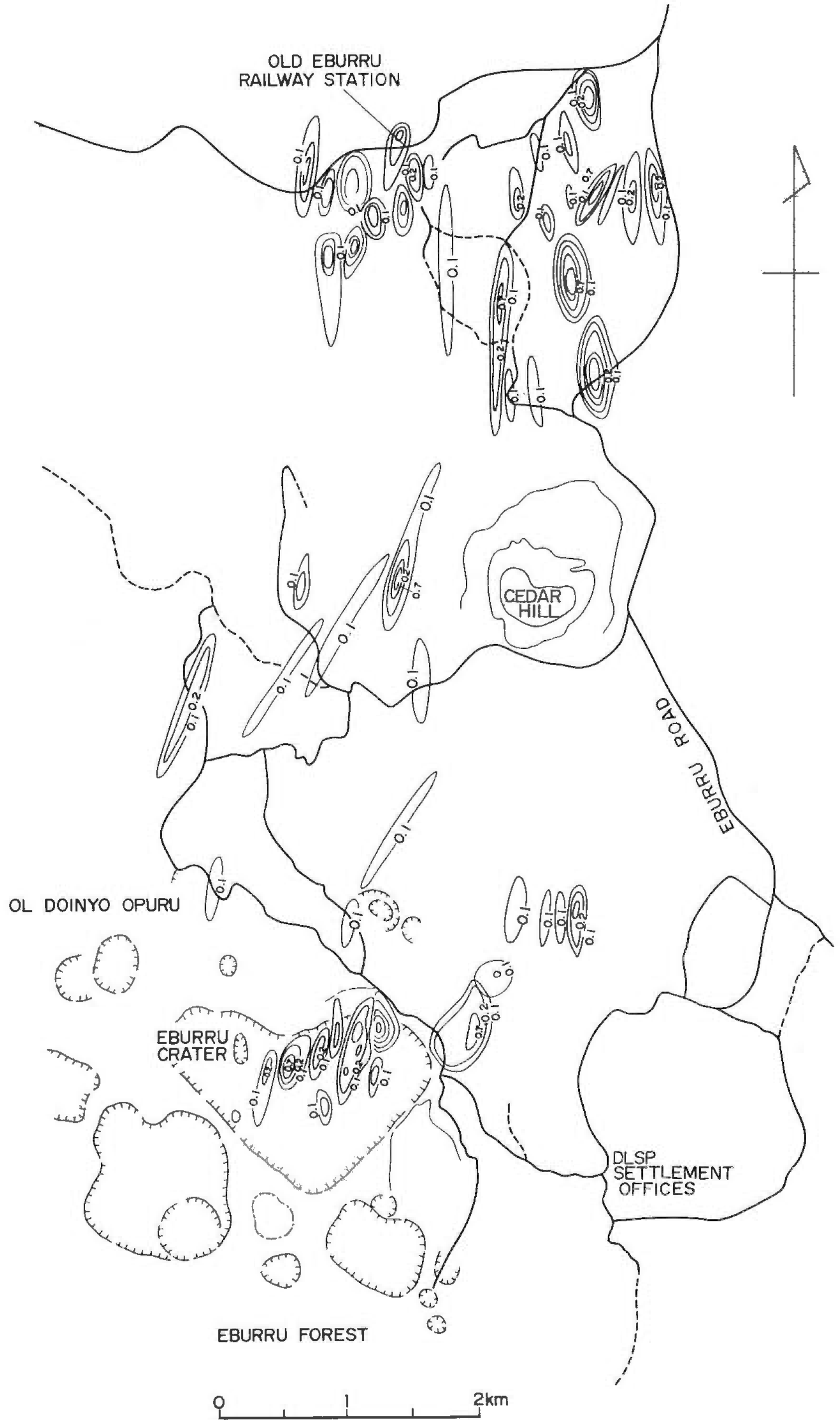

Fig. 6. Compilation map of Hg (mg/l) in soil air at the Eburru geothermal prospecting area.

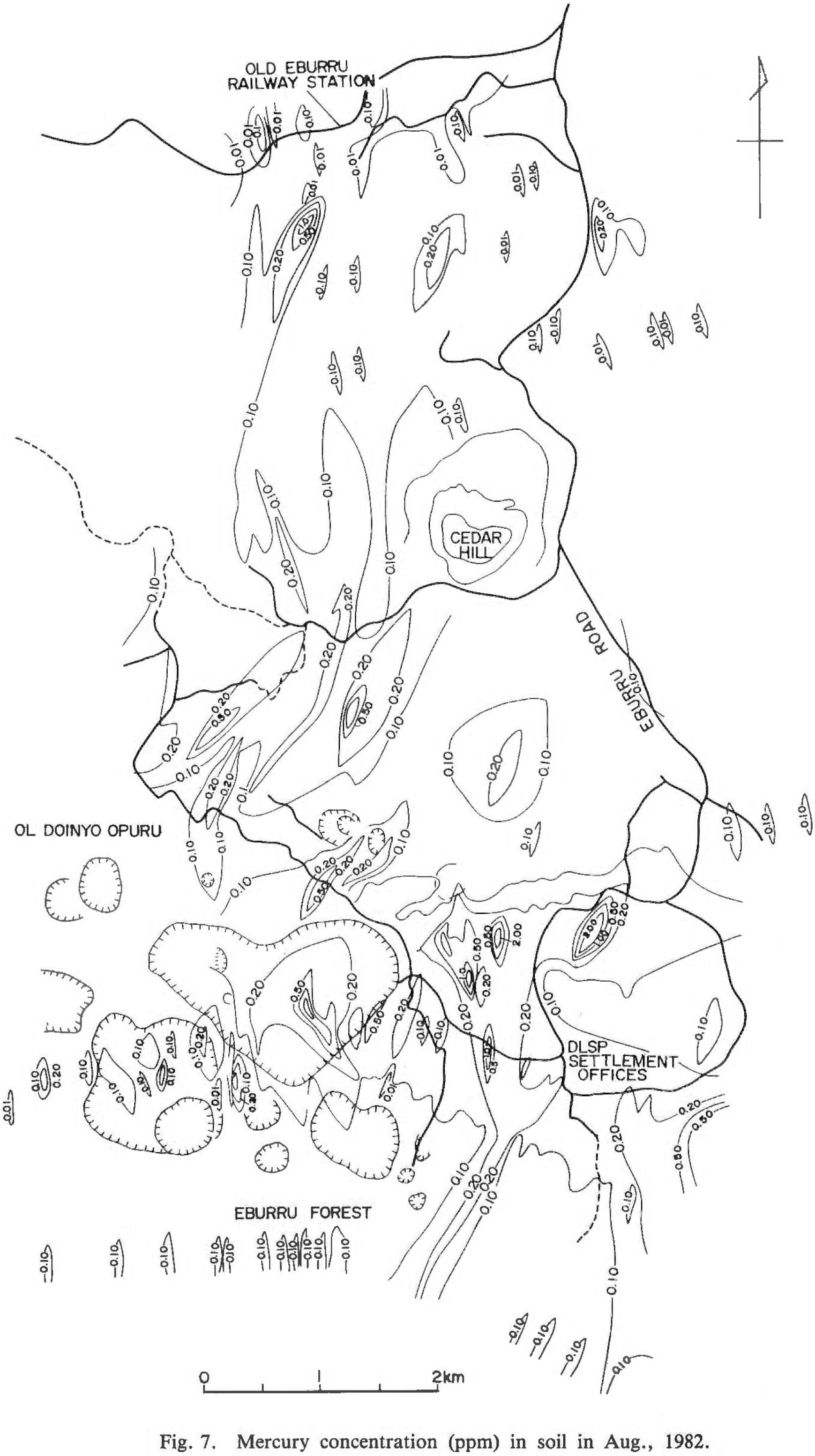

Fig. 7. Mercury concentration (ppm) in soil in Aug., 1982.

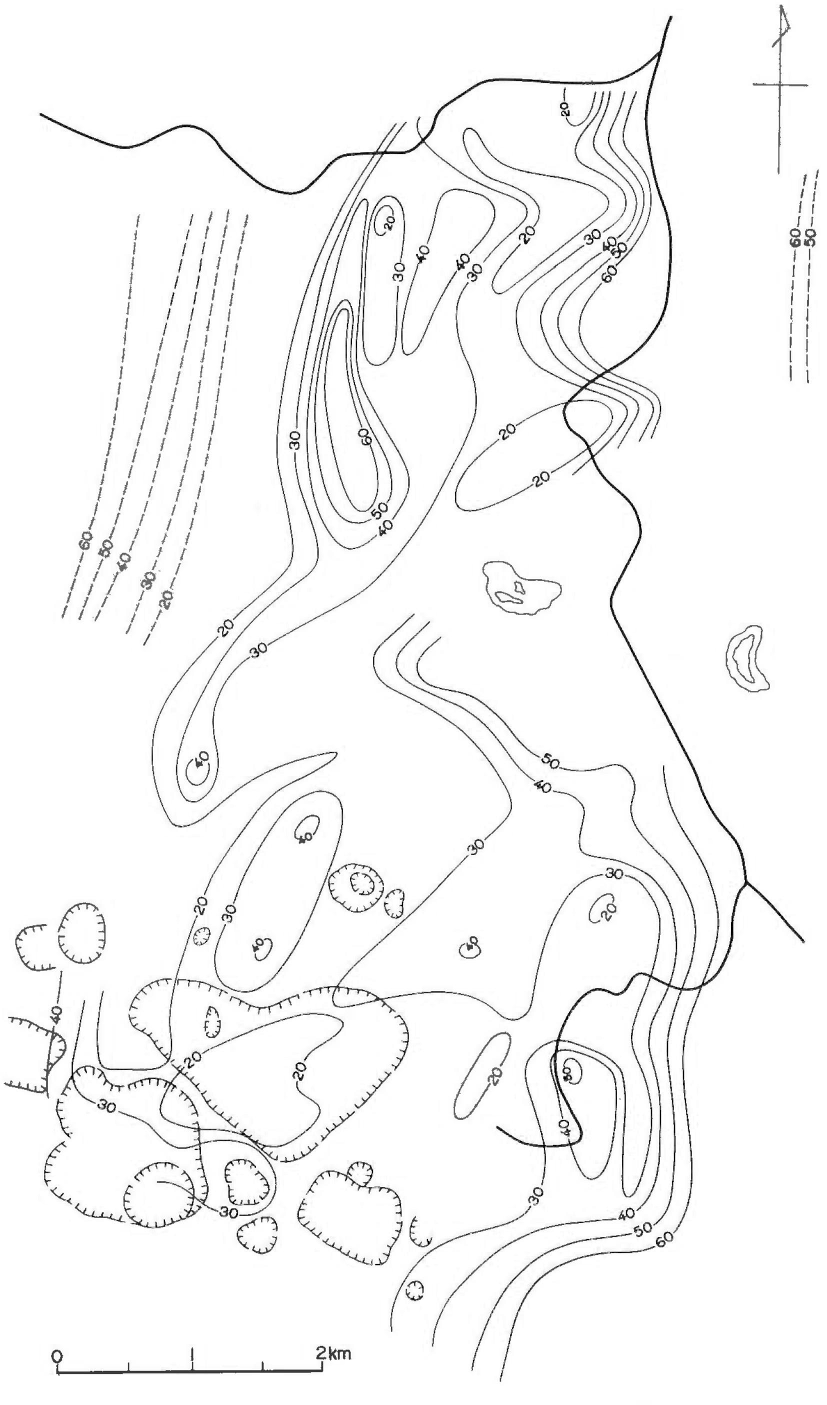

Fig. 8. Distribution of apparent resistivity (ρa) at AB/2 = 500 m at Eburru geothermal prospecting area.

which occurs midway between the potential or current electrodes. To record more readings on the same sounding station, the two current electrodes are moved out in steps while keeping their distances on either side of the sounding station equal.

This investigation has revealed that the Eburru Field is underlain by a large hot water reservoir, possibly of meteoric origin, whose flow pattern indicates that it is being supplied from the high peaks of Eburru Ridge to the southwest. The main heating centre for this water has been postulated to be located underneath the western edge of the "main" Eburru crater where the flow pattern of the entire geothermal field appears to start. The minor heating centres occur on the northern region of the field. The topography and the system of north-south fractures passing across the eastern slope of the ridge have significant influence on the direction of flow. There is one flow to the north and northeast and the other to the east and then to the south.

In vertical section, there are three main resistivty zones which have been recognized. These are, a thin top zone of low to very high resistivities acting as the cap rock, a middle thick zone of low resistivities interpreted as the hot water zone whose maximum horizontal width between the east and west boundaries has been found to be about 7 km. Its vertical thickness is greater in the central and northern regions (about 1000 m or more) and smaller underneath the mountain (about 400 m).

Another zone worth noting is that of moderate resistivities between the top zone and the bottom thick low resistivity zone. Occurring mainly in the central part of the northern region the zone may be due to the mixture of hot water and steam. The steam is a poor conductor of current and any zone covered by the steam will indicate a high resistivity.

The hot water zone at Eburru closes on the southeast and northwest. It is open on the south, north, northeast, where the flow continues underneath the thick layer of lake sediments, and possibly southwest (Fig. 8).

FUTURE PROGRAMME OF GEOTHERMAL EXPLORATION IN MID-RIFT VALLEY

The Rift Valley's geothermally potential areas can be subdivided into three subregions: —

1. Northern Rift Valley — all that area extending from the Silali Caldera to the Ethiopian border.
2. Central Rift Valley — south of the Silali Caldera to the Suswa Caldera both included.
3. Southern Rift Valley — south of the Suswa Caldera to the Kenya's border with Tanzania.

In order to meet the very much needed electricity supply in 1990s and supply other uses of low enthalpy heat, the programme of exploration should be directed as follows: —

1. The first area of operation will be Central Rift Valley purely because of the existing development, and infrastructure. The next exploration subregion will be decided at a later date. The exploration of Central Rift Valley includes the Eburru Geothermal Exploration Project.
2. All surface field exploration should be done comprehensively in the sub-region based on the results of geological, geochemical and geophysical data collection, processing and interpretation.
3. Drilling investigations for geological and temperature gradient based on 200–400 m holes will be intensified to give proper coverage at Eburru.
4. Exploration drilling of 1500 m slim wells at Eburru should be continued after the surface exploration to prove the existence of steam for both electricity generation and other industrial purposes.

In an effort to carry out this programme, a joint MOE/UNDP geothermal exploration project is being finalized and it might start in January 1984. The five year project is referred to as Exploration for Geothermal Energy — Phase II. The project objectives are to carry out surface and drilling exploration and inventory of all geothermal resources in the Central Rift Valley covering the area from Suswa Caldera to Silali Caldera. The area to be covered will be about 260 km long and 30 to 60 km wide. By the year 1987, the project would have identified at least three potential areas that would be recommended to Kenya Power Company for exploration drilling and development of geothermal fields to produce electricity. Some of the low temperature fields can provide industrial heat and meet other low enthalpy requirements.

Following the National Power Development Plan the geothermal energy would then replace the convectional thermal generating power plants (using fossil fuels). After completion of Phase II, further work would be continued towards either northern or southern part of the Rift Valley.

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Philippine Geothermal Resources: An Alternative Indigenous Energy

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ABSTRACT

The philippines is indeed fortunate to be located within the West Pacific Island Arc dotted by Neogene volcanic centers. The multi-stage developments of volcanic plutonic events in this western part of the Circum-Pacific basin have generated regions of high heat flow where known potential geothermal resources are located.

With the increasing power demands, reflecting a favorable growth of the country's economy, the Philippine Government has embarked on an accelerated program to harness the country's geothermal energy for power utilization inmediately following the start of the energy crisis in the early 70's.

For a period of ten years (1972-1982), the Philippines has successfully maintained a systematic and continuing program of assessing, exploring, developing and exploiting its vast potential geothermal resources. Of the several potential areas scattered all over the archipelago, four geothermal fields have already contributed some 556 megawatts to the total electrical power generation.

This paper deals with the geothermal resource development in the Philippines, a major achievement of a developing country of the Third World in regard to the utilization of new and renewable scources of energy.

INTRODUCTION

The Philippine Archipelago has geologic structure arising from multi-stage development of volcanic-tectonic events in the past. These geologic events have been continuously manifested in the forms of volcanisms and seismic activities occurring along the active blocks of major structural lines which traverse most of the major islands of the Philippines.

The extensive volcanism localized along the active tectonic blocks have brought about regions of high heat flow where a vast number of potentially—rich geothermal resoures are located which could be exploited as indigeneous alternative source of energy.

With the systematic and continuing program launched by the Philippine government in harnessing the country's geothermal energy after the successful pilot study made at the Tiwi Geothermal Field in 1967 by the Commission on Volcanology, now called the Philippine Institute of Volcanology (PIV), the Philippines has developed four geothermal fields within a period of ten years (1972-1982). These four areas, namely, Tiwi in Albay, Mak-Ban in Laguna, Tongonan in Leyte, and Palinpinon in Southern Negros, have already contributed 556 MW to the total electrical power supply of the country that is dominantly supplied by petroleum-based power generating units.

The Philippine Government has envisioned that with its accelerated geothermal energy program, it would be able to achieve its target of reducing the country's dependence on imported fossil fuel by about 20 percent within the next decade through the utilization of its vast geothermal energy resources.

OVERVIEW OF GEOTHERMAL OPERATIONS IN THE PHILIPPINES

Highlights on Geothermal Exploration/Development

The Philippines has embarked on an accelerted program of the utilization of geothermal energy at the start of the energy crisis in the early 1970's. This program was initiated through the pioneering work carried out by the PIV in 1964 with the financial assistance of the Philippine National Science and Technology Authority (NSTA), formerly National Science Development Board (NSDB), selecting Tiwi geothermal area in Albay province of Southern Luzon to be the site of the scientific and pilot studies for geothermal power utilization. The studies undertaken by PIV was successful. On April 12, 1967, a small turbo-generator borrowed from the Mapua Institute of Technology, a local engineering college, was operated for the first time by geothermal steam from the 122 m (400 feet) deep and a half-inch borehole drilled by the Philippine Bureau of Mines for PIV's pilot study. Another shallow borehole with a four inch production liner was drilled in 1968 down to 195 m (641 feet) to further test the shallow geothermal aquifer intersected earlier by the 122 m (400 feet) borehole. The well was successfully discharged and was utilized to power a 2.5 kW non-condensing geothermal pilot plant at Tiwi in 1969. This demonstrated to the country the potential power capability of geothermal energy which, when fully utilized, could direct a developing nation like the Philippines towards self reliance on its energy requirements and its quest to reduce total dependence on imported fossil fuel.

The success of the feasibility study undertaken by PIV in Tiwi paved the way for a decision to start with the commercial exploitation of the country's geothermal resources. On August 14, 1970, the government declared 17,660 hectares of land in Tiwi, Albay as a geothermal reservation area and gave the Philippine National Power Corporation (NAPOCOR), the state-owned electric utility firm, the responsibility to administer the exploration/development of the Tiwi Field through a service contract with the Philippine Geothermal Incorporated (PGI), a subsidiary of Union oil Company of California, to develop the field and serve as a supplier of steam for the NAPOCOR geothermal plants.

The first deep wildcat well was spudded in Tiwi on March 1, 1972 to a depth of 1519 m (4,984 feet). This was followed by a second well in February 1973 which was a production well. The activity inspired another NAPOCOR–PGI joint venture agreement for the exploration/develoment of Makiling-Banahaw (MAK–BAN) Geothermal Field in Laguna. On November 25, 1974, the first exploratory well drilled in MAK–BAN to a depth of 1,765 m (5,792 feet) turned out to be also a commercial well.

The success in the geothermal exploration in the two isolated fields gave more encouragement to proceed in the assessment of other potential geothermal areas in the country through the foreign assisted projects. The Philippine government then entered into bilateral agreements with some countries such as New Zeland, Italy, and Japan which have the technical expertise in the utilization of geothermal energy. Through these bilateral agreements, two additional geothermal fields (Tongonan and Southern Negros) were explored and are now ready for full scale commercial power generation. The exploration activities in these two areas are being undertaken by PNOC–Energy Development Corporation (EDC) with the technical assistance of the New Zealand Government and the financial assistance (OECF) of the Government of Japan for the development of the fields.

With the creation of the Philippine Ministry of Energy (MOE) in October 1977 to coordinate and regulate energy development and utilization in the country, the government began to engage in a systematic geothermal energy program. This led to the enactment of Presidential Decree 1442, known as Geothermal Law, providing for the rationalization of geothermal exploration and development.

Concept and Provisions of the Geothermal Service Contract

On June 11, 1978, Presidential Decree 1442 was promulgated into law intended to rationalize the exploration and development of the country's potential geothermal resources through a service contract between a prospective developer and the Bureau of Energy Development (BED), the implementing arm of the MOE.

Under the service contract system, the contractor will provide the necessary expertise, financing and technology. The services of the developer of the field will in turn receive a maximum of 40% of the net proceeds from the selling of steam to the end-user which is the NAPOCOR, the designated official agency of the government on power generation. The net proceeds is computed after deducting the necessary expenses incurred in the exploration and development of the field.

The geothermal service contract also provides exemption from the payment of tariff duties and compensating tax in the importation of machinery and equipment and other materials needed in the geothermal operations. Recovered capital investments and earnings derived from such service contract operations can be remitted through the local banking system subject to the Philippine Central Bank's regulations.

REGIONAL DISTRIBUTION OF POTENTIAL GEOTHERMAL AREAS

Results of Nationwide Survey

The regional survey on Philippine thermal springs commenced as early as 1926 covering 54 hot springs which were later reinvestigated in 1963 by the PIV under the United Nations Development Program (UNDP) technical assistance. The results of such early work led to the selection of Tiwi Geothermal Field as the site for the first scientific and pilot studies on the utilization of geothermal energy for electrical power.

With the continuing success in the exploration/development of the geothermal projects undertaken by NAPOCOR–PGI joint venture as well as the PNOC–EDC and Zealand Government, there has been a rapid growth of interest in the development of the country's geothermal resources. This has prompted the MOE to request the support of the Italian Government for technical assistance in conducting a more detailed regional inventory on the geothermal resources of the country in order to come up with a set of priority areas for immedite development.

The resource inventory undertaken by joint participation of the BED and Italian Electroconsult (ELC) was carried out for one year (1978–1979) on several known and unexplored thermal areas scattered all over the archipelago. The investigation was concentrated on areas with significant geological and geochemical indications as well as socio-economic importance. Based on these merits, 13 of the 35 areas investigated were identified as priority areas to undergo preliminary exploration work. The priority areas selected for further geoscientific studies are as follows:

1.	Batong-Buhay in Kalinga-Apayao	— Luzon Island
2.	Mainit-Bontoc in Mountain Province	— 〃
3.	Buguias in Benguet	— 〃
4.	Daklan in Benguet	— 〃
5.	Acupan-Itogon in Benguet	— 〃
6.	Pinatubo in Zambales	— 〃
7.	Cagua in Cagayan	— 〃
8.	Montelago in Oriental Mindoro	— Mindoro Island
9.	Biliran Island in Northern Leyte	— Eastern Visayas
10.	Anahawan in Southern Leyte	— 〃
11.	Mainit-Placer in Surigao del Norte	— Eastern Mindanao
12.	Balatukan in Misamis Oriental	— Northern Mindanao

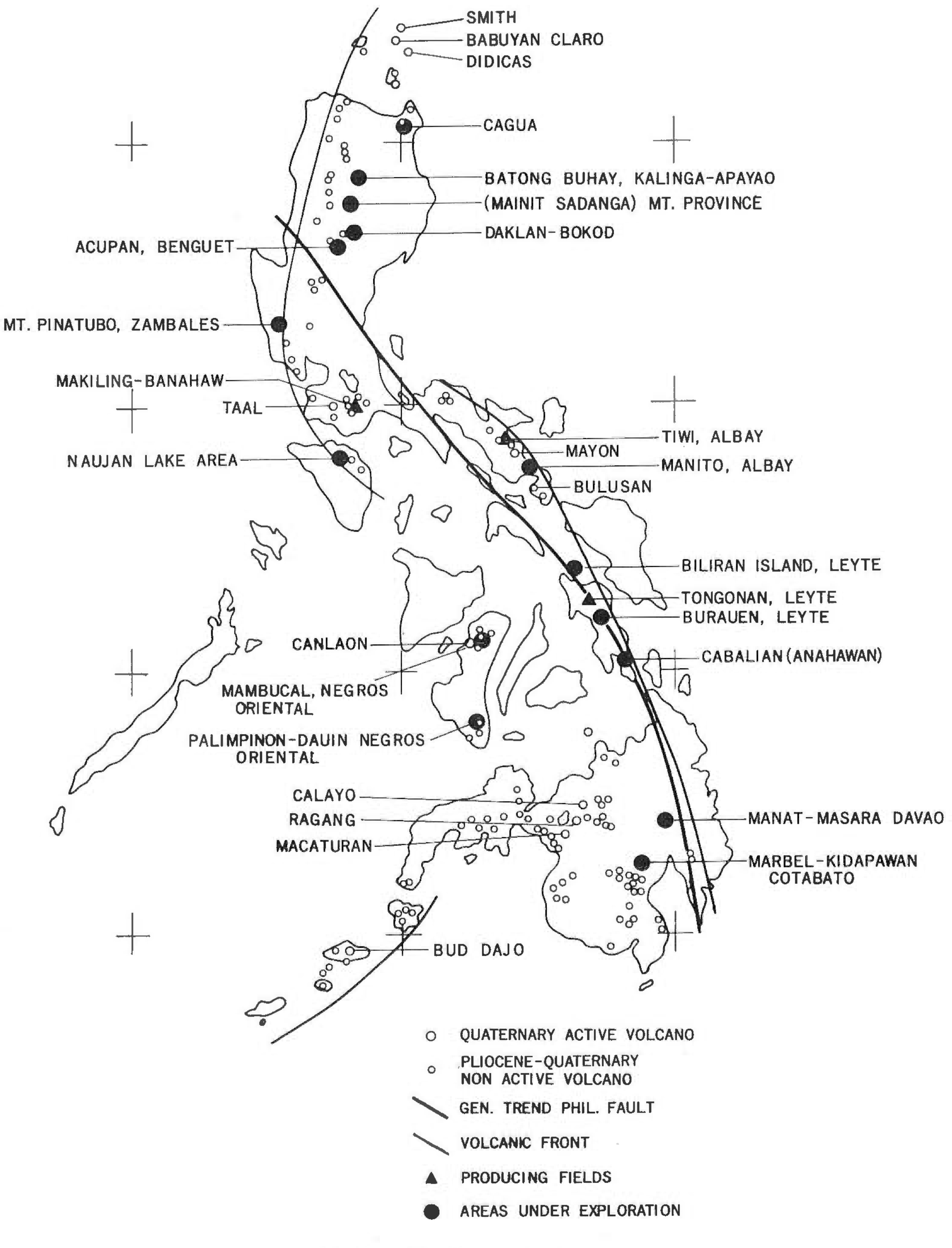

Fig. 1. Philippine geothermal areas.

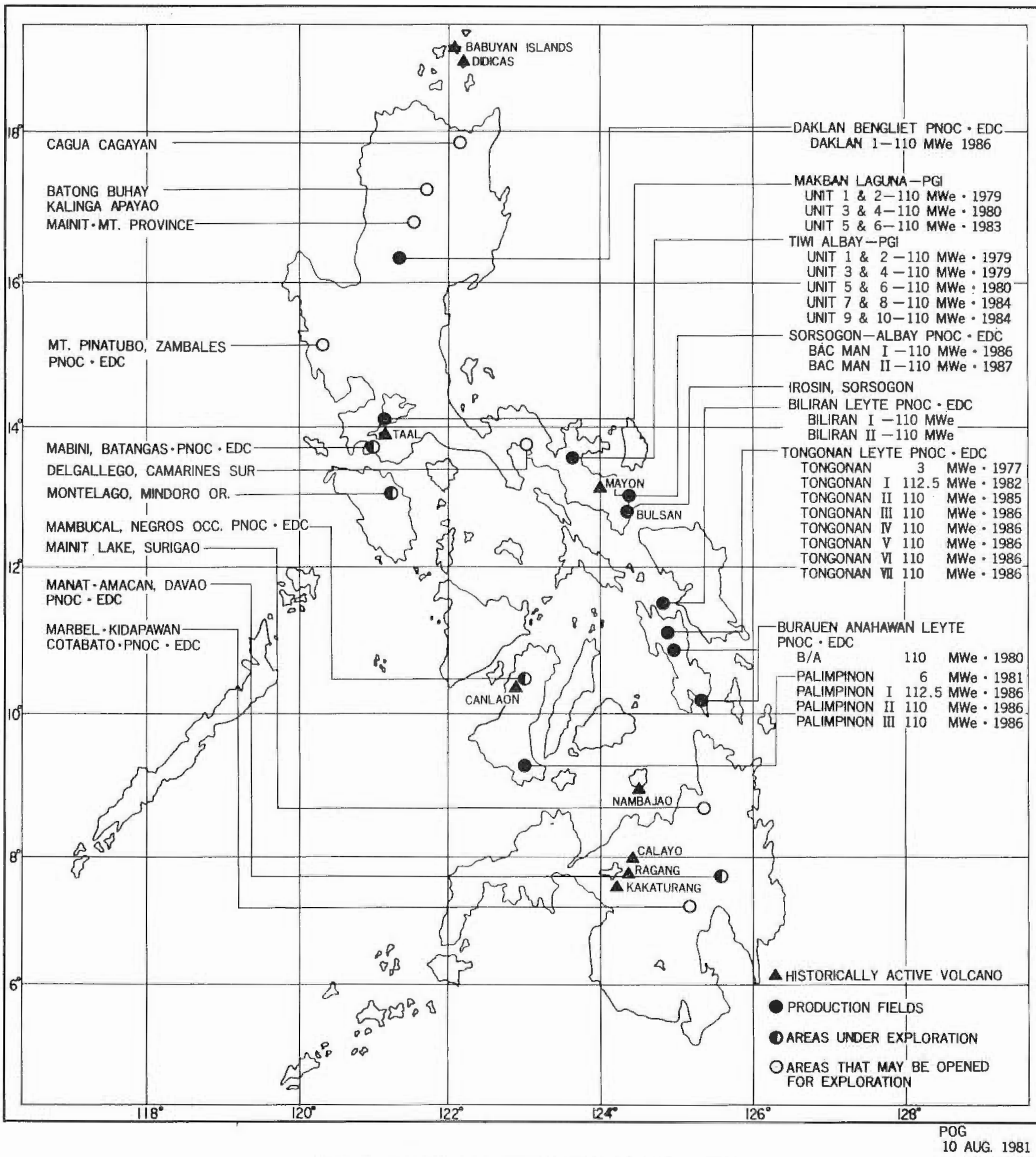

Fig. 2. Philippine geothermal development.

13. Apo-Kidapawan — Central Mindanao

The methods and criteria of evaluation for selecting the priority areas under the geothermal resource inventory program, however, are not without limitation. The ambiguities on the geochemical pattern where varying degrees of interaction between the geothermal fluid and the country rock or fossil alteration minerals, and the complex geologic setting are just some of the complications to be expected in this type of preliminary reconnaissance work. However, in spite of these limitaitons, it is felt that the regional inventory of the country's geothermal resources has satisfactorily achieved the objectives of identifying the promising areas within the range of reasonable probability.

The active involvement of the government in the exploration of geothermal resources, supported by foreign technical assistance under the bilateral agreement program, has enlarged the scale of participation of private sectors to explore and develop the already pinpointed potential areas whereby they are given some incentives under the service contract system on geothermal operations.

Geologic Setting

The geological history of the formation of the Philippine Islands has been studied and investigated by geologists such as DIVIS and HALLOWAY, who are engaged in plate tectonic study of the western Pacific island arc system. A.F. DIVIS (1977) implied that the onset of large-scale volcanism and metallogenic activity in the Philippines appears to be more related with the tectonic evolution of the Caroline Basin than the formation of Marianas Arc. N.H. HALLOWAY (1981), in his studies on the Philippine North Palawan Block, concluded that the Philippine Archipelagic complex rotated towards its present orientation on a counter clockwise movement at the start of Late Eocene when there was a change in Pacific Plate motion. The final phases of the rotation of the Archipelago occurred in Late Miocene. These initiated left-lateral movement on the Philippine master fault system that traverses the major islands of the Philippines from north to south.

The Cenozoic crustal movement in the Philippine Island Arc could have caused the repeatedly intense folding and faulting since the Tertiary. Such intense crustal warping may have induced multiple stages of volcano-plutonic activities which reached the climax of plutonic intrusions during the final rotation of the Archipelago in the Middle to Late Miocene and progressed onward to extensive volcanisms in the Plio-Quaternary.

Many of the potential geothermal resource areas in the Philippines and related young volcanoes are located along the Philippine shear system or its nearby branch faults and some are localized along the fringes of large Intra-Miocene silicic batholith.

The geothermal areas in Northern Luzon are generally confined along the eastern and southern margin of the Agno batholith, the name adopted by SCHAFER (1956) to a portion of the Northern Luzon Cordillera quartz diorite. The entire batholith complex in this region is considered to be the largest in the country. The eastern and southern margin of the batholith are nested with Plio-Quaternary andesite-dacite volcanic centers which could be related to the waning stages of the magnatic evolution in the area. Potential geothermal areas such as Batong-Buhay, Mainit-Bontoc, Buguias, Daklan and Acupan-Itogon are located close to most of these volcanic centers. It appears that the main heat source of these thermal areas is primarily contributed by the residual heat of the batholith which is still confined in the body of the pluton and being gradually released along the open channel-ways of young volcanic fissures in the form of geothermal manifestations.

DATUIN and UY (1978) recognized a number of Plio-Quaternary volcanoes in the Philippines which formed zones of major volcanic fronts. The zonal distribution of these volcanic rocks is grouped into three major belts, namely, the westerly convex volcanic front passing along the western coast of northern and central Luzon facing the South China Mainland; the southeasterly convex volcanic front in Sulu Islands which extends to the north of Zamboanga and swervs towards the western Visayas; and the easterly convex volcanic front facing the Pacific which can be traced from the Bicol region, passing through Leyte Island and extends southward to Surigao and Davao of Mindanao Island. The cluster of young andesite dacite volcanoes (active and non-active) distributed along the easterly convex volcanic front runs parallel with the trend of the Philippine master fault (ALCARAZ, 1947). Of the three major volcanic zones, a number of potential fields are dominantly found along the easterly convex volcanic front where it traverses the eastern block of the Philippine master fault. It appears that the continued transcurrent movement in the master fault have generated the major upheaval of volcanism in the late Tertiary and their activities had progressed during the Quaternary. This could have induced extensive crustal fracturing and high heat flow which produced condition favorable for the presence of potential geothermal resources in this region.

Some of the potential areas located on the eastern volcanic belt are Labo, Isarog, Tiwi, Manito and Bulusan in Bicol regions; Biliran Island, Tongonan, Burauen and Anahawan in Eastern Visayas; and Mainit-Placer and Masara-Amacan in Eastern Mindanao. Among the geothermal areas mentioned, four are already in the advanced stage of exploration and/or development (i.e. Towo, Manito, Biliran and Tongonan).

GEOTHERMAL ACTIVITIES

Recognizing the benefits on the utilizaiton of geothermal energy, exploration and development activities have intensified in the four developed fields and in other equally potential areas in Luzon, Visayas and Mindanao. The power potential of these resource areas, if fully developed could be relied on to supplant a significant portion of electricity being supplied by petroleum-based power generating units.

Tiwi Geothermal Field, Albay

The Tiwi field is developed jointly by the National Power Corportion and Philippine Geothermal, Inc., a subsidiary of Union Oil of California.

Pleistocene lavas and pyroclastics make up most of the present landforms in the contract area. The lavas range from voluminous pyroxene andesite flown from Mt. Malinao to limited hornblende biotite dacite extrusions at Putsan-Bolo.

Malinao Volcano covers nearly half of the contract area. Its lave flows extend to as much as six kilometers from the volcano center while smaller flows cover most of the upper slopes. Two plug domes domprise the Bolo-Putsan hill. Bolo is composed of biotite-hornblende dacite.

The Tiwi fracture system controls the permeability of the underlyng geothermal system. Some components extend down into the besement and serve as major channel ways for ascending parent hot fluids.

The geothermal reservoir is the source of hot fluids being utilized to generate electric power. It has a temperature of 204°C to 316°C at production depth. Tiwi now generates 330 MW of geothermal power supply.

Eighty eight wells were drilled in the area, of the completed wells 70 are production wells with proven steam power capability of 550 MW; ten wells are undergoing tests and stimulation and eight are noncommercial wells.

Makiling-Banahaw Geothermal Field, Laguna

Like Tiwi, the Makban Geothermal Field is being developed as a joint venture of NPC and PGI.

An early episode of volcanism in the region saw the deposition of a subvolcanic basement consisting of intercalated andesite flows, agglomerates, tuffs and breccia interbedded with marine sediments of late Miocene to middle Pliocene. South of Mt. Makiling, geothermal well bores indicate that the basement exceeds several thousand feet in thickness.

The total installed generating power of the field is 220 MW from four 55 MW units. Two more units of 55 MW are under construction.

A total of 78 wells has been drilled in the area of which 50 are steam producing, 23 are non-commercial and five are under well stimulation and testing.

Tongonan Geothermal Field, Leyte

The Tongonan Geothermal Field is located at the northern part of Leyte Island in eastern Visayas. The government has granted PNOC–EDC a service contract to explore and develop the potential of the geothermal resource located inside the 107,620 hectares of land in the designated NW–SE rectangular geothermal concession area covering not only the Tongonan

Field but also the Burauen geothermal prospect area.

Due to the dire need of Ormoc City (capital city of Southern Leyte) for cheaper electrical supply, the Philippine Government through bilateral agreement with the New Zealand Government, started a technical coopertion project in 1973 for deep exploration drilling in Tongonan with PNOC–EDC and Kingston, Reynolds, Thom and Allardice (KRTA) as the implementors for the Philippines and New Zealand, respectively. The exploration program was then expanded for a large-scale power generation after the completion of the feasibility study for the development of the Tongonan Field. This led to the installation in July 1977 of the first commercial pilot plant in the country with 3 MWe power capacity. The objective of the accelerated development of the Tongonan Field was to meet the power requirement of the proposed Philippine Associated Smelting and Refining (PASAR) cooper smelter project in Leyte.

Local Geologic Setting

The Tongonan Geothermal Field including the adjacent prospect areas such as Biliran, Burauen and Anahawan, lie along the eastern tectonic block of the southern extension of the Philippine master fault. The Tongonan area has a typical fault valley bounded by NNE trending rolling upland and steep ridges following the trend of the fault scarp incision generated by the Philippine major shear zone.

Several thermal springs and fumaroles are widely distributed along the Bao River Valley at the intersections of the major faults and its subsidiary fractures curring through the andesite volcanic products and sedimentary complex rocks (Cardoso, 1973). The chemistry of the thermal springs in the Bao Valley has indicated that the temperature of the source ranges from 186°C to 219°C (Glover, 1974) based on Na–K–Ca geothermometer. The several test wells drilled in the area as well as those drilled in the productive zones at Mahiao-Sambaloran and Malitbog Fields located at the northeast highlands of the Bao Valley have measured temperatures of 170°C–325°C.

The producing zones of the two fields (Mahiao-Sambaloran and Malitbog)are generally confined at the contact periphery of the intruded andesite country rocks and diorite. The intrusion of the diorite which caused intense hydro-cracking effects on the intruded country rock could be related with the voluminous andesite volcanic upheaval in the area during the Pliocene-Quaternary period. The lenticular shape of the diorite as reflected by the well and gravity data apparently is parallel to the trend of the NNW regional structure.

Drilling Program

With the expected increase of energy demand in Leyte Island due to the PASAR copper smelter and the proposed inter-island power connection primarily with the Luzon power grid, a revised exploration/development plan has been instituted in the drilling program for Tongonan.

As of May 1982, the total number of wells drilled in the areas of Mahiao-Sambaloran, Malitbog and Mamban-Mahanagdong is 47 with a total power reserve of 327 MW, enough to supply the steam requirements of three 37.5 MWe generating units in Tongonan. About 45 additional wells are programmed to be drilled in the area to cope with the projected increase in power generation within the next five years.

All explortion/production wells including reinjection wells drilled to date are productive with rated power capacity of each well ranging from 3.5 MW to 18.3 MW. The average power capacity of the production wells is between 7.0 to 12.0 MW per well.

Power Potential Reserve

With the completion of several explortory and production wells in the three separte geothermal systems in the Tongonan area, the following are the proven, probable and possible power potential reserves based on the calculations made by joint studies of the PNOC–EDC and KRTA.

a. Proven reserves (from actual wellhead rating)

The total proven power reserves from the production, exploratory and relinjection wells drilled in the Mahiao-Sambaloran, Malitbog and Mamban-Mahanagdong geothermal systems is 326.9 MW. Of the 47 wells drilled in the three fields, 17 wells from the lower Mahiao-Sambaloran Field contributed 161.5 MW, of which the highest recorded well capacity of 18.3 MW comes from a single well in the area.

b. Probable and Possible Reserves (based on minimum and maximum exploitable volume of reservoir and initial mean rock temperature)

The total probable reserves (minimum) and possible reserves (maximum) of exploitable electrical energy estimated for Mahiao-Sambaloran and Malitbog geothermal systems are 18,000 MWe-years (probable) and 25,000 MWe-years (possible) (PNOC-EDC, KRTA, 1982). This exploitable electrical energy in the area of the reservoir has an assumed 25 years equipment life.

Power Generation

The nine power generating units to be installed in Tongonan by the NAPOCOR up to 1987 will have a total installed power capacity of 555.5 MWe. The electrical power output demand, however, is expected to increase to almost a thousand megawatts when the planned submarine power cable across the San Bernardino Strait is completed. This would connect the eastern Visayas to the Luzon power grid and/or to northern Mindanao. In this event, the other known potential geothermal resource areas in Leyte such as Biliran, Burauen and Anahawan would have to be developed to augment the electrical power generation of the Tongonan Field.

Environmental Impact Statement

Initial studies on the environmental protection measures were undertaken in 1977 by PNOC-EDC and KRTA. These works have been conducted first continuously in order to obtain sufficient information for considering of remedial measures to minimize whatever adverse effects the exploitation of the field might have on the environment.

In as much as Tongonan is a wet steam field which is expected to discharge 1,500 tons of waste water per hour (KRTA, PNOC-EDC, 1979) from the 28 wells, several reinjection wells are being drilled in the area for fluid disposal of the waste water. A plan for an alternative disposal system is being laid out by the environmental experts should the reinjection be not completely satisfactory in the long term.

The non-condenseable gases will be discharged to the atmosphere and the spent steam will be condensed, cooled and will be piped into the reinjection wells.

Fluids produced at wellheads during test or short-term emergency conditions are being discarded to rivers through local treatment ponds with facilities to remove some toxic elements such as arsenic.

Southern Negros Geothermal Field, Negros Island

The Southern Negros Geothermal Field (former name was Palimpinon-Dauin prospect area) is located at the southeastern tip of Negros Island in western Visayas. Similar to the Tongonan Field, the exploration activities at southern Negros is receiving technical assistance from the New Zealand Government with the PNOC-EDC as the Philippine implementor.

The geothermal concession area granted by the government to PNOC-EDC to explore and develop the field is about 133,000 hectares.

The preliminary assessment on the possible geothermal potential of the Negros Island started as early as 1973 by the NAPOCOR and PIV in conjunction with the electrification program of the Visayas region. The responsibility to develop the field was later transferred to PNOC-EDC in 1976 in order to keep up with the government's accelerated energy program. The first pilot plant consisting of two turbine units of 1.5 MWe capacity was commissioned in the later part of 1980 and followed of another two 1.5 MWe units in the later part of 1982, thus giving a total of six MW power generation.

Local Geologic Setting

There are two geothermal systems located by exploration drilling in the area. These are the Sogongon-Nasuji Field and Puhagan Field which are separted by the northwesterly trending Sogongon fault. Both fields are structurally controlled. The productive zones appear to be localized along the northeasterly trending fault structures, at the crushed outer boundary of diorite pluton and/or permeable andesitic lavas and its pyroclastic equivalent.

The thermal manifestations in the area are generally hotsprings, steaming vents, mudpools, warm grounds and pervasive rock alterations which are essentially controlled by faults and their subsidiary fractures (ALCARAZ, 1974). Majority of the surface thermal activity in the area is confined along the steep banks and fractured flow channels of the downstream sections of the Okoy river that discharges its water northeasterly. Its flow appears to be controlled by an east-northeast trending fault where it has been off-setted along several sections by three northwesterly trending faults; the Sogongon, Lagunao and Malaunay faults.

There are two prominent Plio-Pleistocene volcanic centers in the area (TOLENTINO, LOO, 1974) namely, Cuernos de Negros to the south and Balinsasayao to the north of Okoy Valley, which are both andesitic and appear to be the source of the widespread distribution of thick andesitic volcanic materials (lavas, lahar and breccias) over the area associated by late extrusion of dacite pyroclastics.

The chemisty of the thermal springs in the area suggested a source temperature of 173°C–279°C which lies whthin the range of the actual measured temperature of the wells drilled in the two fields undergoing development at southern Negros. The temperature measured in the seventeen geothermal wells ranges from 186°C to 320°C.

Drilling Program

A total number of 24 commercial wells have been drilled in Puhagan and Nasuji-Sogongon Fields yielding a total power rating of 91 MW as of May 1982 with an average capacity of 6.3 MW per well. These two fields are projected to supply the steam requirements of the proposed 222.5 MWe power plant for the Negros Island. With the four drilling rigs in operation, the drilling program in southern Negros Geothermal Field has been progressively advancing at a faster rate to cope with the scheduled bigger electrical power generation by the beginning of 1983. Southern extension of the field towards the Cuernos de Negros is being considered by PNOC–EDC for testing. Seventeen additional production wells will be drilled in the two fields by 1983, mostly directional wells with an averge length of 2,895 m per hole.

Potential Reserve

The 22 commercial wells drilled in Puhagan and Nasuji-Sogongon fields have proven power potential reserve of 90 MW, enough to supply the two 37.5 MWe generating units of NAPOCOR.

Reservoir assessment conducted in the two fields have indicated probable power potential of 600 MW.

Assuming that 50% of the field's reserve could be exploited, there would be enough steam to power the proposed installation of 222.5 MW geothermal power units intended to supply the bulk of electrical power requirements of Negros Island which is expected to increase within the next 5–10 years.

Power Generation

The planned electrical power genertion of NAPOCOR in southern Negros Geothermal Field involves the installation of three 37.5 MWe gnerating units at Puhagan Field which are scheduled to be on stream by the end of 1983, and additional two 55 MWe power plant as Nasuji-Sogongon field in 1985, giving a total installed capacity of 222.5 MW for Negros Islans.

With the present probable reserve of 600 MW in the two fields undergoing development, there would be some residual power potential the could be transmitted via submarine cables to the neighboring island provinces of Negros, like Panay and Cebu.

Environmental Impact Statement

The environmental protection measures for the southern Negros geothermal project is also being jointly undertaken by PNOC-EDC and KRTA from 1981. The objective of the initial study is to identify and evaluate the possible environmental effects of the development of the field and to recommend prevention, mitigating and/or monitoring measures for the various phases of the project activities in the area.

Following the results of the initial study, it was recommended that in order to minimize the adverse environmental effects of toxic gases, ions, salts and heat, geothermal waste water and vapor condensate be disposed of by reinjection into the reservoir (PNOC-EDC and KRTA, 1981).

As a contingency to the reinjection facilities, adobe-lined settling ponds will be constructed at strategic locations, particularly near the newly drilled wells, to collect waste water during the temporary discharge of the wells. The fluid will be treated for any toxic elements, such as arsenic, before it will be finally discharged into the rivers through adobe-lined channels.

Continuous monitoring activities, including microseismic survey, are being undertaken by joint participation of the Geothermal Division and Environmental Department of PNOC-EDC and KRTA to serve as an early warning for any impending environmental hazards that may arise in the near furure.

Other Geothermal Prospect Areas Undergoing Drilling and Geoscientific Explorations.

Aside from the four geothermal fields undergoing advanced development, ten potential areas are being explored by both private and government entities. Six of the ten prospect areas are located in Luzon Island, four in Visayan Islands and one in eastern Mindanao Island. Should some of these new potential areas show sufficient economic power potential, their immediate development would be carried out in order to maximize the power utilization of geothermal energy.

These ten other potential areas are currently being investigated and explored by two multinational companies such as the CALTEX Oil Company, TOTAL Exploration-Philippine Oil and Geothermal Energy Incorported (POGEI) and the state-owned PNOC-EDC. The BED likewise has also been assisting in the preliminary geoscientific surveys on new areas under the bilateral agreements with Japan and Italy.

The areas undergoing exploration are as follows:

1.	Batong-Buhay (Kalinga-Apayao)	— Northern Luzon
2.	Mainit-Sandanga (Mountain Province)	— 〃
3.	Daklan-Bokod (Benguet)	— 〃
4.	Acupan-Itogon (Benguet)	— 〃
5.	Labo (Camarines Norte)	— Southern Luzon
6.	Manito (Albay)	— 〃
7.	Biliran (Leyte)	— Eastern Visayas
8.	Burauen (Leyte)	— 〃
9.	Mandalagan (Negros)	— Western Visayas
10.	Masara-Amacan (North Davao)	— Eastern Mindanao

Of the six prospect areas located in Luzon Island, the Daklan and Manito geothermal areas have been undergoing advanced stage of exploration driling.

Five deep geothermal wells were already drilled in Daklan by PNOC–EDC under the technical coopertion program of BED and Italian Electroconsult (ELC). The wells encountered significantly high bottom temperatures ranging from 243°C to 286°C at an average depth of 2,700 meters. The high temperature measured in all of the wells confirmed the existence of an active heat source underlying the Daklan dacite domal complex. However, because of limited permeable zones intersected by the exploratory wells in the underlying thick volcano-sedimentary complex, exploration was not confined within the structural depression. It was further extended northeastward and will be continued to the south of the area where younger criss-crossing structural network have been recognized. These structures could be related to the younger extrusion of dacite lava domes and contain enough rock fracturings to produce better permeable horizons in the area of interest.

Of the five wells drilled in Daklan, only one, Daklan-1A was able to sustain a continuous discharge with an estimated power output varying from 0.6 MW to 2.0 MW while the rest of the wells were all unproductive. Apparently, DK–1A was obstructed by twisted 293 meter length of connected frill pipes (2–7/8″ OD) and bottom hole assembly (4–3/4″) in the last 284 meters of the hole where a series of total loss circulatin of drill mud occurred. The obstruction of the hole due to the stuck drill pipes affected the productive characteristics of the well. DK–1A has a projected temperature of more than 300°C at the bottom depth of 2,700 meters. This is based on the trend of static temperature (280°C) measured above the top of the stuck drill pipes at 2,400 meters. The geothermometer of the fluid samples from DK–1A also indicated a source temperature of more than 300°C which jibes with the projected bottom temperature of the hole.

The second potential area in Luzon which might be developed earlier than Daklan is the Manito geothermal area in Albay. PNOC–EDC spudded a total of eight exploratory wells and two turned out to be commercial wells. The estimated potential capacity of the two wells is 17.6 MW. One of these wells (CN–1) was drilled to a depth of 2,673 m and has a rated capacity of 12.5 MW. The other two wells are non-commercial ones with minimal wellhead ratings of 0.63–1.1 MW and the rest are unproductive.

A reservoir assessment study will be undertaken in the area with the addition of four delineation wells to be drilled within the low resistive anomalous zones.

The maximum temperature recorded in the wlls ranged from 208°C to 268°C, slightly lower than the bottom hole temperatures obtained for the Daklan wells.

The Mandalagan in Negros, Biliran in Leyte and Masara-Amacan in Davao are the areas ready for deep drilling exploration. Hopefully, the results of the surface exploration in the remaining five areas located in Luzon and in Leyte (Batong-Buhay, Mainit-Sandanga, Acupan-Itogon, Labo and Burauen) would warrant deep drilling exploration in order to verify the existence of a potential resource that could be immediately exploited for power generation. Should 50 percent of these ten additional areas become commercially exploitable, the target large-scale power generation of 1,554 MWe from geothermal energy in 1987 could easily be achieved or even exceed.

PROJECTIONS FOR THE FUTURE

Power Genertion Target

Geothermal energy is expected to play a major role in achieving the non-petroleum based electrical power supply of the Philippines. It has been envisioned that with the growing interest of private sectors (both foreign and local) to participate in the exploitaiton of the country's potential geothermal resources, ten more potential areas are expected to be ready for development by 1987 in addition to the currently developed four fields (Mak-Ban, Tiwi, Tongonan and Southern Negros).

Latest physical targets up to 1987 of geothermal energy contribution to the total power requirements of the country is about 19 percent coming from the installed 1,554 MW power generating plants at the end of five years. Assuming sustained discovery ratios in all the 14 fields to be explored/developed, the expected geothermal steam availability from the additional 265 wells to be drilled from 1982 to 1987 will roughly contribute 1,350 MW. This enough to supply geothermal steam for the projected increase of 998 MWe power plant capacities on top of the existing 556 MWe installed capacity of the geothermal plants in Tiwi, Mak-Ban, Tongonan and Southern Negros fields.

Industrial Non-Electrical Applications

It is the intent of the Philippines to fully utilize its geothermal energy resources both for electrical power generation and industrial non-electrical uses. With the consistent high level of encouragement that the private sectors involved with geothermal project have received from the government, it has been envisioned that lage scale non-electrical applications of geothermal energy would fully materialize in a few years time.

The pilot study initiated by the PIV in 1970 at Tiwi, Albay has successfully demonstrated that viability of utilizing geothermal heat to process industrial-grade salt.

The success of the salt making project in Tiwi has served as a catalyst for the government to focus on the research and development of the potential usages of geothermal steam and low enthalpy fluid for non-electrical applications on areas not suitable for power generation and even on areas undergoing power development.

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Geothermal Exploration in Japan

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ABSTACT

Japanese energy consumption has been constantly growing with the development of industry and the advance of living level of the people. Based on this energy situation, the Japanese Government started the program to accelerate the development of alternative energy about ten years ago. Geothermal energy is considered to be the most realistic alternative energy available with present technology and under current economic situation. According to the Japanese long term energy policy, it is expected that, in 1995, the total installed capacity of geothermal power plants will increase to 3,000 MW, although the present capacity is only 215 MW.

To attain this difficult target, the Japanese Government started various geothermal projects including exploration. The exploration can be classified into two major categories, that is, 1) assessment of the nation's geothermal resources and 2) development of deep (2500–3000 m) geothermal reservoirs.

This paper deals with the exploration activities by the Government, especially "Nation-Wide Survey for Geothermal Resources" and "Hohi Project", both of which are presently underway.

INTRODUCTION

According to the Japanese long-term energy policy, 3,000 MW of installed geothermal power capacity is expected in 1995, although the present capacity is 215 MW. The Japanese government started various geothermal exploration programs in 1980 to attain this target and to decrease dependency of foreign supplies of energy.

This paper reviews the governmental geothermal activities in progress.

GEOTHERMAL RESOURCES AND ITS UTILIZATION

Japan is located within the Circum Pacific Volcanic Belt and blessed with geothermal energy especially related to the Quaternary volcanic activity. The research works of the Nation's geothermal energy initiated in 1940's by the Geological Survey of Japan which revealed the existence of many promising geothermal fields and led to the construction of the first geother-

Table 1 Geothermal power plants in operation.

name of station	location	capacity (MW)	starting operation date
Matsukawa	Iwate	22.0	1966, Oct.
Otake	Oita	12.5	1967, Oct.
Onuma	Akita	10.0	1974, June
Onikobe	Miyagi	12.5	1975, Mar.
Hachobaru	Oita	55.0	1977, June
Kakkonda	Iwate	50.0	1978, May
Suginoi	Oita	3.0	1981, Aug.
Mori	Hokkaido	50.0	1982, Nov.
	Total	215.0	

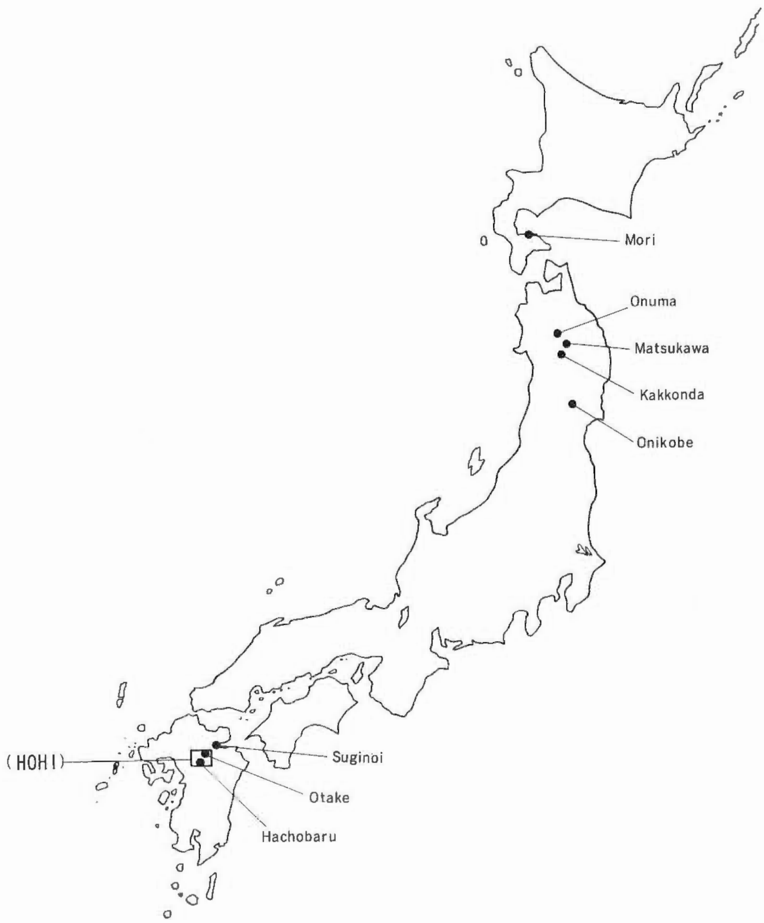

Fig. 1. Geothermal power plants in operation; location map.

mal power plant at Matsukawa in 1966. Table 1 and Figure 1 show the geothermal power plants in operation in 1982. It is commonly agreed that the capacity of geothermal electricity generation in the Japanese Islands is at least 10,000 MWe, although the science-based quantitative assessment has not been made.

GEOTHERMAL AREAS AND ASSESSMENT IN JAPAN

Japan has 170 Quaternary volcanoes. Sixty seven of them are still active. It has numerous hot springs and fumaroles mainly related to Quatermary volcanic activities. Based on the basic survey and research works on geothermal fields in the last couple of decades, the Geological survey of Japan published in 1977 maps showing 185 areas of high temperature water good for electricity generation including binary cycle and 26 areas of low to intermdiate temperature water suitable for non-electricity utilization (GSJ and NEDO, 1981). Along with maps, the preliminary resources assessment was made by using three different methods, that is, 1) area of hydrothermal alteration, 2) heat discharge, and 3) stored heat (Table 2). The methods employed for the 1977 assessment were not based on data sufficient for quantitative assessment. However, it is commonly agreed that capacity of geothrmal electricity generation in

Table 2 Assessment of high temperature resources for electricity generation in Japan.

Year	No. of Areas	Area km^2	Electricity MW_e	Method	Organization
1970a		A.J.	40,000	circulating water	JGEA
1970b		A.J.	20,000	residual magma chamber	JGEA
1977a	26	122	7,300	area of hydrothermal alteration	GSJ
1977b	30	(10,000)	26,580	heat discharge	GSJ
1977c	6	8,800	20,000	stored water	GSJ
1984		A.J.	??????	volumetric	GSJ

A.J.: All Japan (380,000 km^2)

the Japanese Islands is at least 10,000 Mwe.

GEOTHERMAL EXPLORATION ACTIVITIES BY THE GOVERNMENT

The government has made various efforts to accelerate the development of nation's geothermal resources in the last decade. The office of "The Sun-shine Project" was established in 1975 within the government (MITI) to promote alternative energy including geothermal energy. Later in 1980, New Energy Development Organization (NEDO) was founded under the governmental sponsorship to carry out large-scale surveys and research projects which may be classified into two major categories, that is, 1) assessment of nation's geothermal resources and 2) development of deep (2,500–3,000 m) geothermal resources (Fig. 2). To assess the nation's geothermal resources, three projects are now underway. Those are A) Nationwide Survey for Geothermal Resources, B) Survey for Promoting Geothermal Development, and C) Geothermal Information Data Base System. Hohi and Sengan-Kurikoma projects are also in progress to confirm and develop the deep geothermal resources, which is not yet utilized in Japan. Figure 3 shows the principal concept of the surveys to be conducted by the government and the developer. Nationwide and regional surveys are conducted by the government to assess and define high potential areas (like K.G.R.A. of USA). The private developers can begin local or detailed survey and develop the resources if possible in the areas thus defined by the government. At this stage the government may assist the developers by granting subsidies and low interest loans. Through these governmental geothermal exploration activities, very massive geothermal data are being accumulated. The geothermal data thus accumulated are processed, analized and published by using the Data Base System SIGMA (System for Interactive Geothermal Mapping and Assessment) of the Geological Survey of Japan (Fig. 4).

This paper will briefly describe the outline of a) Nationwide Survey for Geothermal Resources,

I. ASSESSMENT OF THE NATION'S GEOTHERMAL RESOURCES

A) NATION-WIDE SURVEY FOR GEOTHERMAL RESOURCES
B) SURVEY FOR PROMOTING GEOTHERMAL DEVELOPMENT
C) GEOTHERMAL INFORMATION DATA BASE SYSTEM

II. DEVELOPMENT OF DEEP (2,500-3,000M) GEOTHERMAL RESOURCES

A) HOHI PROJECT
B) SENGAN-KURIKOMA PROJECT

Fig. 2. Important problems of geothermal resources exploration and development for government.

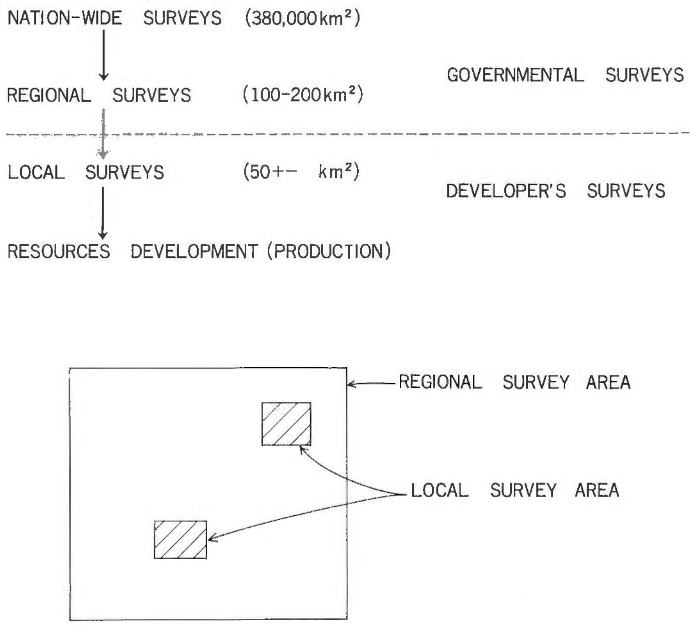

Fig. 3. Survey approach of geothermal resources.

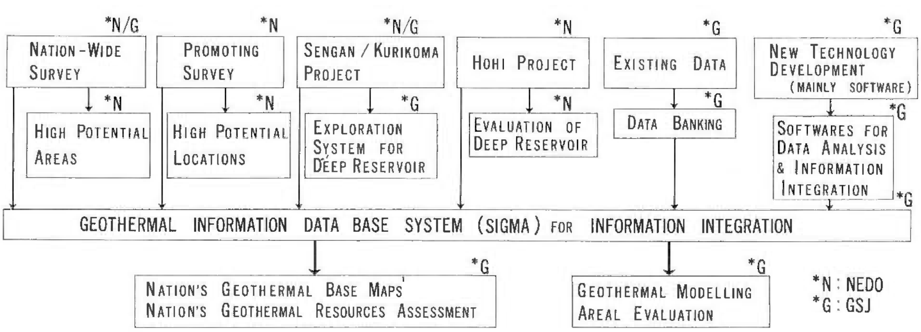

Fig. 4. Information flow chart of governmental exploration activities.

b) Hohi Project and c) Geothermal Data Base System in the following chapters.

Nationwide Survey for Geothermal Resources

This survey was commenced in 1980 by NEDO under close cooperation with the Geological Survey of Japan. The purpose of the survey is to gather fundamental data of the Japanese Islands for the preliminary assessment of geothermal resources. Remote sensing, gravity and Curie depth methods are included in the survey (Fig. 5).

Remote sensing data will provide information on subsurface fracture zones which may give channel way or reservoir space for geothermal fluids. Whole Japanese Islands were covered by microwave radar (SAR: Synthetic Aperture Radar). Based on SAR imagery as well as Landsat MSS imagery, several kinds of maps such as lineament map and SAR geologic map were prepared. Figure 6 is a north-look SAR imagery of middle Kyushu. Many geologic features such as linear, circular, and texture pattern can be seen on the imagery. Figure 7 is a lineament map derived from the imagery (Fig. 6) (SUYAMA *et al*, 1982). This lineament map was con-

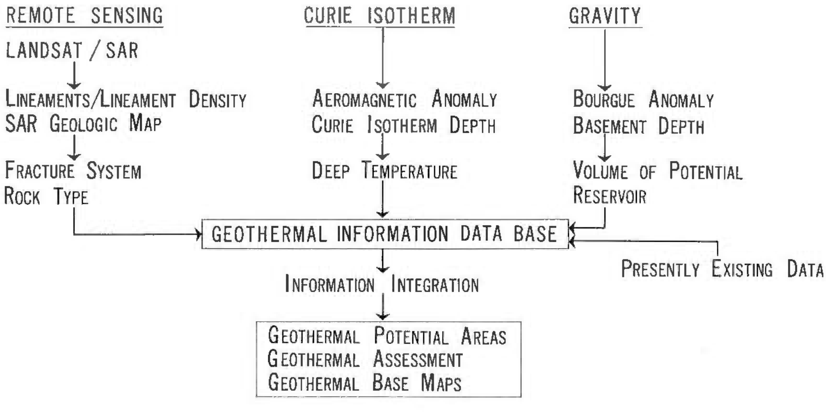

Fig. 5. Nationwide survey for geothermal resources.

verted to the lineament density map by using SIGMA which allows easy statistic processing necessary for resources assessment.

The rocks of the earth crust lose their magnetization at the depth of Curie temperature. This depth is called the Curie depth. The distribution of Curie depth may represent the temperature features of the deeper part of the earth crust, and hence, gives important geothermal information.

The information on Curie depth is considered to be included in the earth magnetic field observed on or above the earth surface. Aero-magnetic survey was conducted for the Japanese Islands with the line spacing of 3 km. The aeromagnetic data were processed and presented as aeromagnetic anomaly map and reduction-to-the-pole map. Some special analysis was made to present Curie depth map based on this reduction-to-the-pole map. Figure 8 shows Curie depth map of the Kyushu area (OKUBO et al, 1983). The regional features of the temperature distribution in deeper zones of Kyushu are well presented in this map. Shallow Curie depth is obtained at Hohi (B in fig. 8), Unzen (A) and Kirishima-Sakurajima (D). These are all located in geothermal fields. Curie depth of 7–8 km in these areas may correspond to 70–80 degrees centigrade/km of temperature gradient. Curie depth maps of all the Japanese Islands were made by this survey.

Gravity anomaly shows the framework of subsurface geologic structure especially depth to the top of basement rocks. In the case of impermeable basement rocks such as granite, it gives the maximum depth of possible reservoir area. Gravity data were acquired in the areas where Miocene to Quatermary volcanic rocks are distributed. Gravity basement depth maps were made based on Bouguer anomaly maps.

The trial of geothermal resources assessment was carried out by utilizing 1) lineament density map, 2) Curie depth map, 3) gravity basement depth map. The weighted-function method was used to rank geothermal potential of Kyushu. The areas above 55 marks (full marks is 100) are shown in Figure 9. Known geothermal fields such as Hohi, Unzen, Kirishima, Sakurajima are located inside the high marks areas and some unknown areas also have high marks.

After this computer-based assessment, a little more complicated manual-based assessment using other kinds of data (distribution of Quaternary volcanic rocks and surface manifestations) and employing the combination of weighted-function and pattern recognition methods were carried out. A more detailed classification map of geothermal potential of Kyushu was prepared. Figure 10 is an example of this map (southern Kyushu area). The area is divided into three major geothermal resource types, that is, 1) high temperature hydrothermal convection, 2) low temperature deep water in sedimentary basin, 3) undefined high temperature.

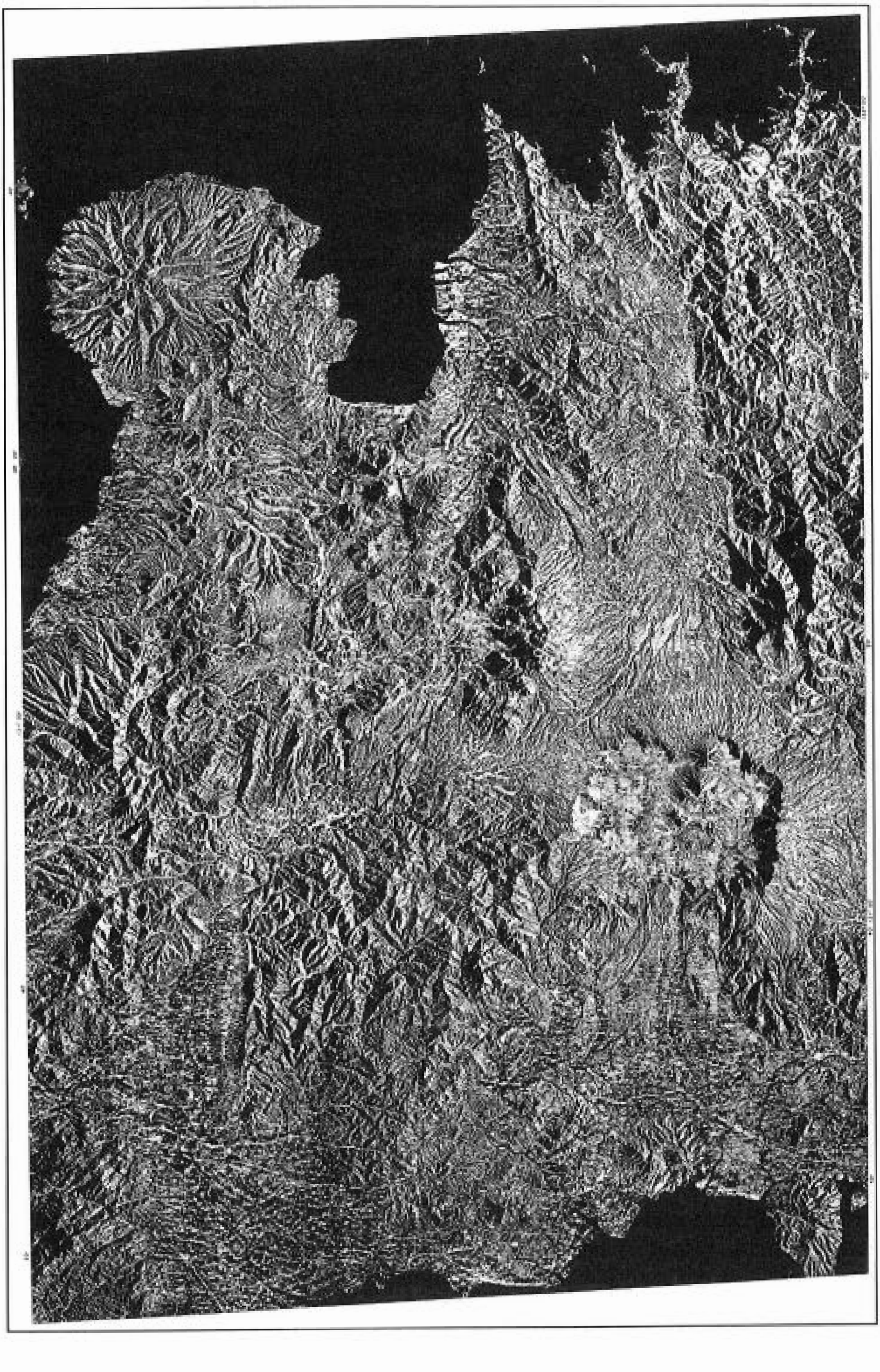

Fig. 6. An example of SAR imagery — central Kyushu area (north-look image data).

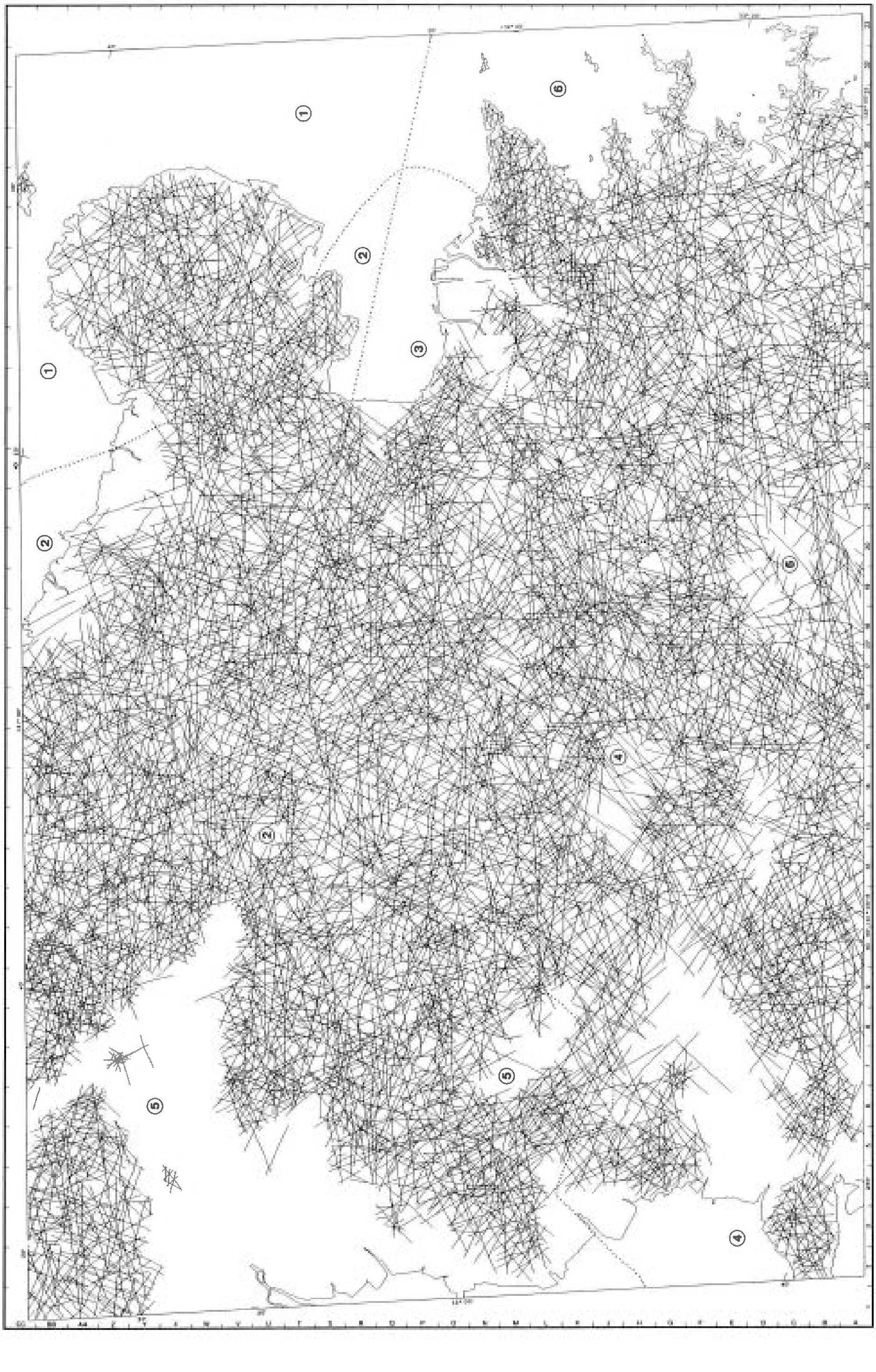

Fig. 7. An example of analysis of SAR data in the central Kyushu area (NEDO).

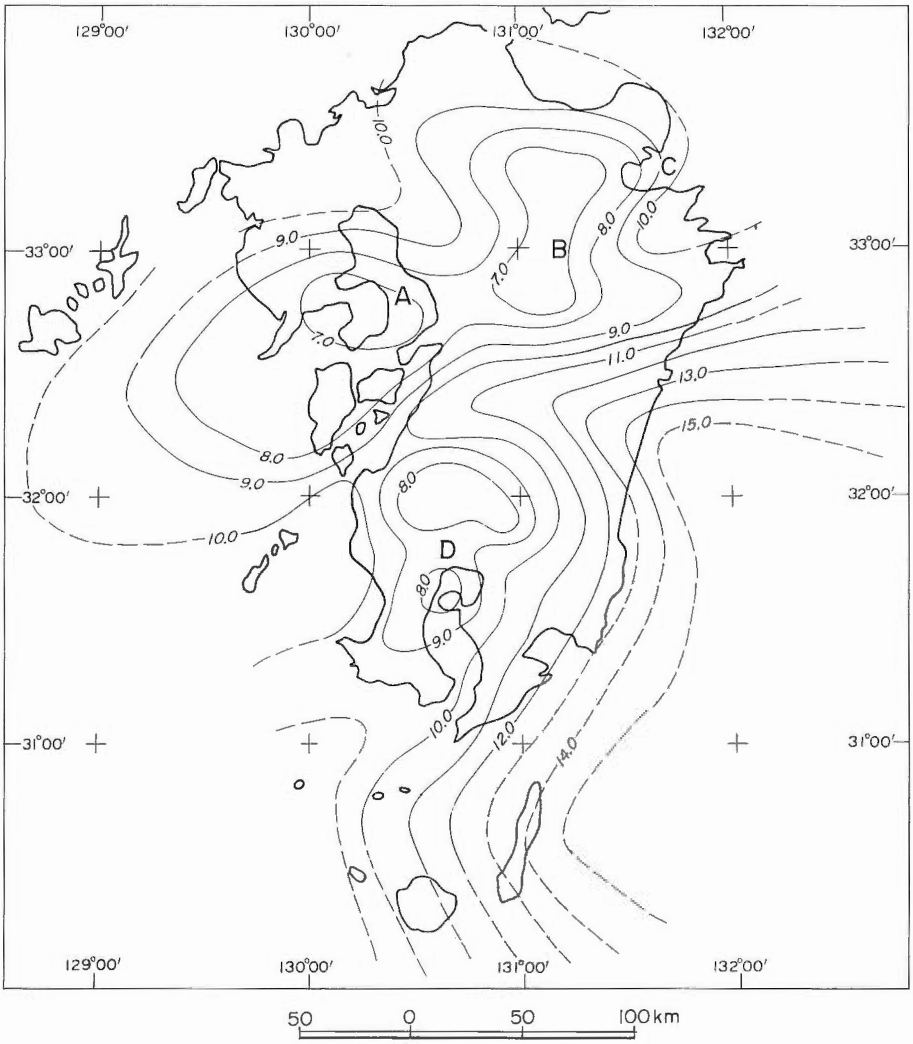

Fig. 8. Curie depth map of Kyushu.
Contours indicate Curie point depth below sea level in kilometers.

Hydrothermal covection type is classified into three sub-types, that is, 1-a) high lineament density along with high temperature hot springs, 1-b) high lineament density without high temperature hot springs and 1-c) low lineament density.

The quantitative assessment of geothermal potential of the Japanese Islands using a volumetric method will be carried out by the Geological Survey of Japan in the near future.

Hohi Project

This project was initiated in 1978 by the government (the Thermal Electric Power Division, MITI) to confirm the feasibility of the development of deep (2,500–3,000 m) geothermal resources. The Hohi geothermal area in central Kyushu was selected as an experimental site (Fig. 11). Two geothermal power stations, Hachobaru and Otake are located in the selected area. Exploration works were carried out based on the general exploration procedure shown in Figure 12. Various kinds of geological, geophysical and geochemical surveys including shallow

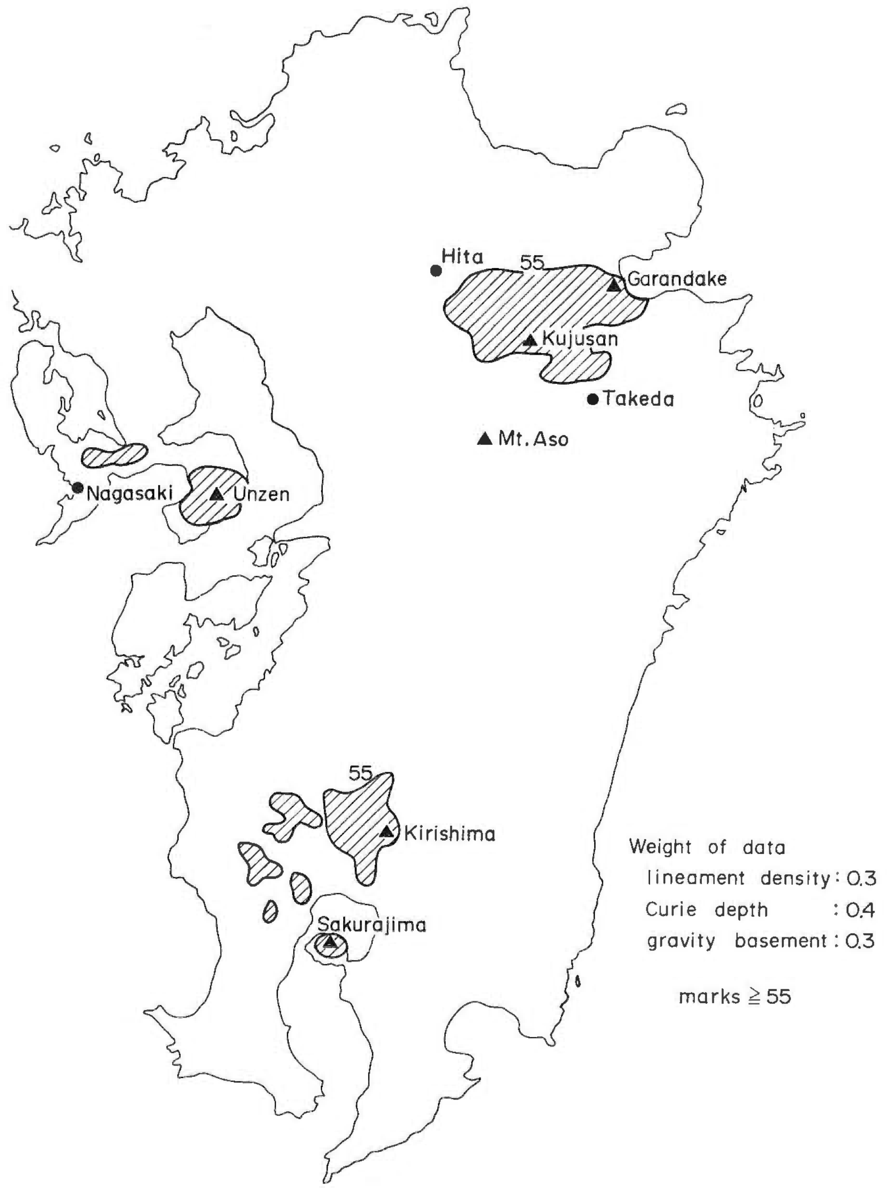

Fig. 9. An example of computer-based assessment using weighted-function method, Kyushu area.

heat holes were made in the first two years (see list in Fig. 11) and the target area for future drilling was selected. In the next two years, ten shallow (500 m) wells were drilled to confirm the results of surface surveys. After this, six intermediate (1,500 m) wells were drilled and the rough outline of the hydrothermal system down to 1,500 meters was estimated. In the following years three deep (2,200–2,600 m) wells were drilled. The first well hit two reservoirs at the depth of 2,000 m and 2,600 m, and produced 100 tons of hot water and 10 tons of steam. Both second and third wells reached the crystalline basement rocks of Mesozoic age. The permeability of the basement rocks seems to be very low judging from very little circulation loss and typical conductive type of heat transfer although temperature is very high. Considering the above results, the survey area was moved to the adjacent area of deeper

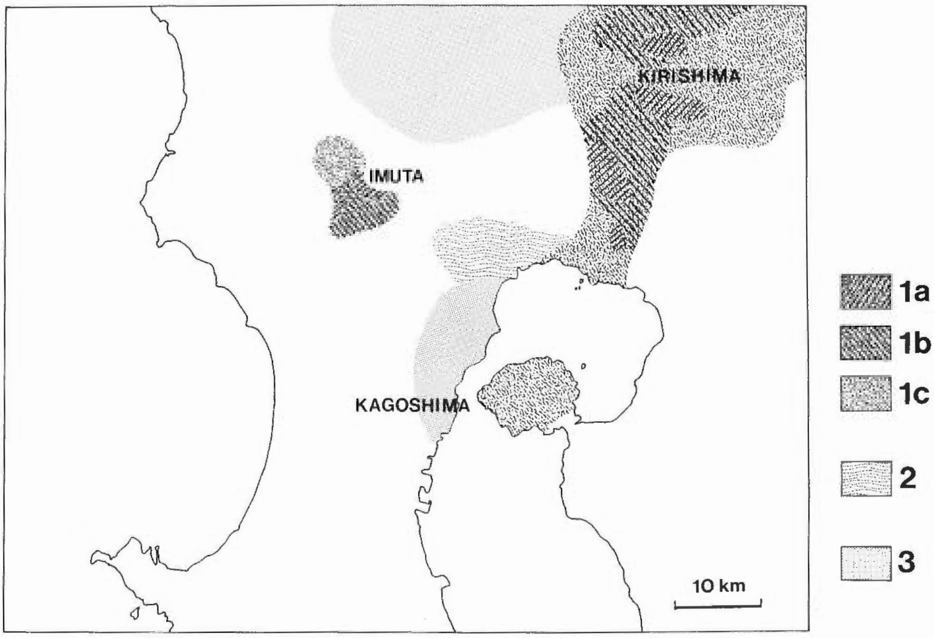

Fig. 10. An example of manual-based assessment using pattern recognition method, southern Kyushu area.

I. GEOPHYSICAL SURVEY
1. GRAVITY*
2. AEROMAGNETIC*
3. REMOTE SENSING (LANDSAT, SAR)*
4. ELECTRIC
5. AFMT MAPPING
6. MT SOUNDING
7. SP
8. SEISMIC REFLECTION
9. SEISMIC REFRACTION
10. MICRO SEISMIC
11. AIRBORNE THERMAL MAPPING

II. GEOLOGICAL SURVEY
1. GEOLOGICAL MAPPING*
2. PHOTO GEOLOGY*
3. ALTERATION SURVEY

III. GEOCHEMICAL SURVEY
1. SOIL HG MAPPING
2. CHEMICAL ANALYSIS OF HOT WATER

IV. WELL SURVEY
1. SHALLOW HEAT HOLE (80M)····80 HOLES
2. DEEP HEAT HOLE (500M) ······11 HOLES
3. SHALLOW WELL (1500M) 7 HOLES
4. DEEP WELL (2500–3000M) 3 HOLES + 3 HOLES

WITH LOGGINGS

* REGIONAL SURVEY (70×70 KM^2)
NO-MARK DETAIL SURVEY (15×12 KM^2)

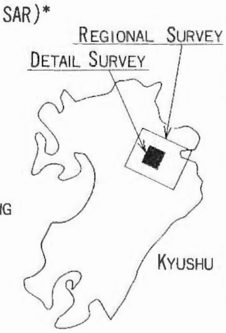

Fig. 11. Hohi project survey items.

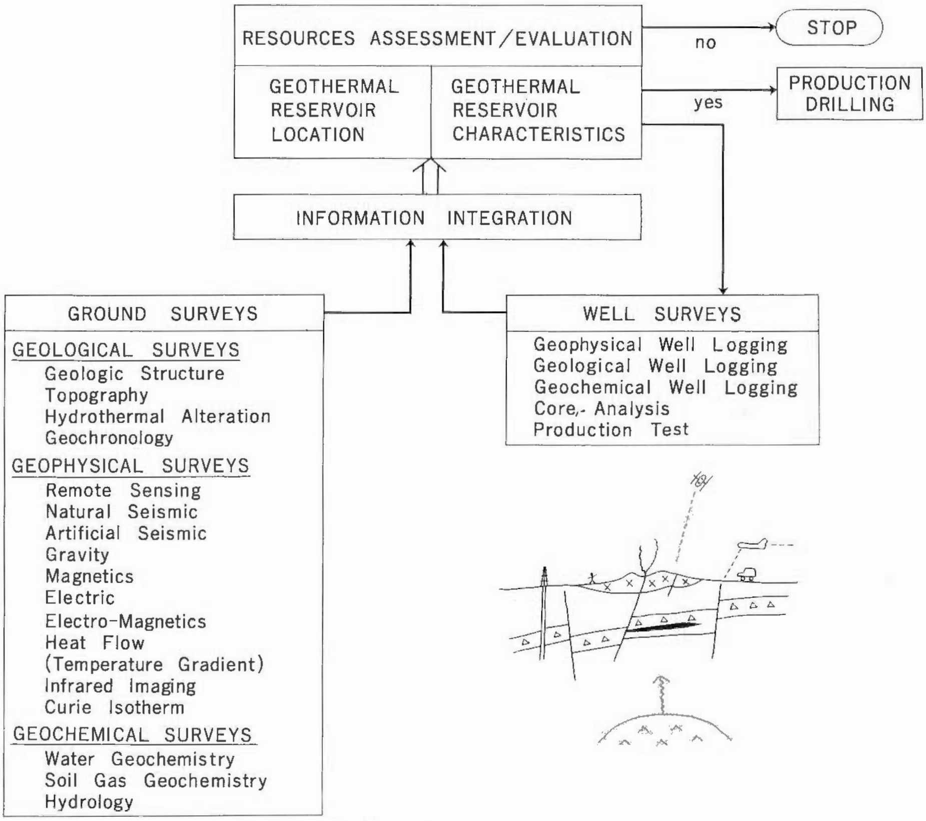

Fig. 12. Geothermal resources exploration system.

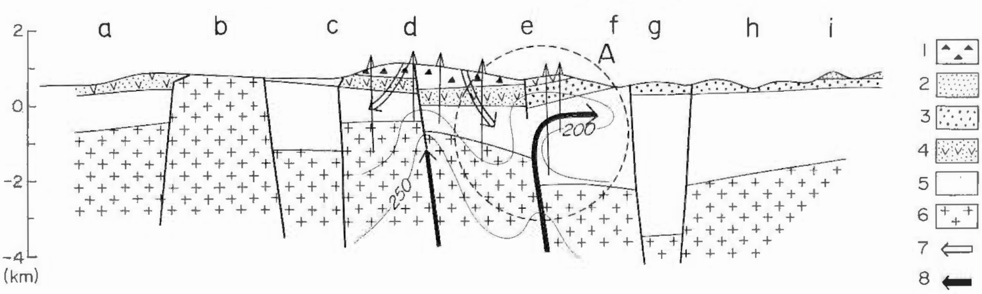

Fig. 13. Conceptual model of hydrothermal circulation of the Hohi geothermal field. 1: Kuju volcanic rocks 2: Haneyama volcanic rocks 3: Hohi volcanic rocks 4: Kusu Formation 5: Pre-Kusu altered volcanic rocks 6: basement rocks 7: down flow 8: up flow a: Aso volcano b: Kashinomure c: east of Kurokawa d: west of Hachobaru e: Takenoyu f: Kawazoko g: Hosenji h: Kusu river i: Hozan

basement rocks and several additional surface surveys including magneto-telluric survey were carried out in 1982 and 1983. Several deep (3,000 m) wells will be drilled in 1984 to confirm the higher temperature part of the reservoir whose existence has been confirmed by previously drilled well.

Figure 13 shows a conceptual model made based on various kinds of data including well temperature deta (OGAWA and KIMBARA, 1984). Geothermal reservoirs exist in permeable volcanic rocks but not in impermeable basement rocks. Magma chambers may supply heat to the reservoirs in two different ways, that is, 1) regional conductive heat transfer through impermeable basement and 2) local convective heat transfer by high temperature up-flow through faults cutting the basement rocks. This conceptual model shows that 1) conductive heat supply is not enough to heat up fluid in the volcanic rocks, 2) recharging meteoric water penetrates into considerably deeper part of the volcanic rocks because of their high net permeability, 3) recharge of meteoric water is greatly controlled by the topographic features. This may lead to the conclusion that the area of local convective heat supply through the fault system in the basement is the target of high temperarure reservoirs, and hence, determination of the location of these faults system is very important role of exploration.

It was clarified through this survey that relatively shallow (less than 1,500 m) geothermal fluids which are utilized for electricity generation at Hachobaru and Otake power plants is a part of the larger scale hydrothermal circulation system in this area. We believe that understanding the nature of the hydrothermal convection system is of utmost importance for further development of geothermal resources in Japan.

Geothermal Information Data Base System

As a result of active exploration works by the government during the last decade, massive geothermal data have been accumulated. This trend will continue for another decade. Considering this situation, the Geological Survey of Japan initiated the construction of a computer-based data base system which is now called 'SIGMA'. The purpose of data base system is 1) efficient use of data, 2) extraction of relevant information from data, and 3) rapid publication of data. The principlal functions of SIGMA are

A) mapping (Atlas data base)
B) image processing (Image data base)
C) information integration (Project data base)
D) resources assessment (Assessment data base)
E) application (Application program package).

Data types stored in SIGMA up to 1983 are as follows:

1) well: wireline logging, geologic formation, core test, casing, circulation loss, mud, etc.
2) gravity: original data, processed data
3) aeromagnetics: processed data (grid data)
4) geology: geologic map of the Japanese Islands (1:1,000,000)
5) hydrothermal alteration: location of altered minerals
6) cartography: topography, coast lines, rail ways, roads, lakes, rivers, mountains, etc.
7) water geochemistry: chemical analysis of hot spring waters
8) electric sounding: Schlumberger electric surveys
9) magneto-telluric: resistivity-frequency curves, etc
10) seismic: refraction seismic travel time curves
11) active faults: active faults published by the University of Tokyo
12) lineament: SAR lineaments
13) location of hot springs
14) geothermal survey index: type and area of geothermal surveys by the government

These data can be presented as color contour maps, color perspective maps of three dimensions and four dimensions (space plus one dimension such as three dimensional geologic map), numerical tables and many other ways. Overlays of several different types of data are also available. A good example is subsurface resistivity contour overlaid on color contour of gravity anomalies.

CONCLUSION

It is generally agreed that the geothermal resources in Japan is huge. The full development of these resources will require tremendous efforts including improvement of exploration and assessment technology; understanding the nature of the hydrothermal systems; application of the above techonology and the understanding for accelerating the identification of geothemal resources, particularly the deep-seated large resources; development of techonology for more effective, economical, and environmentally safe utilization of resources; and alleviation of many institutional constraints.

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III. Energy Resources—Fossil Fuels

Chairman K. FUJII

1. Non-Marine Petroleum Geology in China.
2. Petroleum Geological Features and Technical Problems related to Hydrocarbon Exploration in Japan ——Geological Problems in Island Arc Systems——
3. Deep-Sea Basins in Indonesia.
4. Preliminary Report on Characteristics of Coal in Some Continental and Island Arc Region.

Geological Survey of Japan Report, No. 263, 1984, p. 123–126.

Non-Marine Petroleum geology in China

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EXTENDED ABSTRACT

From an overall view of the geological history of China, it seems that the formation of the petroliferous basins can be divided into two stages, namely, the stage of the development of the marine basins with platforms as their main bodies from the end of early Proterozoic to late Paleozoic, and that of the development of the non-marine petroliferous basins during the Meso-Cenozoic. Over the past thirty years, the Chinese geologists have taken the non-marine basins of Meso-Cenozoic as the focal point of their work. Non-marine Meso-Cenozoic strata are widely distributed in China, spreading not only on land, but also on the offshore shelf. Hundreds of oil and gas fields including some large oil fields have been found in the non-marine strata, the Daqing Oil Field being one of them.

At the early stage of exploration for oil in the non-marine strata, there once prevailed the view that there was no oil or only a little oil in the continental facies. There is a well-known saying in China that goes: "Genuine knowledge comes from practice". Great amount of investigations and scientific researches by the Chinese petroleum geologists since 1949 have shown that the previous viewpoint is untrue. Ever since 1959, a number of large oil fields have been found successively in the non-marine basins, and a large amount of geological data acquired, which enables us to put forward the new theory that tremendous amount of hydrocarbon can be generated and accumulated to form giant oil and gas fields in the non-marine basins. It is such new theory that has been an effective guide to the geological survey of petroleum in China.

The Problem of Oil Generation

The study on oil generation of non-marine facies has revealed the fact that there is no fundamental difference between the non-marine strata and the marine strata in the mechanism of oil generation, such as the abundance of organic matter and the various factors impelling the reformation and conversion of organic matter into hydrocarbon. Hence conditions do exist for the generation of oil and gas in the non-marine strata. Of course, when comparing the non-marine strata with that of marine facies, it is seen that there are some differences between the two in the sedimentary environment, the nature of the organic matter and the specific features of the oil generated, for example the crude oil generated in the non-marine strata usually has a higher content of wax and a lower content of sulfur.

The relationship between the sedimentary environment and the nature of organic matter can be exemplified by the study of inland lacustrine facies. The inland lacustrine basins can be divided into the marsh-beach zone, the shallow water zone, the moderately deep water zone and the deep water zone, ranging from their margin to the center. Organisms in the marsh-beach zone are mainly of higher plant, the kerogen formed by them is of the humic type, poor in oil potential. Consequently, this is basically a zone of coal and gas deposits. The moderately deep and the deep water zones are suitable places for planktons to thrive. A large amount of clay from terrigenous zones deposited to the bottom of the lakes associated with the dead organisms, resulting in dark argillaceous sediments of sapropelic kerogen, which have the greatest oil potential. The shallow water zone lies between the two as a transitional zone, in which the organic matter is also of the transitional type. It is thus clear that various types of organic matter are controlled by different paleogeographic settings, thus yielding different products in the evolution. It is quite true in China that areas of best oil prospects in the non-marine basins are mostly distributed in the zones of moderately deep and deep lakes.

The sedimentation rate and the geothermal gradient in the lacustrine basins are most favourable for the generation of oil and gas. The lower Tertiary strata of large sedimentary basins in China may reach the thickness of 5,000 m and the sedimentation rate up to 0.1–0.4 mm/year. The geothermal gradient is generally over 3°C/100 m.

The Characteristics of the Reservoir Rocks

As for the reservoir rocks, the clastic rocks are the overwhelming and most widespread ones in the petroliferous basins of non-marine facies. Among them the medium- and fine-grained sandstones have the best physical properties. The sandstone reservoir beds of continental facies are characterized by their diversity in form, which is rarely seen in a homogenous bedded distribution, but rather take the shape of the tongue, the strip or other irregular forms with great lateral variations in thickness, lithology and physical properties. Regarding the genetic types, up-to-date results have been achieved one after another in the study of beach-deltaic sediments which are closely related with the formation of large oil and gas fields, and turbidites have also been found. It is expected that there will be bright prospects for the discovery of various kinds of oil and gas-bearing sandstone bodies. All this has opened up a new domain for the study of non-anticlinal traps.

Types of the Petroliferous Basins

The Meso-Cenozoic petroliferous basins in China vary greatly in size. The largest basin can be up to 400,000 square kilometers while the smallest is only some tens of square kilometers. These basins can be divided into two major categories according to their texture. One is called the accumulated basin, which has a definite boundary and the deposits in it get thicker with finer grains regularly from the margin to the center. Many of the non-marine basins are of this type. The other is called the structural basin, which is a regional synclinal structure resulting from tectonic movements. According to the principle that the tectonic setting is the essential factor controlling the formation and development of the basins, the basins in China can be grouped into the three major categories as follows:

1 Those related to the folded zones and controlled by orogeny in the formation and the development. This type of basins are largely distributed in western China, which include: depressions formed during the development of various geosynclines since the Caledonian movement, namely the foredeep basins, such as Jiuquan basin in Gansu Province; the intermontane basins formed after the fully uplifting and faulting of geosynclines, such as Turpan basin in Xinjiang Province; and the intramassif basins cutting apart the geosynclinal systems, such as the Tarim basin in Xinjiang. The petroliferous basins in the western part of China have the following characteristics:

a Great thickness of the non-marine Meso-Cenozoic strata;

b The basins are composed of stable blocks and unstable foredeeps with different structural features;

c Oil is generated in a number of geological periods. Oil-bearing beds are found in Permian, Triassic, Jurassic and Tertiary.

2 Those related with platforms and controlled by epeirogeny in the formation and the development. One type of these basins are those developed on the background of the platform syneclises, such as the Ordos basin. Another type is those developed on the background of the platform anteclise or shields. Basins of great oil-bearing prospects fall in the former category, which is characteristic of a unified Precambrian crystalline besement with an extensive and stable distributin of covering stratum. There are not only Meso-Cenozoic sediments of continental facies, but also a complete sequence of marine sediments of Paleozoic and lower

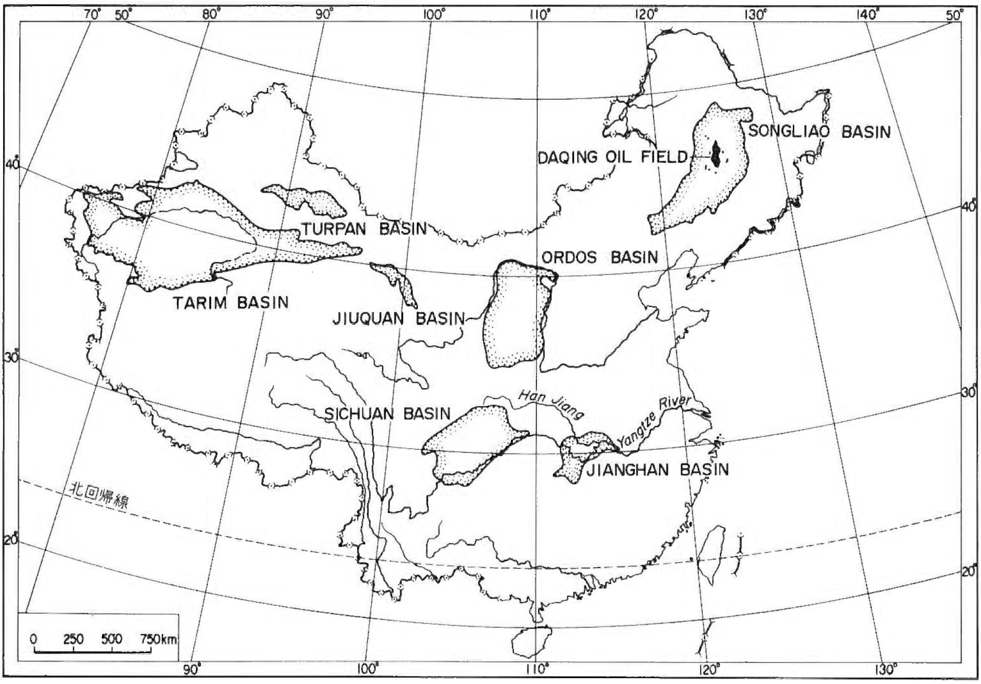

Fig. 1. Location of some petroliferous basins of China.

Mesozoic developed in the basins. Therefore, they have a wide span of geological age for the oil-bearing strata. Commercial oil and gas flows have been struck in the strata of Precombrian, Ordovician, Permian, Triassic, Jurassic, Cretaceous and Tertiary. The Ordos basin which is under joint investigation by China and Japan is one of the basins of this type.

3 The third type of basins are those sedimentary depressions which have developed on the complicated basement of various ages and different structures under the effect of the Alpine movement, for example the Songliao basin. In the Songliao basin, the besement of the central and southern parts is of pre-Sinian, while that of the eastern and western parts is of Hercynian. The Meso-Cenozoic deposits overlie the basement of different geological ages. The development of such basins is not controlled by the tectonic element of earlier periods, that is that part of basement formed by the folded zones is not characteristic of a foredeep basin or an intermontane basin. The other part of basement formed by platforms is also different from the depressions within a platform in essence, it is evoluted under an entirely new tectonic regime.

Most of the basins of the latter two categories are distributed in the eastern part of China, which have the following features:

a Most of them are superimposed basins, the lower part being the Paleozoic structural basins and the upper part the Meso-Cenozoic accumulated basins.

b Their regional center of deposition has been shifted eastwards with a regular pattern since Mesozoic. There are very thick layers of Triassic and Jurassic but very thin layers of Tertiary (only some tens of meters thick) developed in Sichuan and Ordos in the western part of eastern China. In north China and Jianghan (the Yangtze and Hanjiang Rivers) districts, layers of Triassic are absent, and Jurassic-Cretaceous strata are not very thick, but sediments of great thickness are developed in Tertiary. However, in the seaward areas Tertiary, especially the upper Tertiary, is well developed. Such a regularity of deposition might be the result of undulation and oscillation of the earth crust. It is because of this regularity that oil and gas is produced from Mesozoic in the west side of eastern China, while in the east side, it is produced from Tertiary.

c The undulation and oscillation of the earth crust is shown mainly in the elevation and subsidence of block faulting, resulting in upheavals and depressions of various sizes, which plays an important role in controlling the formation and distribution of oil and gas accumulation.

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Petroleum Geological Features and Technical Problems related to Hydrocarbon Exploration in Japan ——Geological Problems in Island Arc Systems——

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ABSTRACT

The geology of the Japanese Islands is complicated because several island arcs meet there. The geological features of those island arcs essentially resemble each other, but in detail, they show various differences. Indeed, economic oil and/or gas production has been done only from the inner arc of the Northeast Japan Arc, except for a very small production from the central zone of Hokkaido and the outer arc of the Southwest Japan Arc. Recently, a gas field was discovered at the outer arc of the Northeast Japan Arc, which will be developed soon.

The basins of the inner arc of the Northeast Japan Arc, which are the most productive, began to develop at the Oligocene time and has grown where the Asian continent fractured along its margin by the tensional stress resulting from the subduction of the Pacific plate. The basin is characterized by strong volcanism and differential movement of the small blocks within the basin. From the view point of petroleum geology, these characters cause the following features: 1. distinct horizontal changes in thickness and lithology of the sediments, 2. discontinuity of the reservoirs, 3. development of volcanic or tuffaceous sand reservoirs, 4. complicated and steep traps, 5. abundance of highly pressured and caving formations, 6. relatively high geothermal gradient, and so on. These features bring about various technical problems in hydrocarbon exploration.

INTRODUCTION

The Japanese Islands are well known as a good example of typical island arc together with Indonesia. The islands have been studied in detail geologically since the middle of the 19th century and now the distribution of rocks and geologic formation is practically all clarified.

Table 1. Numbers of exploratory wells and explored fields and cumulative production in the areas of the Japanese island arc.

AREA			No. OF EXPLORATORY WELLS						No. OF FIELD		CUMUL. PRODUCTION	
			~1000m	1000~2000m	2000~3000m	3000~4000m	4000m~	BASAL or BASE	OIL	GAS	OIL (x 10³ KL)	GAS (x 10⁶ M)
KURIL ARC		BACK A.	3	2	1	0	0	2	0	0	—	—
		FORE A.	4	1	1	0	0	4	0	0	—	—
CENTRAL HOKKAIDO			131	49	13	18	14	12	8	1	396	396
NE JAPAN ARC		BACK A.	769	780	292	164	26	271	50	22	31194	31180
		FORE A.	0	0	4	11	1	13	0	1	—	—
SW JAPAN ARC		BACK A.	0	0	2	5	1	? 2	0	0	—	—
		FORE A.	32	4	0	0	1	? 1	1	0	5	—
RYUKYU ARC		BACK A.	0	0	1	0	0	1	0	0	—	—
		FORE A.	0	0	0	2	0	? 0	0	0	—	—
EAST CHINA SEA			0	0	4	3	4	? 4	0	0	—	—
ONSHORE	AKITA PREFEC.	5700km²	343	263	66	10	0	50	22	0	12073	1730
	YAMAGATA PREF.	1200km²	58	98	19	7	0	58	7	0	883	181
	NIIGATA PREF.	8100km²	328	387	166	132	21	147	20	0	17652	27307

A number of ambiguities remain, however, regarding the mutual relationship and the genetic environment of some of these units and also regarding the history and the mechanism of the structural development of the islands. These problems are presently subjects of lively discussions. This situation is partly caused by the fact that the Japanese Islands do not form a single arc as in the case of the Sunda Arc, but are positioned where several arcs meet and thus is structually very complex. Each arc exerts influence on the others and the interaction results in a complicated geological arrangement. The meridional zone running through Sakhalin to central Hokkaido cuts into the island arc system as a structural unit and amplifies the complexity, although it is not classified as an arc.

It is true that there are no remarkable oil and gas production in the island arc system, except for the Sunda Arc, especially in its western part, which forms the most productive province in southeastern Asia, and large even by world standard. However, I do not interpret this as due to insufficient exploration efforts in areas other than the western Sunda Arc. The Japan Sea side of northern Honshu (mainland of Japan) is indeed one of the most explored provinces in the world (Table 1)

The fact that some island arc areas produce large amount of hydrocarbons while others do not, possibly indicates that there are different types of geologic setting within the island arc system or that the generation and accumulation of hydrocarbon are essentially controlled by local geologic factors rather than by large crustal divisions such as an island arc, a stable continent or a collision zone.

Nevertheless, it is also without doubt that the stratigraphy, geologic structure and history of the areas of the island arc system show a common feature between each other. Thus, in considering the geologic history of a certain island arc area and for the exploration of natural resources there, the knowledge and the experience in other island arcs are much more important than those obtained in stable continents.

Although Japan is a very small country regarding hydrocabon production as is well known, it is one of the most highly explored areas belonging to the island arc system. Therefore, I consider the knowledge and experience obtained in Japan can contribute to the hydrocarbon exploration in the Asian region where island arc systems are widely distributed in a complex manner. In the light of the recent development of geological sciences, I believe that it is worthwhile to review the petroleum geological features in Japan from the standpoint of an island arc system with some comments on technical problems in hydrocabon exploration.

DISTRIBUTION OF ISLAND ARCS IN JAPAN

The distribution of island arcs around Japan is shown in Figure 1. They are the Kuril, Northeast Japan, Southwest Japan, Ryukyu and Izu-Bonin Arcs.

The Kuril Arc extends from Kamchatka with a subduction zone at the Kuril Trench and a volcanic front along the Kuril Islands which are arranged in echelon. The island arc encloses the Kuril Basin under which an oceanic crust exists. The Cretaceous to Quaternary sediments overlie granitic and metamorphic rocks of the late Paleozoic to Mesozoic age. The Oligocene to Miocene volcanoclastic rocks, which are called Green Tuff in Japan, predominate. The slope down to the Kuril Basin is steep and the shelf is extremely narrow. In the Kuril Basin, sediments of 5 to 5.5 km in thickness and of probably younger than the upper Cretaceous rest on the oceanic crust without severe deformation. Many geologists claim that the Kuril Arc extends to western Hokkaido crossing the Hidaka Range, but I think that the arc terminates at the eastern flank of the range.

Along the Northeast Japan Arc, the subduction zone is located at the Japan Trench and the volcanic front runs along the backbone of northern Honshu. Thick sediments younger than Jurassic exist below the wide shelf between the trench and the island. A basin with thick sediments ranging from Tertiary to Quaternary lies between the island and the Japan

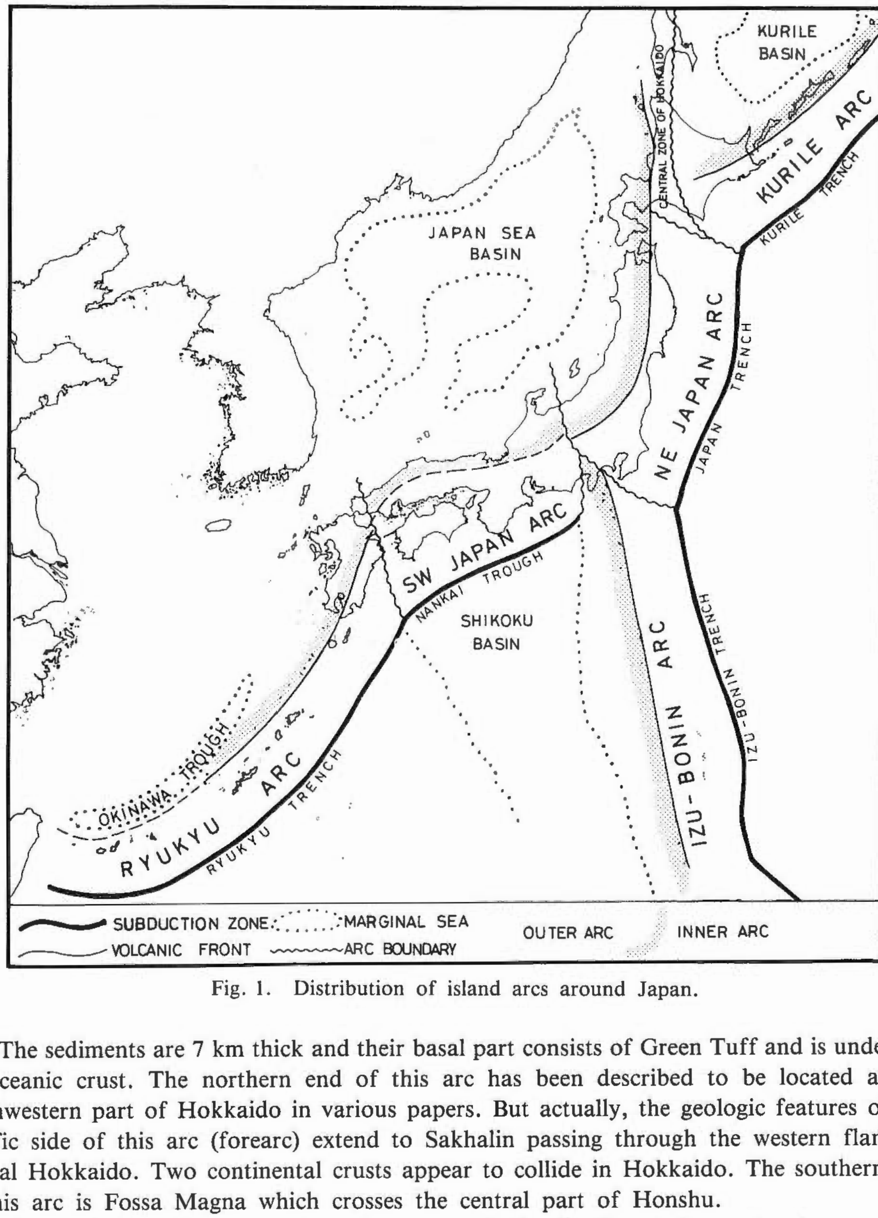

Fig. 1. Distribution of island arcs around Japan.

Sea. The sediments are 7 km thick and their basal part consists of Green Tuff and is underlain by oceanic crust. The northern end of this arc has been described to be located at the southwestern part of Hokkaido in various papers. But actually, the geologic features of the Pacific side of this arc (forearc) extend to Sakhalin passing through the western flank of central Hokkaido. Two continental crusts appear to collide in Hokkaido. The southern end of this arc is Fossa Magna which crosses the central part of Honshu.

As far as the Pre-Tertiary geology is concerned, the Southwest Japan Arc is essentially continuous with the Northeast Japan Arc, although a distinct flexure is recognized at the point of the two regions. However, the two regions clearly make up separate island arcs. Compared with the other island arcs, the Southwest Japan Arc is very inactive seismically and volcanically. It has a shallow trough for a subduction zone. A thick sedimentary basin is developed below the wide shelf spread out under the Japan Sea side. The basin is filled with Tertiary to Quaternary clastics with a maximum thickness of 7 km. The basal part of the pediments is Green Tuff.

The Ryukyu Arc has typical island arc features with a subduction zone along the Ryukyu Trench and with the East China Sea as the marginal sea. The East China Sea is enclosed inside double arcs, namely the outer non-volcanic Okinawa and the inner volcanic Tokara

Arcs. The Okinawa Trough with 2000 m water depth, which lies between the Tokara Islands and the continental shelf of the East China Sea, is generally considered as a marginal sea presently spreading. Sediments younger than the middle Miocene has accumulated in this trough. The connection with the Southeast Japan Arc may be located in the vicinity of the Bungo Strait.

The Izu-Bonin Arc extends meridionally as if it stabs Honshu, and consists of a subduction zone along the Mariana Trench and double arcs, namely the non-volcanic outer and the volcanic inner arcs. The Shikoku Basin which consists of oceanic crust occupies the back arc side. Though the continental crust thickens around the archipelago, sedimentary rocks occupy only a small part of the crust. Green Tuff, which was formed by volcanism during Miocene, is distributed at the Izu Peninsula, the northern end of this arc.

In addition, the Kyushu-Palau Arc, which is said to be the remnant of an old island arc, is present. Detailed explanation about this arc is omitted here.

The central zone of Hokkaido runs meridionally near the area where the Kuril and the Northeast Japan Arcs collide, and its geological features continue onto Sakhalin. The central zone does not belong to the category of the island arc. At least until the Cretaceous, this zone faced the open sea occupying the same position as the Pacific side of Northeast Japan. It became a narrow embayment at the Paleogene time due to the approach of the Okhotsk paleoland. Still later, this area was lifted up due to compression from the Kuril Arc around middle Miocene and created the mountain range.

DISTRIBUTION OF OIL AND GAS FIELDS

Geographical Distribution

Almost all of the oil and gas fields are concentrated in the back arc of the Northeast Japan Arc. The next productive province is the western part of the central zone of Hokkaido. This zone, however, can hardly be considered from the view point of an island arc system as mentioned above. Tracing this zone southward, it continues to the forearc of the Northeast Japan Arc, where the Joban-Oki Gas Field was discovered and will be developed soon. Besides this field, only the tiny Sagara Field (cumulative production is 4600 kl) at the outer zone of the Southwest Japan Arc is established in the forearc regions around Japan. Even oil seapage is scarcely known in those regions. The Sagara Field could be considered as the back arc of the Izu-Bonin Arc.

In the forearc of the Kuril Arc, only small oil seapages have been known in the Pliocene and very little gas was tested in the upper part of Miocene. Although gas fields are present in Chiba, Miyazaki and Okinawa prefectures on the forearc, the gas is immature methane dissolved in brine.

Oil seapages have been reported from the back arc of the Kuril Arc, but no oil and gas field has been discovered, partly because of insufficient exploration.

Though eight exploratory wells have been drilled in the back arc of the Southwest Japan Arc whose geological features resemble those of the back arc of the Northeast Japan Arc, only weak gas shows have been detected so far.

Oil and gas flows and shows were reported from some wells drilled off northwestern Kyushu, but economic production has not been realized yet. It may be preferable to treat this region as an intracratonic basin rather than as the back arc of the Ryukyu Arc.

Stratigraphic Distribution

Oil is mainly produced from the upper Miocene and the lower Pliocene both in northern Honshu and Hokkaido. Small production from younger horizons is considered to be from secondary accumulation. In Hokkaido, waxy oil flowed on a test in a Paleogene interval. Oil of the Sagara Field is from the upper Miocene, and that from a well drilled off Kyushu was recovered from the middle Miocene.

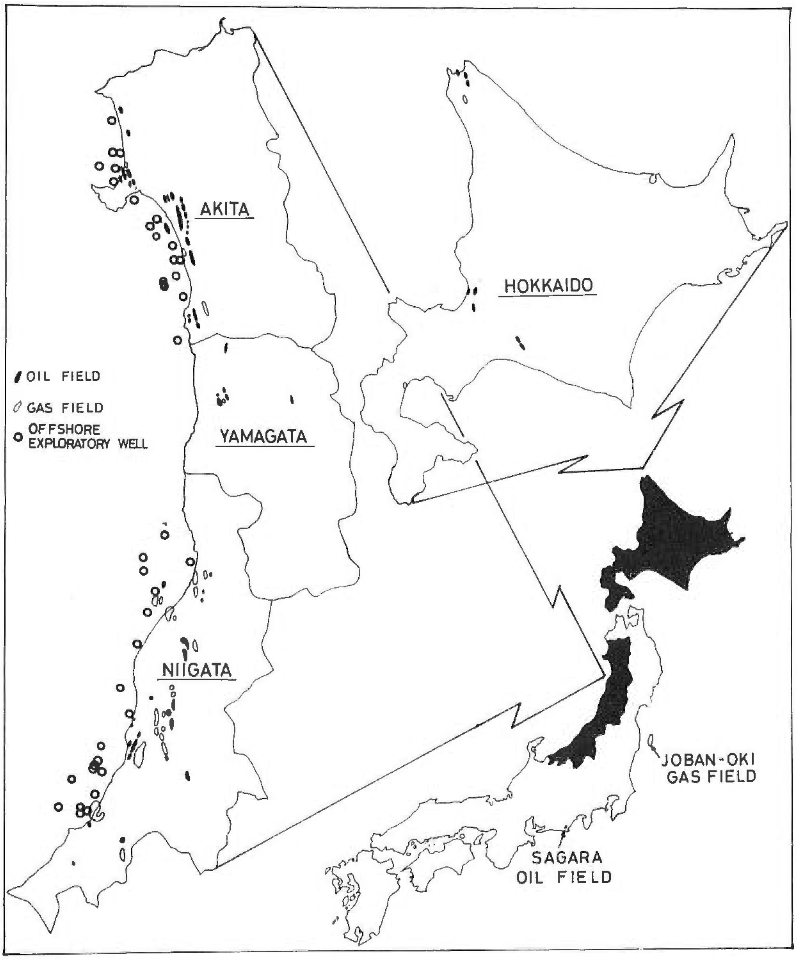

Fig. 2. Oil and gas fields in Japan and locations of offshore exploratory wells off northeast Honshu.

Gas is mainly produced in the Niigata Prefecture, and the producing horizons range from the Miocene to the Pliocene. The middle Miocene gas is derived from type I and II rich overmatured sources, whereas the Pliocene gas comes from source abundant in type III despite its marine origin. In Hokkaido, besides economic production from the Miocene, gas flowed on tests in the Eocene section. The source of the Eocene gas is allied to coaly matter, and that of the Miocene gas is derived from sources rich in type II and III. Gas of the Joban-Oki Field is produced from the lower Miocene and the Oligocene, and is derived from type III source materials closely related to terrigenous sediments.

Vertical Distribution

Economic production of black oil generally comes from depths shallower than 2000 m, with the deepest being 3600 m below sea level which is in the Yoshida Field. In the case of gas and condensate, the economic pool is known to be as deep as 4800 m below sea level.

Lithology of Reservoirs

Reflecting the active volcanism which characterizes the island arc, volcanic reservoirs are abundant in Japan. Reservoir-forming volcanic rocks are of the middle Miocene to the Pliocene and are subaqueous lavas and tuff breccias of andesite, dacite and rhyolite. Those of the middle Miocene are generally called Green Tuff because of the green color which is due to various mineral alterations. Pore spaces of volcanic reservoirs are primary fractures and vugs in autobrecciated lavas, intergranular pores in tuff breccias and tuffs, and secondary fracture spaces of tectonic origin.

As mafic minerals are easily altered to clay, which decreases porosity, and the alteration progresses with depth and time, rhyolitic reservoirs, which are poor in mafic minerals, are predominant in the Green Tuff horizon. In other words, even andesitic or basaltic rocks can form reservoirs in shallow or young cases. The other reason why acidic rocks are better than basic rocks as reservoir is that they have higher viscosity, so that they can form piles with larger vertical to horizontal ratio, and can have more primary fracture pores, which could be favorable for migration and accumulation of hydrocarbons.

Besides volcanic reservoirs, sandstone reservoirs are also abundant. Those of the upper Miocene to the Pliocene are considered to be turbidite. Most of them are tuffaceous reflecting strong volcanic activities, and have low permeability relative to their porosity.

Carbonate rocks are very scarce because the climatic conditions at the time of deposition was unfavorable and the tectonic movement was very severe. There is only one oil field with carbonate reservoir in Japan.

Type of Traps

Due to active tectonic movement, most of the Japanese oil and gas fields have anticlinal traps with steep wings. But the presence of hydrocarbon pools is strongly affected by stratigraphic control, that is, distribution of reservoirs is irregular and local due to severe tectonism at the time of deposition. Some fields are also controlled by faults.

ISLAND ARC HISTORY AND HYDROCARBON OCCURRENCE

At least, until the end of Cretaceous time, the region surrounding the present Northeast

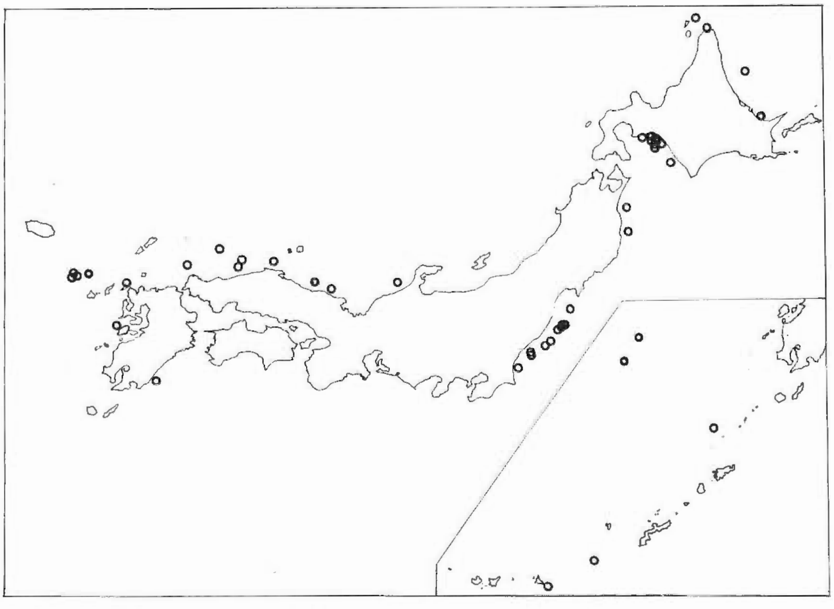

Fig. 3. Exploratory wells offshore Japan except those off northeast Honshu.

Japan Arc was a part of the Asian continent together with Southwest Japan, and the Japan Sea did not exist. The Cretaceous sediments accumulated from the shelf to the deep ocean facing the Pacific from Sakhalin in the north to at least Kyushu in the south. Off Southwest Japan, a considerably large land mass called the Kuroshio paleocontinent is inferred to have existed.

At the end of the Cretaceous to the Eocene, swampy low lands were formed at the inner side of the shelf edge of the Cretaceous sedimentary basins at least in the area of the present Northeast Japan Arc, and coal beds were deposited there. Such coal bearing sequence is distributed in southern Sakhalin, the western part of central Hokkaido and the Joban district. The formation of the coal basins in Hokkaido and northward most probably resulted from the formation of an embayment due to the westward movement of the Okhotsk paleoland. Those in Northeast Japan Arc were formed by the development of a barrier caused by the uplifting of the continental margin accompanied with subduction of the Pacific plate. The barrier is often called the Oyashio paleoland. Hydrocarbon source materials deposited in those coal basins are of type II and III, and possibly generated gas and waxy oil in the Paleogene sections of northern Hokkaido, off southern Hokkaido and the Joban-Oki Field.

Open sea sedimentation continued off southwestern Japan even during Paleogene time, because that region was not affected by subduction of the Pacific plate due to the presence of the Kuroshio paleocontinent. The paleocontinent was continuously subducted under the Asian plate, consistently supplying sediments into the sea between the Asian continent and itself. A barrier was formed at the southern margin of the Okhotsk paleoland by the same mechanism as in northeast Japan, and the Kushiro Coal Field was formed.

Subduction of the Pacific plate against the Kuroshio paleocontinent took place. The subduction zone became that which is along the Izu-Bonin Arc later.

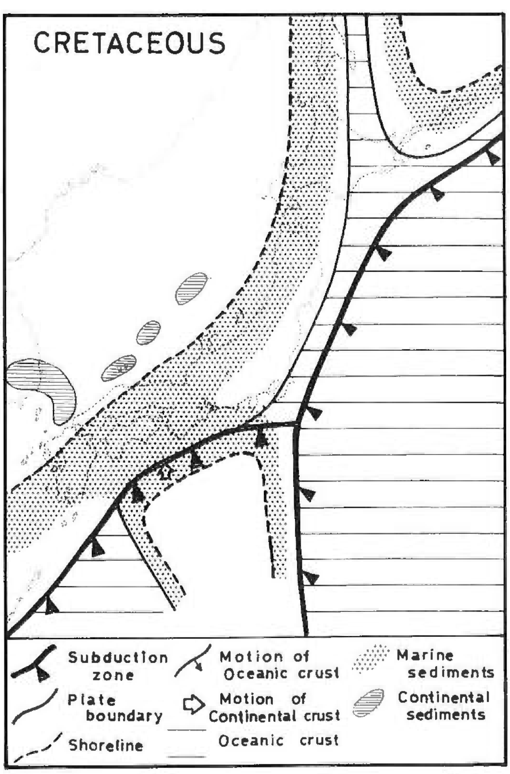

Fig. 4. Crustal distribution during Cretaceous.

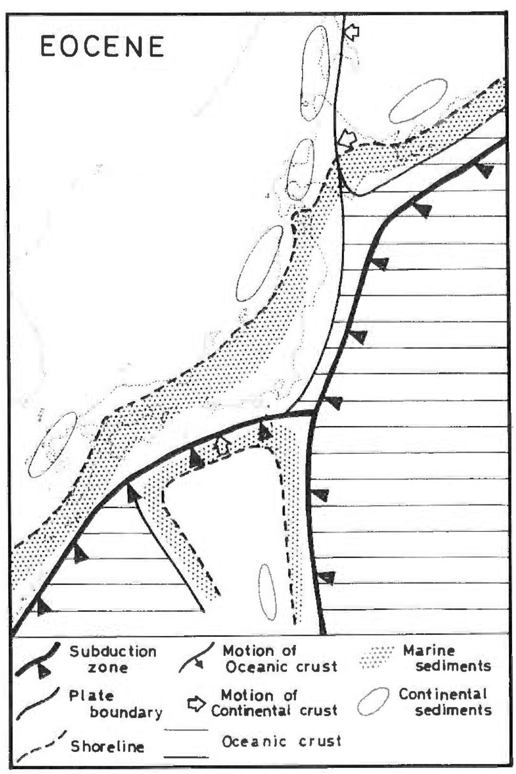

Fig. 5. Crustal distribution during Eocene.

Coming into the Oligocene time, a regional rise of the sea level occurred, sea water invaded the coal basins and holomarine sediments were deposited there. The phenomenon may be interpreted as the barriers being pulled down because of the strengthening of subduction of the Pacific plate. The pulling stress may have resulted in the fracturing of the Asian continent along its margin and the fracturing of the basement. Strong volcanic activities took place along the cracks and thick volcanic rocks accumulated in the depressions formed by the tension. This volcanic activity is called the Green Tuff activity. Green Tuff erupted also from cracks formed on the Kuroshio paleocontinent by subduction of the Pacific plate. The Green Tuff is now distributed on the Izu peninsula.

Such cracks widened and extended into the Japan Sea and the Shikoku Basin. As tensional stress of east to west direction superposed on the old northward movement in the Shikoku Basin, the latter movement was weakened, therefore, the Green Tuff activity and the fracturing of the basement are less distinct in the back arc side of the Southwest Japan Arc than in that of the Northeast Japan Arc.

The Okhotsk paleoland was also cracked by the subduction of the Pacific plate under the Kuril Arc opening the Kuril Basin, where Green Tuff erupted.

Basement fracturing and Green Tuff activity continued until the early Miocene. The Pacific water flowed onto the down thrown blocks and into the newly formed Japan Sea, so that the region of the present Japanese Islands became an archipelago. The complexity of the submarine topography increased due to subaqueous volcanci eruptions. Subsea volcanic knolls thus formed would later become oil and gas fields with Green Tuff reservoir.

In the central zone of Hokkaido, a meridionally extended land with thrusts or overturned structures appeared in an area where it had been covered by sea water during the Oligocene due to the pushing force of the Okhotsk paleoland. Therefore, coal basins and shallow marine

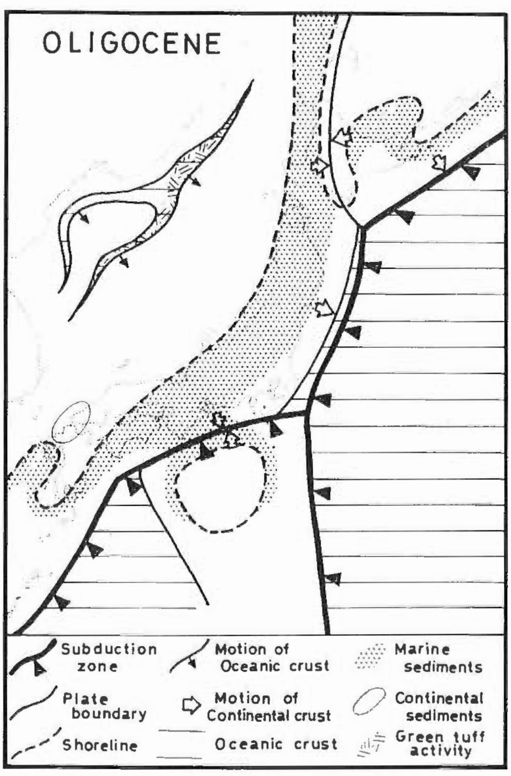

Fig. 6. Crustal distribution during Oligocene.

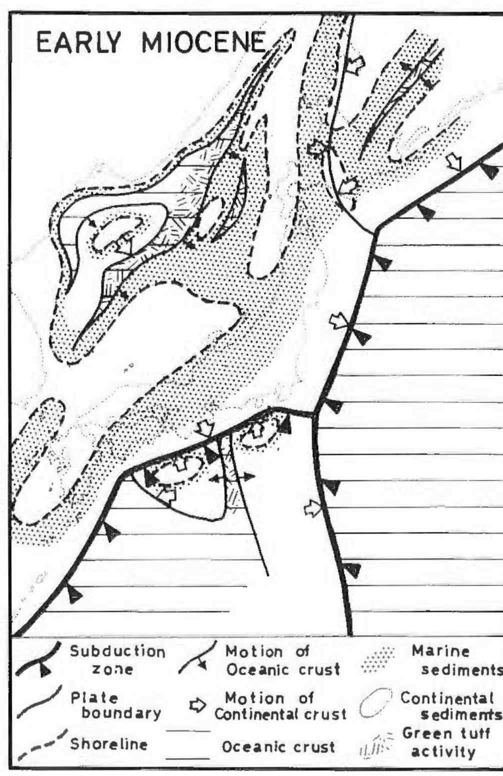

Fig. 7. Crustal distribution during early Miocene.

basins were formed in various places in front of the meridional land.

The Kuroshio paleocontinent was completely subducted below the Asian plate, so that the Shikoku Basin was covered by an oceanic crust.

Towards the middle Miocene, the Japan Sea widened further, rapid and regional rise of sea level took place again, and thick deep sea sediments were accumulated, burying the topographic relief. As the depressional areas were stagnant, sediments of this time are generally good source rock.

In the Pacific side, pull down by subduction resulted in diminishing barriers which in turn caused an oxidizing environment and thus the sediments of this time are not good sources rockes.

In the central zone of Hokkaido, compressional stress from the Okhotsk together with the westward advance of the Kuril Arc caused violent uplifting of the Hidaka Range. Thick sediments with rubble and slumped structures were deposited in the fore deep of the Hidaka Range. These sediments contain abundant argillaceous materials, because much of these sediments had been derived from the Cretaceous and the Oligocene sediments which are rich in mudstone. But it may be preferable to consider that they are essentially coarse clastics, because the distance of transportation was quite short. Consequently, the argillaceous appearance does not necessarily mean the environment being stagnant. In addition, the deposition rate was very high, therefore, the concentration of organic matter is low in the sediments of this time.

Sediments of this stage often underwent abnormally high pressures in various areas in Japan, which was caused by the argillaceous materials and their high deposition rate.

At the last stage of the Miocene, the persent backbone area of Japan rose up, and the Pacific and the Japan Sea sides were almost completely separated from each other. This phenomenon could be interpreted to be the result of buoyancy caused by thickening of sialic crust along the island acr which had been brought about by the sialic materials being dragged under due to the subduction.

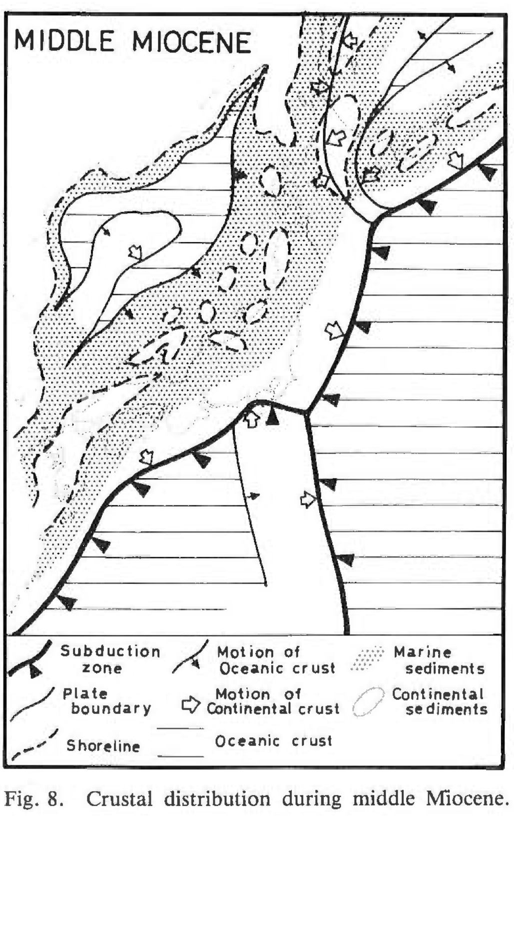

Fig. 8. Crustal distribution during middle Miocene.

The uplifting of the backbone resulted in deposition of coarse sediments of turbidite type, which form one of the main hydrocarbon reservoirs in the inner zone of the Northeast Japan Arc. In the central zone of Hokkaido, compression from Okhotsk decreased followed by fine sediments being deposited in rather quiet basins. In southwestern Japan, compression from the Philippine plate was so inactive that uplifting of the backbone was slack, thus, coarse sediments are scarce in the area. Even though the sediments of this stage constitute the main reservoirs in the inner zone of the Northeast Japan Arc, the field size is not so large, because the sands are not uniformly distributed, but are locally developed, owing to the complicated topography of both the supply areas and the basins due to differential movement of fractured blocks.

Entering the Pliocene time, the tectonism of the backbone area became more active and not only downwarping with growth faults took place to compensate for the uplifting of the backbone, but also folding parallel to the orientation of the island arc and reverse faults began to be formed due to compressional stress occuring in places. In addition, the sea level throughout the Pan Pacific started to rise. These phenomena caused an increase of complexity of the basinal feature. Consequently, although argillaceous sediments are essential, sands also are often developed locally, which also constitute hydrocarbon reservoirs.

Since the last stage of the Miocene, small scale andesitic volcanism often occurred, and some of the volcanics form gas reservoirs.

Opening of the Japan Sea continually progressed, thus, the basin center succesively migrated inward. In the central zone of Hokkaido and the Southwest Japan Arc, relatively calm conditions continued since the previous stage, and deposition of fine clastics prevailed.

After entering the Quatenary, the sea level fell again. Coarsening-upward regressive sequence rapidly filled up the relief of the sea floor and many places rose above the sea. Uplifting of the backbone became even more active, possibly because the activity of the Pacific plate increased, and marked folding and faulting took place. In Hokkaido, westward advance of the Kuril Arc was conspicuous reflecting the motion of the Pacific plate. Accordingly, the Hidaka Range violently uplifted, which in turn, generated steep folds accompanied with thrust faults on the west flank as though sliding up on the easterly inclining basement.

GEOTHERMAL GRADIENT

It is well known that geothermal gradient and heat flow are smaller in the forearc than in the back arc of an island arc system. The mechanism of this phenomenon is fairly well explained. Such a tendency is also typically observed in Japan. Geothermal gradient is 3°–7°C/100 m in the oil province of Japan (=back arc of the Northeast Japan Arc),

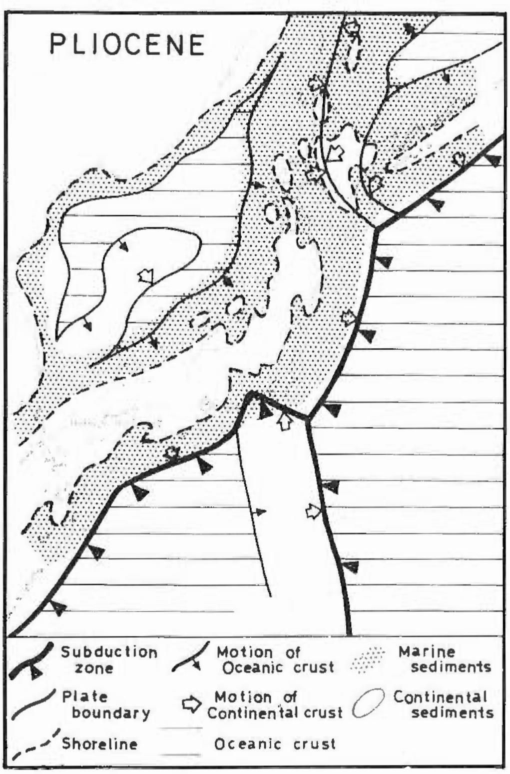

Fig. 9. Crustal distribution at the Pliocene time.

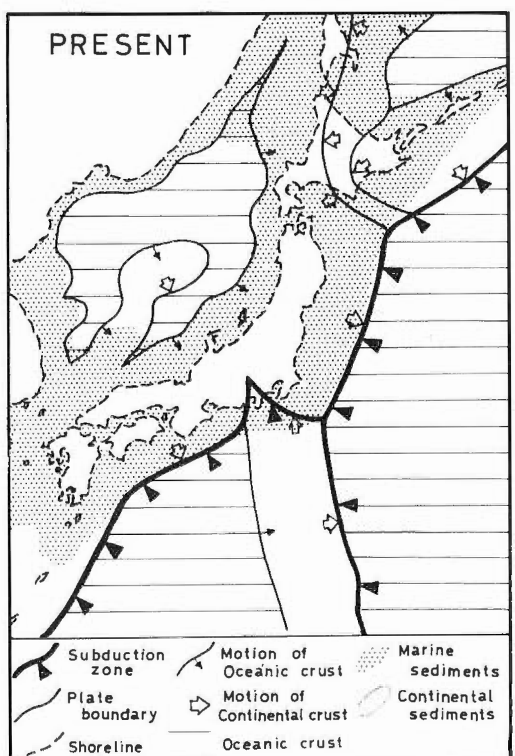

Fig. 10. Crustal distribution at present.

4°C/100 m in the back arc of the Southwest Japan Arc, 5°C/100 m in the back arc of the Ryukyu Arc, whereas 2.5°–3°C/100 m in the central zone of Hokkaido, 1.5°C–2.5°C/100 m in the forearc of the Northeast Japan Arc and 2.5°C/100 m in the forearc of the Ryukyu Arc.

The fact that oil fields are concentrated in the Japan Sea side of the Northeast Japan Arc can be referred mainly to the effect of the higher geothermal gradient. Even in the Pacific side, the area corresponding to the back arc of the Izu-Bonin Arc shows high heat flow. It is interesting that the Sagara Oil Field is located there, although it is a very small field. The fact that an economic field has not yet been discovered in the back arcs, other than in the Northeast Japan Arc, despite their high geothermal gradient, may depend not only on the scarcity of exploration efforts but also on the insufficient development of reservoir facies, and scarcity of anticlines, which are easily discoverable traps, resulting from the tectonic movements being gentler than in the Northeast Japan Arc. In fact, the source rock potential in the inner arc of the Southwest Japan Arc is known to be on the same level as that in the oil provinces of Japan.

In the central zone of Hokkaido, oil and gas fields are scarce and small relative to the thickness of the sediments and the abundance of anticlines. This may be caused by low source concentration due to high deposition rate, scarcity of type I source, limited volume of coarse sediments in potential productive horizons, time lag between oil generation and trap formation due to the growth of anticlines being rapid and too late, and also by the low geothermal gradient.

TECHNICAL PROBLEMS IN HYDROCARBON EXPLORATION

Complexity of the geological history of Japan which is an island arc is the cause for various difficulties in hydrocarbon exploration. Some of the important factors are mentioned below.

(1) Changes in thickness and facies of formations are conspicuous due to complexity of paleoenvironment, especially of submarine topography.

(2) Large field was not formed, because the basins were separated into such small areas and long distance migration of hydrocarbons did not take place.

(3) The extent of a reservoir is so limited that pools are not necessarily located at the top of anticlines. Accordingly, multiple exploratory drilling on a structure must usually be conducted, and possibility of excessive expenditure is great.

(4) In many cases, the configuration of a shallow structure differs from that of the deeper ones because of the complicated structural development.

(5) Structures are small and often accompanied with faults or steep zones.

(6) In case of Japan, which is an active island arc system at present, anticlinal areas show rugged and hilly topography as a result of the young tectonism.

The last three facts together with the prominent facies change make the quality of seismic survey records poor.

(7) Rapid and thick sedimentation resulted in insufficient discharge of pore water from argillaceous rocks, so that numerous high pressure formations are developed.

(8) On the other hand, caving formation are also frequently developed due to their being subjected to strong tectonic stress.

(9) Swelling shales are developed in places caused by abundant tuffaceous materials.

These three facts sometimes bring about difficulties in casing programing, mud controlling and cementing activities.

(10) As the geothermal gradient is high and the drilling depth increases, high temparature is frequently encountered in wells. That often causes problems in cementing, logging and mud control.

(11) Sandstone reservoirs are generally tuffaceous because of active valcanism. As tuffaceous materials have various effects on reading values of logs according to the grade of alteration (=clay mineralization), they make log interpretation difficult. Generally speaking, they make

the Sw value pessimistic, so that water free hydrocarbons are often produced from an interval with Sw from logs as high as 60 % . On the other hand, tuffaceous materials decrease permeability resulting in low productivity even though the log interpretative values are good.

To cope with these problems, the following measures are taken:

(a) Detailed interpretaion of geological history and paleogeography is conducted by using careful correlation, dating and paleoenvironmental analysis based on micropaleontological study on various kind of fossils including foraminifera, diatom, radiolaria, pollen, spore and nannoplankton.

(b) In the field of seismic survey, not only time migration but also depth migration processing has become routine. Moreover, wavelet processing, true amplitude recovery and detailed velocity analysis are performed for facies interpretation and direct hydrocarbon detection. Sophisticated techniques for noise tests or filtering are performed at various stages from data acquisition to processing. Surveys are repeatedly conducted both onshore and offshore whenever a new technique is developed. Recently, 3D survey has become popular, especially in hilly areas the Gus Bus type 3D survey is generally used.

(c) As the drilling mud to cope with highly pressured, caving or swelling formations, lignate mud is commonly used.

(d) Special logging and perforation tools for high temperature are always close at hand.

(e) All kinds of logging including ISF, DLL, MPL (MLL), BHC, FDC, CNL and GR are always run. Logs are basically interpreted by using the shaly sand method. Recently, CEC measurement has become popular to remove the effect of tuffaceous materials on log interpretative values. For log interpretation of volcanic reservoirs, no definite method has been established.

(f) It has been confirmed that hydrofrac technique which has rarely been used is effective for oil and gas reservoirs of Japan. But the effectiveness of acidizing volcanic reservoirs which are abundant in Japan has not verified yet.

(g) To pick up prospective areas by connecting complicated basin history with hydrocarbon accumulation, sophisticated computer programs based on the kerogen origin theory are widely used.

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Deep-sea Basins in Indonesia

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ABSTRACT

Recent offshore sedimentary basins in Indonesia, located in water depths below 200 m, are discussed on the basis of their tectonic origin and evolution. They are described in terms of their shape, their sedimentary fill and petroleum potential.

Some of the basins discussed have sedimentary thickness up to 5 seconds two way seismic time. In cases where the basins are underlain by continental crust, the sedimentary column can be considerably thicker if the sedimentary rocks of the underlying continent are added. Basins are delineated by the 1.0 second thickness isopach which is considered the minimum sedimentary thickness for hydrocarbon prospecting.

Forty-one basins fulfill the definition of having a sedimentary fill of more than 1 second of seismic data (TWT). These basins cover an area 1,252,250 km^2 and occupy 55% of the total area of all basins in Indonesia.

The basins can be situated either marginal to emerged land or isolated from it. In the first type, basins are narrow, parallel to the emerged land, often bounded by faults and are filled with clastic erosional products. Shales are dominant but fill also includes coarser clastics. Deltaic and littoral clastics are subordinate while turbidites predominate. Carbonates are developed occasionally on basement highs or near shore. The second type of basin is often located in deep water. Recent sediments are only deposited as veneer.

Structural deformations, which are visible on many seismic sections show a larger amplitude at depth as compared to those in the Recent deposits. A large variety of possible traps including compressional folds, dragfolds, block faulting and also shale diapirism, draping-over-highs and reef-buildups are exhibited in recent sedimentary basins throughout Indonesia.

INTRODUCTION

Deep-sea basins in this paper refer to offshore sedimentary basins which are located in water depths exceeding 200 meters. Extensive exploration surveys directed towards finding hydrocarbons in these basins have not yet been seriously undertaken.

Data concerning these basins are now available to describe the general characteristics of most of these basins. The importance of sediment filling and the type of tectonic deformation is brought out by the results of recent seismic scientific surveys, from which a number of selected profiles were reprocessed by PERTAMINA. Recent regional geologic surveys also help to shed some light on the geologic history of basins and thereby improve the knowledge of plate tectonic concepts in the general area, especially with regard to size, type and characteristics of deep-sea basins. In some cases lithology of the rocks in basins can also be inferred from the nature of the source of material.

Each of the individual basins has its own depocenter, sedimentary section, structural features, although some common characteristics are recorded in neighbouring basins which have often been partly connected. They are presently 41 in number but more can be individualized when more data is produced (Table 1).

High risk, associated mostly with the need for high level of technology and huge capital

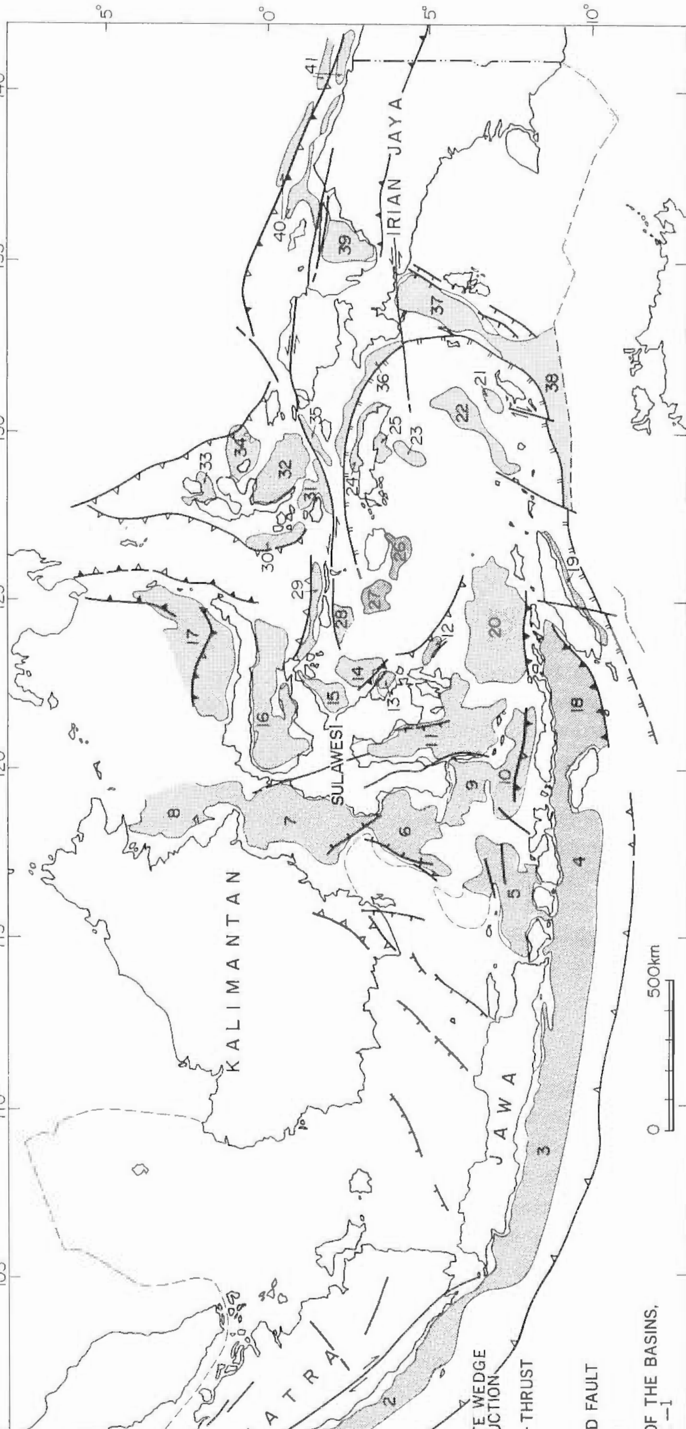

Fig. 1. Tectonic elements of Indonesia and location of deep sea basins.

investment was a limiting factor inhibiting active hydrocarbon exploration in deep-sea basins. New exploration techniques, specially for deep offshore, are now available and 200 m water depth is no longer a barrier for offshore drilling and production. The deepest water depth where an exploration well has been drilled in the world is 1480 m (Canada offshore in 1979), whereas a water depth of 312 m (Gulf of Mexico) is the deepest water where a production platform has been installed.

Although onshore and shallow offshore areas in Indonesia have by no means been exhaustively explored yet, it is not too early to begin the search for prospects in deep water. Recently two Production Sharing Contracts have been signed this year pertaining to areas of deep water and this activity can be considered the beginning of a new exploration era in Indonesia.

GEOTECTONIC FRAMEWORK

The distribution, nature and age of infilling sediments of the deep-sea basins are strongly controlled by the tectonic history of the region. Plate tectonic concepts offer an insight of the geological setting, past and present, helping to define, delineate and classify different sedimentary basins and, particularly, the deep-sea basins (Fig. 1).

The continental lithospheric plates represented by the Asiatic plate in the northwest (Kalimantan, Java Sea) and the Australian plate in the southeast are stable domains mainly comprising onshore and shallow offshore areas. Most of the deep-sea basins are either present over oceanic plates or distributed along the mobile arcs resulting from subduction processes. Deep-sea sediments deposited directly on oceanic crust are represented on the Wharton plate in the Indian Ocean, south of Sumatra and Java, on the Pacific plate north of Irian Jaya, and presumably in the Banda Sea. The most prominent basins are the ones occurring all along the collision zones at the plate margions, i.e. the Sunda Arc and the extremely dispersed Australo-Melanesian arc. Thus, in Western Indonesia, the deep-sea basins show a continuous elongated shape south of Sumatra and Java, while in Eastern Indonesia, east of the Makassar Strait, they are scattered and very variable in size, shape and thickness of deposit.

In Western Indonesia, the process of subduction of an oceanic plate beneath the cratonic Sundaland created the following fore-land basins:

- —The back arc basins northeast of the Barisan Range in Sumatra and mainly onshore except in the northwesternmost part (North Aceh).
- —The forearc basins, filled with thick sediments and limited to the southwest by the outer-arc ridge (emergent in the north) and called the Mentawai Islands Arc. The latter arc results from the recent frontal uplift with tectonic imbrication and melange of the outer depositional wedge of sediments laid down in the Tertiary Sumatra-Java Trench.
- —The Sumatra-Java Trench, south of the outer non-volcanic arc, filled with thin turbiditic deposits and generally interpreted as the superficial trace of a deep subduction zone.

In Eastern Indonesia the setting is more complex. After the start of the collision between the continental Australian plate and the oceanic domain (proto-Pacific and future Banda Sea) during the early Tertiary, a new phase of deformation began in the middle Miocene. During this latter period, Gondwanaland broke up and its elements were dispersed. They are now represented in Indonesia by Irian Jaya, Banggai and Sula Islands, and the Tukang Besi Archipelago, and the continental material also constitutes a large proportion of the imbricate wedges on the Banda arc, eastern arms of Sulawesi and Halmahera, and northern Irian Jaya. Several basins are located on the outer margin of the dispersed elements of the Australian craton, most of them offshore in a foredeep, forearc or back arc position.

Finally, during late Neogene, some basins developed with the opening of subsiding depressions bounded by faults. Their general pattern is rhomboidal, like Bone Basin or the South and North Halmahera basins. The South and North Makassar basins are also assumed to have originated as subsiding depressions created by tensional movements. In this latter case, the underlying crust is stretched to an ill-defined intermediate stage or even split and spread into an oceanic domain.

DESCRIPTION OF THE DEEP-SEA BASINS

A good number of deep-sea basins are to be distinguished in Indonesian waters (Fig. 1 and Table 1). There are 3 large basins in Western Indonesia distributed to the south of the

Table 1 List of Deep Sea Basins

No.	Name of Basin	Areal Extent (1000 km^2)	Maximum Sediment Thickness (sec)	Maximum Water Depth (m)
1	North Aceh	53.25	Appr. 4.0	1000
2	Southwest Sumatra	120.75	Appr. 4.0	1000
3	South Java	135.75	Appr. 5.0	3000
4	Lombok	67.75	3.5	4000
5	Bali	49.50	3.0	1000
6	South Makassar	42.25	4.0	2000
7	North Makassar	71.00	4.0	2500
8	Tarakan	44.25	4.0	4000
9	Spermonde	35.25	3.0	1500
10	Flores	33.75	2.5	5000
11	Bone	54.25	3.0	2500
12	Buton	1.25	3.0	2000
13	Manoui	2.75	1.5	<1000
14	Salabangka	11.25	2.0	3000
15	Banggai	5.50	2.0	2500
16	Gorontalo	54.50	3.0	3000
17	Minahasa	71.50	2.5	5000
18	Sawu	52.00	3.0	3000
19	South Timor	6.50	2.0	1000
20	Tukang Besi	67.50	2.0	4000
21	Tanimbar	4.75	1.5	4000
22	Weber	18.25	1.5	7000
23	West Weber	5.25	1.5	3000
24	North Seram	8.00	2.0	1000
25	South Seram	3.50	1.5	3000
26	Buru	8.25	1.5	5000
27	West Buru	9.25	1.0	5000
28	South Sula	6.25	2.0	5000
29	Sula	7.50	1.0	2000
30	North Obi	10.00	1.5	2000
31	South Obi	8.50	1.5	1000
32	South Halmahera	26.00	2.0	2000
33	North Halmahera	5.00	2.0	2000
34	East Halmahera	15.25	>2.0	2500
35	Salawati Deep	5.50	4.0	1000
36	Kepala Burung Foredeep	15.50	>3.0	2000
37	Aru Trough	30.25	4.0	3000
38	Arafura Deep	58.75	>3.0	1000
39	Waipoga	11.00	4.5	2000
40	Waropen	12.00	2.5	3000
41	Jayapura	2.50	1.0	3000

Asiatic craton. In eastern Indonesia, particularly mobile and complex zone, numerous deep sea basins are scattered throughout the area, very variable in size and shape. Presently 38 of them have been recorded but more can be identified as more data is produced.

They are described from west to east in 6 sub-sections:

—Sumatra Java Region
—Makassar Strait Region
—Sulawesi Region
—Banda Arc Region
—Molucca Region
—Irian Jaya Region

DEEP-SEA BASINS OF THE SUMATRA-JAVA REGION

North Aceh Basin

The North Aceh Basin is an extension of the North Sumatra back arc basin. A discontinuous submarine ridge, prolongation of the Barisan volcanic inner arc limits the basin to the southwest. The northern part of the basin is possibly connected to the Andaman Basin. The infilling of the basin reaches 4 secs (TWT) thickness of sediments and it is mostly lying in water depth less than 1000 metres. From shallow offshore and onshore data of the North Sumatra Basin and Mergui Terrace, the prospective series are likely to be constituted by transgressive sands and by reefs beneath lower Miocene shales.

Southwest Sumatra Basin

The SW Sumatra Basin extends along the offshore area on the southwest side of Sumatra. Water depths in the range of 200–2000 m cover most of the area. Regionally there is a progressive deepening of the basement going southwestwards away from the Sumatra mainland, while the opposite flank of the trough, near the outer-arc islands is much steeper and probably frequently faulted (Fig. 2). Thick sediments infill most of the basin and lap onto the basement on the mainland side. The sediment thickness gradually increases to 4 secs in some parts of the depocenter. The Palaeogene strata penetrated by the wells in the shelf area or outcropping along the coast of several (offshore) islands in the northern part of the basin consist of fluviatile to littoral conglomerates, sandstones and carbonaceous shales. The younger sediments, of Neogene age, are mainly clays and carbonates rather than well-developed quartz sands. Upper and lower Miocene carbonates were considered as potential objectives and several wells found gas in both reservoirs. In the central and southern parts of the basin, tuffaceous sandstones dominated the Eocene-Oligocene deposition. These sediments are overlain by tuffaceous clays, shales, carbonates and marls of Miocene-Pliocene age. A small amount of oil was recovered from the Miocene carbonates in one well drilled in the offshore Bengkulu area.

Generally, the sediments are slightly deformed in the center and the mainland side of the basin. Oceanward, the sediments are increasingly deformed with structures apparently overturned away from the ridge, near the outer island arc ridge. It is likely that the sediments in the basin are largely sourced from the island of Sumatra. The smooth floor of the basin and its slopes between saddles and lows indicate deposition is dominated by longitudinally flowing turbidites in the deeper part of the basin. Low geothermal gradients, mostly 2–3°C/100 m, have been found in wells drilled in the SW Sumatra Basin (Kenyon and Beddoes, 1977). Such low gradients are generally characteristic of outer-arc basins.

South Java Basin

The South Java Basin is the prolongation of the SW Sumatra outer-arc basin. The basin is situated between the inner arc of Java in the north and the non-volcanic arc ridge in the south (Fig. 3). In contrast to the SW Sumatra Basin, the non-volcanic arc in this area is

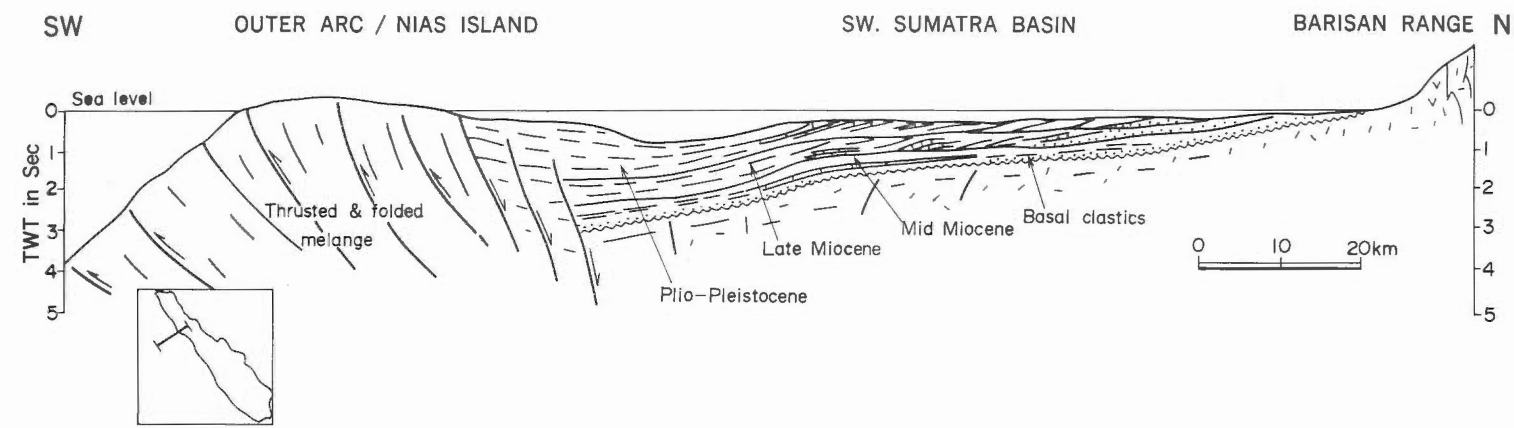

Fig. 2. SW. Sumatra Basin cross section.

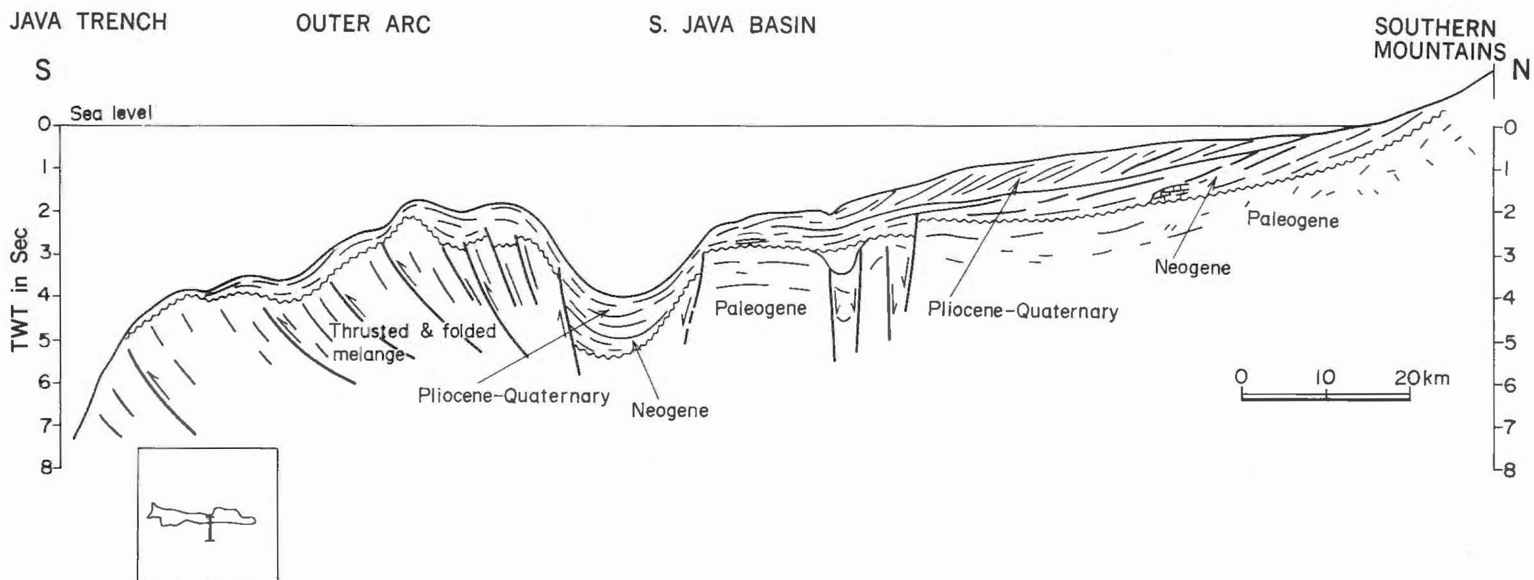

Fig. 3. South Java Basin cross section.

a wholly submarine feature. Its crest lies mostly 1000–3000 m below sea level. To the east the South Java Basin is connected to the Lombok Basin. The water depth deepens from west to east and reaches 3000 m. Only the northern part of the basin, along the South Java shelf area, is situated in water depths less than 1000 m.

Thick sediments were deposited in the basin, with a thickness exceeding 5 secs in the depocenter. Similarly to the SW Sumatra Basin, the sediments are slightly deformed in the northern part of the basin. South of Central Java the basin bends northward and even extends onshore. The sediments in this northern extension are more than 3000 m thick in some sectors of the shallow waters area. This area is separated from the deeper part of the basin by a prominent ridge parallel to the axis of the basin.

The drilling of two wells in the shallow area encountered deep marine Pliocene clays, shallow marine middle Miocene limestones and clays, upper Oligocene tuffs, clays and undated volcanic agglomerates (Bolliger & de Ruiter, 1975). The main basin south of the ridge is presumably filled with deep marine clastics of volcanic origin and deep marine clays or turbidites of Paleogene to Quaternary age.

The geothermal gradient measured from the two wells is very low, less than 1.5°F/100 ft.

Lombok Basin

The Lombok Basin corresponds to the eastern prolongation of the South Java Basin. It is expected to present similar characteristics. Some ridges are existing between the two basins with a minimum of 1 sec (TWT) thickness of sediments. The basin is lying mostly in water depth more than 2000 m. Generally the sediments thicken to the south up to 3.5 secs (TWT).

Bali Basin

In the northern part of the Bali Basin very thick sediments have been deposited. A maximum thickness of 4500 m of Tertiary sediment is reached in the highly faulted downblock. Similarly to the Spermonde Basin the increase in thickness is due to the thickening of the Eocene-Paleocene sediments. Their lithology is rather speculative, as only the platform of Lombok Block has been explored. The basal sediments possibly consist of dominantly fine grained clastics, clays and mudstones. They are overlain by clastic series of carbonate layers of Neogene-Pleistocene age. The structural trend in the northern part of the basin is oriented in the east northeast-west south-west direction. In the southern part, the dominant trend runs east-west, parallel to the axis of the inner volcanic arc. Prominent diapiric structures are also present.

DEEP-SEA BASINS OF THE MAKASSAR STRAIT REGION

Makassar Basins

Two individual basins are identified in the Makassar Strait: the North and South Makassar Basins.

The North Makassar Basin lies between the stable Paternoster Platform to the south and the offshore continuation of the Mangkalihat Peninsula, in Kalimantan, to the northwest.

Seismic information indicates that the basement descends regularly from the Mangkalihat Peninsula towards the center of the basin, where the cumulative thickness of un-deformed sediments could reach 4000 m. Around 20 km west of the coastal Karama-Lariang areas, basement rises up and the sedimentary cover is reduced to 2000 m. Here the sediments show signs of compressional deformation which could well be related to that of the onshore Karama-Lariang basins, where complex compressional tectonics affects sediments of the same age.

In the neighbouring Kutei Basin of Kalimantan the pre-Tertiary basement can be as deep as 6000 to 8000 m. It includes about 4000 m of mid-Miocene to Recent sediments overlying 2000 m of pre-Miocene sediments. The clastics of the Mahakam delta are restricted to the present shelf. They do not extend into the North Makassar Basin where the bathyal facies of the Mid-Miocene are thought to have been deposited under 1000 m water depth. The fluiviatile and deltaic sequence of the Karama-Lariang basins are not expected to extend far beyond the present very narrow shelf. Even onshore, the sandstones are largely argillaceous and provide only poor to fair reservoirs. Mature source rocks exist in the Karama Basin (oil seeps). Also, they are known to be prolific in the Kutei Basin but less rich in the prodelta facies.

The South Makassar Basin is a major depocentre (more than 4.0 secs of sediments) below 2000 m of water. The structures of the Makassar Basins, still poorly documented, probably consist of draping-over basement highs. En echelon drag-folds also are likely, as those evidenced in the Spermonde Basin.

Tarakan Basin

The shallow offshore part of the Tarakan Basin, substantially developed in areal extent and thickness of sediments (5000 m in the southern Muaras part), has already been proven hydrocarbon productive. The southern part of the basin (north of the Mangkalihat Peninsula) is a thick depocenter devoid of structural deformation. Possible stratigraphic traps formed by onlap of sediments were tested by drilling in a series found to be mainly carbonate facies. The northern part shows several northwest trending anticlines transected by numerous northeast trending growth-faults providing local roll-over structures, due to the poor seismic quality the location of the potential traps is difficult to delineate and only two of the most prominent features have been drilled successfully in the shallow portin of the basin. 130 km east of Tarakan Island, where the water depth attains 3300 m, the cumulative thickness of sediments is 4000 m. West of this area, the sedimentary cover is strongly deformed showing features of argillokinesis related to compression; in this case, diffraction noise prevents observation of the basement reflectors.

The deltaic type series contain excellent multi-layered reservoirs of clean sands interbedded with source rocks which were found to be at their suitable stage of maturation between 1000 and 2500 m in depth.

Spermonde Basin

The Spermonde basin is lying beneath a water depth mostly between 200–1000 m. To the southwest, a shallow area of about 200 m depth separates this basin from the Bali Basin.

This area roughly consists of a carbonate platform. A zone of flexures from the northeastern rim of the basin, borders the Spermonde shelf. The total thickness of Tertiary sediments deposited in the Spermonde Basin slightly exceeds 3000 m. Based on the drilling data in the Spermonde shelf the thickening of sediments compared to the adjacent positive zone is mostly in basal series. The Paleocene-Eocene basal clastics can be expected on and around paleo-reliefs. Overlying clastics and reefal developments of Oligocene which were deposited together with clay and mud could be another objective in this area. Several positive trends are striking from northwest to southeast, parallel to the axis of the basin.

DEEP-SEA BASINS OF THE SULAWESI REGION

Flores Basin

The Flores Basin, north of Flores and Sumbawa Islands is very deep and supposed to be oceanic in crustal structure. The Flores Sea could have opened in Late Miocene time, so the basin is likely to be filled with relatively recent deposits. Their thickness would not exceed 2.5 secs TWT, but the sedimentary sequence is abruptly truncated along an east-west south dipping thrust fault which bounds the basin to the south. This fault is a regional feature as it also exists further east, to the north of Alor Island. It might represent the prelude of the subduction of the Banda Sea oceanic plate beneath the Australian lithospheric plate.

Bone Basin

The general configuratin of the basin is that of a long rhomboid whose southern margin is formed by two coalescing faults. The northern part is also terminated by a fault which is connected to the onshore Palu rift feature. Due to the presence of marginal faults, the slopes are abrupt and the sea bottom reaches nearly 3000 m in depth.

Geologically, the Bone Basin is a fore-arc basin situated between the volcanic arc of western Sulawesi and the non-volcanic arc of eastern Sulawesi which is comprised of metamorphic rocks and tectonic melange. Fault systems rim the eastern and western margins of the basin forming a grabenlike feature. The subsidence relating to this opening is evidenced by the successive onlapping of late Neogene to Recent series onto Miocene sediments.

The Sengkang Basin, as a western extension of the Bone Basin, is filled with 3000 metres of clastics and reefal limestones. Most of the reefs drilled onshore by BP were found gas bearing. Some others exist in shallow offshore, also along north-south trends.

In the deeper part of the basin, sedimentation can be expected as dominant clastics with rare carbonates. Shales are probably plentiful in the Neogene-Pleistocene sequence of the Bone Basin. The geothermal gradient in the offshore BBA–1X well is rather low, only 1.0°F/100 ft. The only well drilled in the northern part of the Bone Basin penetrated about 3000 metres of Miocene-Pliocene clastic sediments without reaching the basement.

Buton Basins

Small basins, partly extending onshore are present in the vicinity of Buton and adjacent islands. The one, located in shallow offshore between Muna and Buton Islands contains up to 3.0 secs of sediments. The others do not exceed 2.0 secs in thickness.

Overlying a high disturbed Mesozoic and Paleogene series, the Late Miocene consists of the clastic Tondo beds and of the Sampolakosa dolomitic limestones. These two formations are also involved in the tectonic process and show prominent SSW–NNE folds.

According to the wells drilled on the onshore basin margins, reservoirs, are scarce, but numerous oil shows were recorded. The oil likely originated in the Triassic sediments and migrated vertically along fault planes.

Manoui-Salabangka and Banggai Basins

These basins, of moderately small size, are all located on the eastern front of the tectonic melange of eastern Sulawesi.

From seismic data it can be said that the cumulative thickness of sediments tends to get thinner towards the deep offshore. Correlation of the offshore seismic data with the surface geology enable the following observations:

—the lowest horizon could correspond to a Mesozoic series.

—Paleogene carbonates are likely represented by the band of strong low frequency and continuous horizons. They show features of compressional deformations.

—Miocene molasse series, about 1.5 secs thick, are characterized by progradational features, somewhat transparent in character and having discontinuous reflections, where tectonic deformation takes place; only non coherent noise is recorded.

—a Pliocene quaternary series, overlying an angular unconformity.

Two areas of provenance could have furnished complementary type deposits:

1. Potential reservoirs in the quartzose influx yielded by the core of the Sula Spur and Banggai archipelago of continental origin.
2. Potential source and seal rocks resulting from the erosion of mafic and ultramafic rocks in the eastern arm of Sulawesi.

Offshore extensions of the Celebes molasse and of carbonates of the Banggai Islands also could have provided potential reservoirs.

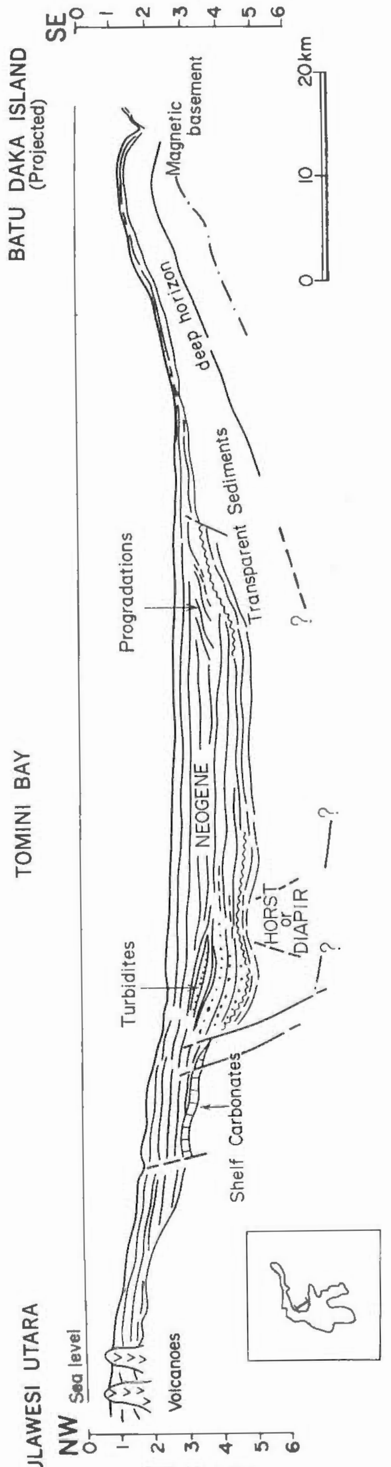

Fig. 4. Gorontalo Basin cross section.

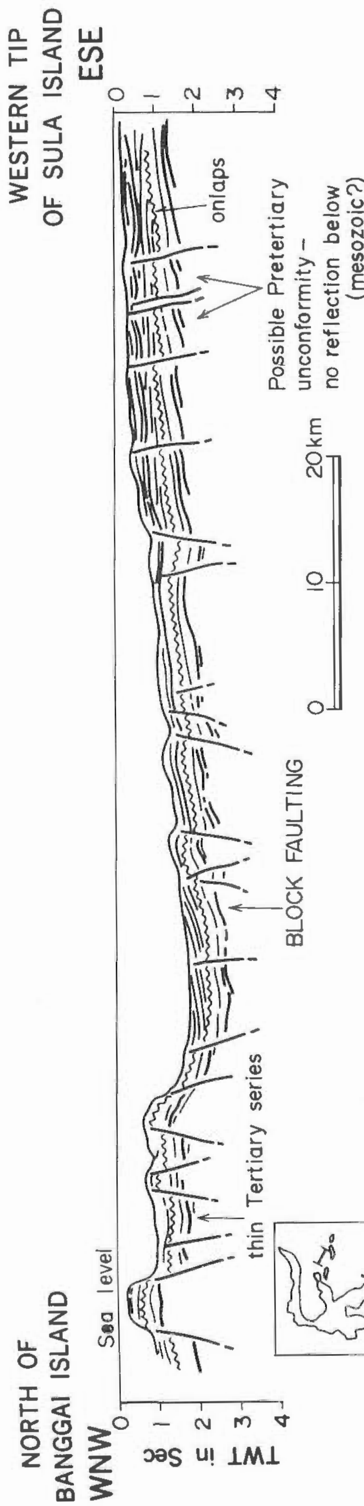

Fig. 5. North Sula Basin and western extension cross section.

Gorontalo Basin

The Gorontalo Basin has a structural configuration and a type of infilling largely similar to that of the Bone Basin. However, carbonates are barely developed onshore and sediments in the basin are probably mostly clastics with both volcanic and quartzose derived elements.

The limits of the basin are not distinct and correspond only locally to some faults. In places the basin extends onshore, as in the Poso Graben, a southern prolongation of the Tomini Bay depocentre, filled by molasse type deposits. Elsewhere turbidites are likely to be the predominant deposits with subordinate small size deltaic features (Fig. 4).

The northwest part of the section in Figure 4 shows a deep horizon exhibiting diffraction patterns which can be correlated to the top of the metamorphic series. These series are overlain by a thin Plio-Quaternary section which is mostly composed of clastic sediments, but locally carbonates could have developed. Further southeast, rapid subsidence is evidenced by a thick section, limited to the northwest by a set of normal faults. In the vicinity of these faults, reflections show wedge shaped sequences, thinning towards the centre of the basin. In general the interval velocities decrease towards the southeast.

Minahasa Basin

Largely in deep water, the Minahasa Basin is still poorly known. The deposits are up to 2.5 secs (TWT) thick, but they thin out drastically in the shallow water zone along the northern arm of Sulawesi.

DEEP-SEA BASINS OF THE BANDA ARC REGION

Sawu basin

The fore-arc Sawu Basin lies in 3000 m of water and a maximm 3.0 secs (TWT) to acoustic basement is recorded. This reflector corresponds to the envelope of a severely tectonized series, which locally exhibits short segments of reflectors. The only well drilled in this basin in a marginal position intersected a non-clastic interval (globigerina marls and pelagic limestones). The absence of potential reservoir can be explained by the lack of siliceous material in the Sawu Island outcrops. The lithology to be expected in the basin is probably rich in volcaniclastics whose material is originated from the volcanic arc. Quartzose components could also have been supplied from Sumba and Timor. Argillaceous sediments are another important part of the Tertiary sequence as known in similar basins.

Prominent tectonic features have been observed in the Sawu Basin. A regional NE–SW fault limits the thick deposits to the south. The reverse thrusting movement of the principal fault is confirmed by the presence of a narrow fold 5 kms away and parallel to it. This fault and fold may be the trace of the Benioff subduction zone running betwen the non-volcanic Banda Arc and the volcanic arc islands. Compressional stress could have resulted in the formaiton of prospective structural traps.

South Timor and Seram Basins

Numerous small basins to the south of Timor Island and several others north-northeast of Seram Islands should be considered. Although lying mainly in shallow waters or even onshore they also have deep offshore extensions. Valuable information is gained from the study of extensive seismic surveys and wells in the shallower water and onshore areas.

In Timor, thick marine sediments were deposited in Late Tertiary times, just after or even concomittant with the emplacement, by gravity sliding, of allochtonous units (Bobonaro clays). They consist of bathyal deposits covered in turn by molasse-type sediments and attain 2000 m in thickness, which is quite appreciable compared to the equivalent deposits over the northwest shelf of Australia.

The occurrences of nappes and of thick deposits imply the presence of high topography located to the north. The lithologies encountered are, from base to top:

—Deep carbonate ooze made of planktonic foraminiferal tests, up to several hundreds of metres thick.

—Globigerina marls which also reach several hundreds of metres in thickness.

—Clastic deposits of turbiditic origin, characterized by graded bedding and slump structures. Deposition ended with estuarine nearshore material.

The same type of deposits occur in the northern part of the island of Seram. In the Bula oil field, coral reefs are associated with sand bars and both are hydrocarbon producers.

A number of medium size depocenters have been identified, generally bounded by a synsedimentary fault (growth-fault), downthrown towards the sea (Fig. 6). The strata are dipping towards the faults where they reach the maximum thickness and could result in some roll-over features. On the opposite flank of the basin there is progressive onlap onto the basement with draping over paleohighs. The thinning of sequences in the direction could be conducive to the formation up-dip of stratigraphic traps. Small suspended sedimentary basins are found further down the slope on the imbricate wedge where a slight slope reversal allows accumulation of the deposits. They generally consist of deep water Plio-Pleistocene oozes accumulatd over a limited thickness and then deformed by the progressive motion of the wedge. Most of them are slumped, contorted and chaotic beds not considered to be valuable objectives.

In the trough itself, in front of the imbrication, strongly deformed sediments pass progressively to layered deposits of a similar deep-water carbonate nature, but the bedding of which has been preserved from tectonic deformation on the continental shelf.

Tukang Besi Basin

Of a large areal extent, but with 2.0 secs of sediments utmost, The Tukang Besi Basin lies south of the Tukang Besi Islands, in water depths attaining 3000 to 4000 m. The basin is bounded on the south by a reverse south-dipping fault and extends eastwards to the Banda Sea Basins. Clastics deposits, provided by erosion of igneous and metamorphic rocks on Tukang Basi Islands, are likely in its northern flank while its southern part is probably filled with oceanic-type sediments locally associated with volcanic rocks.

Tanimbar-Weber Basins

The same geological setting as that of the Sawu Basin, is encountered in the Tanimbar and Weber depocentres. But in contrast to the Sawu Basin, they are not bordered by emerged lands, particularly the deep-sea Weber Trough. There, the lithological column should consist of oceanic-type ooze and radiolarian cherts and might lack clastic material, as suggested by their absence on Jamdena Island.

The great water depth in the Tanimbar Basin and even deeper in the Weber Trough are major deterents to exploration at this time.

Buru Island Basins

Two depocenters are evidenced west and south of Buru Island; they are closely related to the location of the island indicating that the emerged land is the major source of erosin products (silicatic and carbonatic material). The thickness of sediments is not more than 1.0 secs (TWT) for the western basin but in the southern basin the section is up to 1.5 secs thick, and controlled by east-west striking faults on both the north and south flanks of the basin.

Late Tertiary transgression started with reef limestones south of the island but they probably do not extend far in the present offshore area. The infill of the southern basin is likely to consist both of volcaniclastics as known on the island of Ambelan and of non volcaniclastics and limestones also described onshore.

DEEP-SEA BASINS OF THE MOLUCCA REGION

North and South Sula Basins

The North Sula Basin is abruptly terminated to the north by the thrust of the Molucca Sea collision complex. This is small depocenter with only about 1.0 sec of sediments.

A strong reflection corresponding to the basement can be traced approaching deep waters (Fig. 5). Correlating with the surface geology, the series above the basement could be Jurassic overlain by Plio-Quaternary sediments. The block-faulting style can be compared with the westernmost part of the Arafura Platform (Irian Jaya).

The South Sula Basin is markedly larger and reaches 2.0 secs in thickness of deposits. It is separated from Sula Island by a regional east-west fault having more than 1.0 sec of throw, creating a prominent escarpment on the sea floor.

Thus, most of the depocenter is lying in deep waters (1000–3000 m). The infilling sediments are likely to be predominantly quartzose material as a large part of the island is made of metamorphic and granitic rocks. The structural deformation, not known in detail, can include fault blocks and drag-folds related to vertical and lateral movements of the main fault.

South and North Obi Basins

They have, respectively, an east-west and a north-south orientation and show an elongated shape in water depths usually greater than 1000 m. The southern basin is bordered to the west by Obi Island which exhibits large exposures of metamorphic rocks, possible source of siliceous material. The west margin of the northern basin is severely overthrusted by the Molucca Sea collision complex. Thicknesses are up to 1.5 secs (TWT) and sediments consist mainly of volcanics and volcaniclastic products with a possible limestones lateral equivalent.

North and South Halmahera Basins

Their geological situation as outer-arc basins is comparable to that of the Gorontalo or Bone Basins and confirm the similarities between Sulawesi and Halmahera Islands. With a 2.0 secs (TWT) thickness of deposits below water up to 2000 m deep, the two basins are mainly different in the areal extent, the southern one being about twice as large. Its rhomboidal shape suggests a possible stretching of the deep crust. The type of lithology will be influenced both by the ophiolites and melange of the eastern arm and by the volcanics of the western arm. However, most of the outcrops are consituted by the Mio-Pliocene Tingtong and Weda formations of sedimentary origin.

Structural features exposed on land sometimes can be traced to the offshore.

The deepest strong reflector, corresponding to the top of Mio-Pliocene carbonates illustrates the lateral variation of facies - a carbonate reefal shelf to the southeast with its corresponding basinal area to the northwest. Above this reflector the whole section can be interpreted as fine clastic sequences of Plio-Quaternary age.

East Halmahera Basin

Widespread ultrabasic rocks and Tertiary limestones, sands and shales constitute the source for the infill of the East Halmahera Basin. With approximately 2.0 secs (TWT) thickness of sediments this basin lies partly in moderate water depth. Seismic data suggests the presence of Mio-Pliocene carbonates and of a Plio-Quaternary fine grained clastic series. All these sediments are locally affected by compressional tectonics, exhibiting asymmetrical anticlines.

DEEP-SEA BASINS IN IRIAN JAYA REGION

Salawati Deep

Elongated in a NE–SW direction, it lies south of the Sorong Fault Zone, from Misool to Salawati Island, in water depths between 100 and 1000 m. The total sedimentary thickness over the presumed Permian or older basement rocks reaches 4.5 secs (TWT). Lithology is mainly represented by open marine influenced marls of the Klasafet formation of Upper Miocene age, a lateral equivalent of the Kais carbonates present eastward on the Ajamaru Shelf of Irian Jaya. Coarser detritus are present in the upper part of the section in the molasse-type Klasaman Formation and basal sands are possible along the Sorong Fault, equivalent to the Sirga Formation known to exist in the onshore extension of the basin.

Rich total organic carbon percentages are reported in the basinal shales whose degree of maturity attains that of oil generation. They have provided the oil trapped in the onshore Salawati fields and migration is still active (oil seeps). Numerous shale diapirs created domal-shaped structures or, more commonly, elongated anticlines often bounded by faults parallel to the Sorong Fault Zone. Turtle-back features with potential as traps are also present.

Kepala Burung Foredeep

In the Kepala Burung foredeep, plunging southwards to the Seram Trough, thick Mesozoic and Tertiary series are potential objectives for exploration (Fig. 6). The existence of sands and sealing rocks in a predominantly carbonate environment, is expected.

Strongly eroded on the onshore or shallow water Misool-Onin Kumawa ridge, the series are thought to be complete in the prominent structures present on the slope in a foredeep position. Water depths do not exceed 500 m south of Onin and about 1000 m between Misool and Onin.

Aru Trough

The large Arafura Platform on the east plunges to the Aru Trough by successive step-faults (Fig. 7). A very recent age is inferred for the formation of the Aru Trough as no thickness of the Mesozoic and Tertiary series up to late Neogene is observed on seismic sections. During Plio-Pleistocene times, very thick sediments, as much as 4.0 secs thick, accumulated in the trough.

Beyond the 200 m bathymetric contour, Mesozoic and Tertiary are still accessible and prospective in the areas where block-faulting is developed and provides traps. The objectives are mainly the clastics of the Kembelangan Formation and the Tertiary carbonates. Recent Tertiary deposits should be considered as they can either generate hydrocarbons in the deepest part of the trough or trap petroleum migrating from the underlying formations.

South Arafura Foredeep

To the south of Tanimbar Island a triangular shaped area lying in water depths between 200 and 1000 m can be considered as the prolongation of the Calder Graben in the Australian waters. There, Cenozoic and Cretaceous sediments gradually thicken northwestward from a shelf area to a more basinal region. Simultaneously, the older Mesozoic beds abruptly thicken onto the so-called Calder Graben northwest of a SW–NE structural feature interpreted as a hinge-zone. In this entirely marine section Jurassic and Cretaceous reservoirs are possible objectives.

Offshore Waipoga-Cendrawashih Bay

From shallow offshore and onshore data the prospective series are represented by the Makats and Mamberamo Formations of Middle Miocene to Recent age. They consist of a dominantly shaly sequence with intercalations of coarser clastics better developed in the southern part

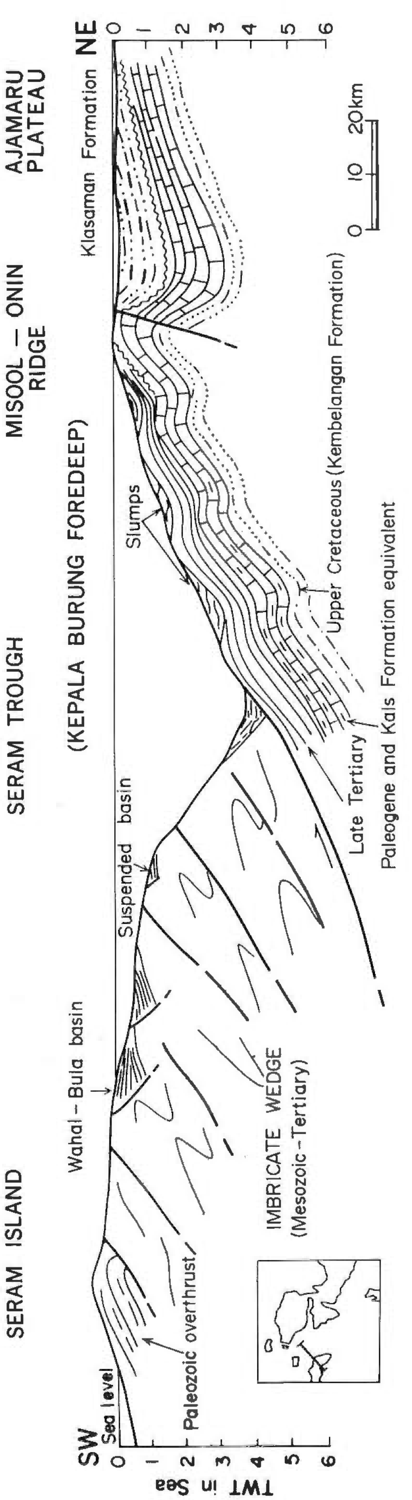

Fig. 6. Seram-Kepala Burung cross section.

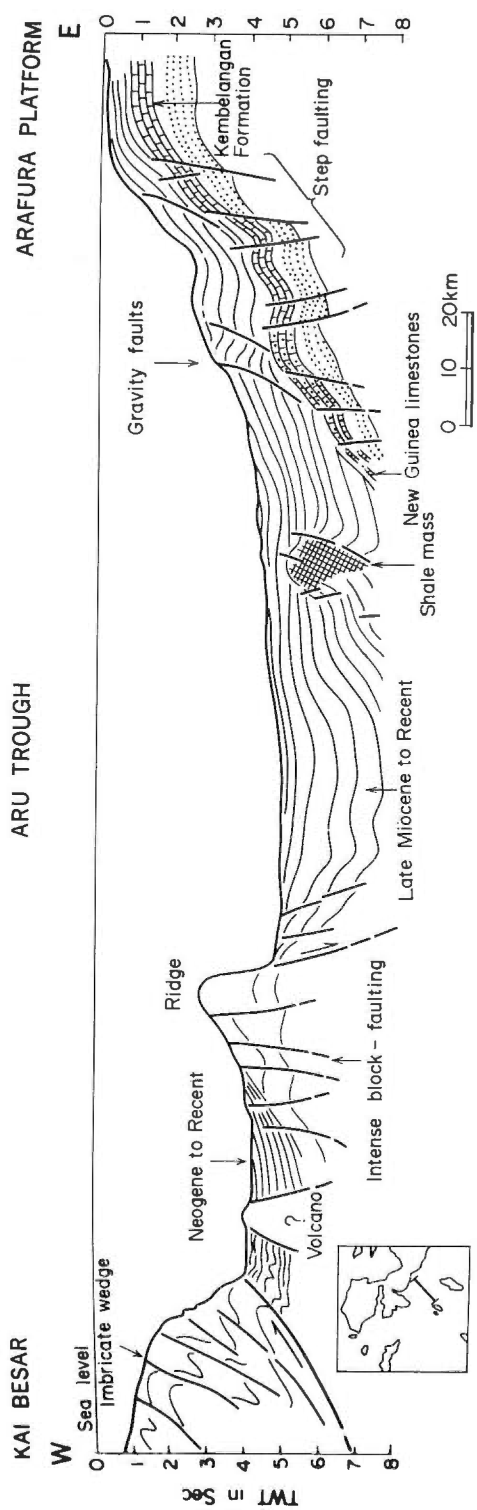

Fig. 7. Aru trough cross section.

of the bay where they were sourced partly from quartzose rocks. The total sediment thickness above economic basement reaches 4.5 secs in the shallow water offshore Waipoga Plains area but they are still 3.0 secs thick in the Cendrawasih Bay north of Nabire.

The water depth is less than 1000 m in the southern part of the bay where shale diapiric structures are likely to exist together with other tectonic deformation in the area close to the Central Range.

Deep Waropen-Jayapura Basins

Depocentres down to 2.5 secs below sea bottom exist in the deep offshore area where flat-lying sediments overlying the oceanic crust are interpreted to be Oligocene to younger in age (Hamilton, 1978). They are sharply bounded to the south by south-dipping reverse faults corresponding to a possible trace of a Benioff subduction plane where the Pacific crust plunges beneath continental Irian Jaya.

GENERAL CHARACTERISTICS OF THE DEEO-SEA BASINS

The estimate of the thickness of sedimentary infilling of basins, the interpretation of tectonic deformation can generally be determined with reasonably certainty from seismic record sections.*

The lithology of the deposits and their depositional environment can be inferred from the nature and distance of the emerged lands. But some parameters are still unpredictable without direct information. These are, for example, the age of the deposits or their organic content, the knowledge of which will be much improved when a few deep-sea (DSDP) wells are drilled in the Banda Sea or the Makassar Strait.

Very distinct and different characteristics are predicted for basins located far from emerged lands in contrast with characteristics of basins bounded to the presently positive areas with, occasionally, an onshore extension.

Recent Basins, Marginal to Energed Lands

1. The collison process resulted in the creation of positive areas, generally partly or totally emerged like the dual volcanic and nonvolcanic arcs of Indonesia. Consequently to the major uplift in Late Neogene to Recent time, erosion and sedimentation were very active and participate in the creation of numerous basinal areas in the fore-arc, trench or occasionally back arc situation.

   The characteistics of these basinal areas are as follows:

   —They are depocenters with an axis parallel to the emerged land. Examples: Mentawai Basin, Timor Basin.

   —They are relatively narrow depressions, whose lenghth corresponds strictly to the extent of the emerged land. It is evident that the influx of erosional products into the subsiding basins were directly supplied by emerged land. Examples: Buru Basin, North Sula Basin.

   —Margins of the bounding positive areas are abrupt, occasionally faulted flexures on one side of the basin. Those faults have generally acted as synsedimentary movements (e.g. Mentawai Basin bounded by faults on its southern flank). In this

*Remarks

Wherever seismic detection of acoustic basement is not evident, it is possible due to:

—lack of contrast in acoustic impedance between basement and overlying sediments.

—seismic survey field parameters and energy sources suitable only to oil exploration on continental shelves. Therefore, in some areas of deeper waters and considerable thickness of sediments, the deepest reflectors are neither sensitive to velocity variations nor have enough energy to be enhanced by stacking.

—deepest reflectors badly overtaken by coherent and/or non-coherent noise, in the case of single fold data.

case the thickness distribution of the depositis will be strictly controlled by the faults giving an asymmetrical cross section with the axis of the basin closer to the faulted flank. Thus, the thicker sedimentary section is not necessarily located on the flank closer to the source of material.

—Where they are rimmed by faults on two sides, the basins can be grabenlike depressions. Example: South Buru Basin. The thicknesses of the deposits are moderate to substantial in the case of basins bounded by relatively high emerged lands. Example: Sawu Basin with more than 3.0 secs (TWT) of sediments. The thickness is less when the basins are located close to land of small areal extent. Example: Buru or Tanimbar Basins with only 1.5 secs of depositis.

—Lithology of the sediments can be expected as:

- Dominantly clastics. However, deltaic formations would be restricted, sonsidering the small size of rivers on narrow positive lands (except Kalimantan with the Mahakam delta). Location of present rivers can, in certain cases give indications of slight build-up of fans or deltaic deposits in the late Neogene-Pleistocene. But turbidites and molasse-type deposits are expected to be dominant, both sediments are known to be common in furrows along orogenic belts.
- Quartzose clastics and volcaniclastics constitute part of the erosional products depending on the rocks in the onshore provenance; their relative proportion can be predictable. Fine grained material, of volcanic origin, is obviously predominant on both sides of the volcanic arcs.
- Rare carbonates

2. In addition to the lithospheric plate collision process, tensional features can contribute to the creation of a subcategory known as the rhombochasm. Their characteristics are: a distinct elongated geometric shape of broad basinal area bounded by land on two sides, with thick deposits resulting from an intense subsidence related to the tensional movements.

The thickness of deposits exceeds 3.0 secs in the Bone Basin and 4.0 secs in the South Makassar Basin, where the distribution indicates mainly symmetrical basins. There basins are interpreted by some authors as underlain by oceanic crust.

Basins Isolated from Positive Lands

These basins do not necessarily have a distinctive shape: in particular they lack an axial depocentre parallel to an emerged land.

They can be divided in two subcategories:

1. Above oceanic crust.

   Their characteristics are as follows:

   —These basins appear where clearly defined depocentres with axes parallel to emerged land, flatter out and lose their shape. Example: South of Seram, South of Sula, Tukang Besi Basins.

   —The thickness and lithology of the deposits are both related to the distance to the land area but the thickness of sediments is reduced comparatively to those described above.

   —Deep-sea deposition includes ooze, pink to red calcilutites and radiolarian cherts, frequently deposited only as a thin veneer above oceanic crust. This contrasts with the sedimentation rich in clays and sands in depocentres near to emerged lands. Example: this is the typical case in the Banda Sea Basins.

2. Above continental crust shelf.

   Their main characteristic is that these basins normally correspond to a portion of continental shelf that has been foundered (Bali Basin, Tarakan Basin) or is being subducted (Arafura Fore deep of Kepala Burung Fore deep). Consequently, older sediments are found without prominent angular unconformity below the recent deposits.

The complete Tertiary section can be found on the Asiatic continental shelf (Makassar Basins) and further east, on the margins of the Australian continent. Mesozoic and occasionally some Paleozoic also are present in the sedimentary section. Early sedimentation was in a shelf to slope environment without any characteristics of oceanic deposits. In some cases, massive deeply buried clay deposits could have originated or shale diapirism activated by lateral faulting. Example: South Makassar Triangle area, Salawati Deep Basin. An alternative of this configuration is the formation of a rift-like feature over a shelf. Beginning only in the Tertiary, subsidence is contemporaneous with severe tensional faulting on the margins of the depression and is accompanied by rapid sinking of the sea bottom. Example: Aru trough.

PETROLEUM POTENTIAL OF THE DEEP SEA BASINS

Documented only by essentially reconnaissance surveys and drilled only in a few marginal locations, the deep-sea basins remain insufficiently known to assess, satisfactorily, their petroleum potential; comments on hydrocarbon prospects, should generally be considered speculative. In spite of their large size and substantial important thickness of sediments which is favourable to their theoretical potential, only very recently have they been regarded as worth exploration. The areas to be given priority consideration are, obviously, the basins, or parts of the basins, lying in 200 m to 2000 m of water depth. They represent about one third of the total area. Considering this large area, further selectivity can be exercised on the basis of the expected presence of potential reservoirs, source rocks and traps in those moderately deep water areas.

Potential Reservoirs in Clastic Series

The potential of these basins in terms of reservoir is related to the sand percentage in sediments frequently rich in claystones, as well as the proportion of quartzose material vs generally argillaceous volcaniclastics. High sand percentages are to be expected close to emerged lands in the molasse series or littoral type deposits (bar sand, channel fill, etc.). Less strictly related to the proximity of land are transgressive sands, turbidites and deltaic series, the latter being rather restricted due to the limited size of rivers on narrow islands.

Turbidites and molasse sediments are present and more frequent in deep furrows along orogenic belts. Argillaceous martix or beds are unpredictable in amount, but outer-arc basins are examples of largely claystone deposition. Clastic material is likely to by found more fine grained towards the depocenter of the basins. The geometry of the sand bodies is complex. They have appreciable thickness although of generally small lateral extent.

Potential Reservoirs in Carbonates

Basal carbonates, deposited on basement highs, are frequently observed on seismic sections and locally could be interpreted as reefal in origin (example: South Halmahera Basin). Other reefal facies occur frequently in the more recent series (Pliocene, Pleistocene) on the margins of the basins, sometime in the presence of overlying and surrounding seal-rocks.

In deep-sea basins, carbonates are expected to be rare and subordinate to clastic series, except in basins overlying oceanic crust, where deposition is in the form of carbonate ooze, calcilutites and radiolarian cherts.

The two latter deposits are unlikely to present encouraging reservoir properties; some carbonate ooze intervals have been found porous in DSPD 262 in the Timor Trough.

Source Rock Potential

Organic carbon content and degree of maturation of this organic matter are the two main parameters controlling the potential for generation of hydrocarbons. Both parameters should be measured on rock samples, but very few wells have been drilled in Indonesian waters deeper than 200 m, and none for scientific purposes, therefore only speculative ideas can be presented. The great volume of sediments deposited, the high proportion of argillaceous material, and the predominant marine environment are favorable for the presence of an adequate type of organic matter. In some "privileged" continental crust or along continental margins where high rates of deposition are recorded.

Preservations of the organic matter is effective in restricted conditions such as shallow lagoonal or littoral waters or in the basins characterized by sea floor spreading. Conservation conditions are less favorable in depocentres where oxydizing environments prevail. From measurements carried out in other basins in the world it seems that the maturation process begins almost immediately even in very recent sediments. Apart from methane, frequently recorded but which does not indicate maturation processes, heavier hydrocarbons were detected in DSDP cores in the Indian Ocean in Neogene sediments and liquid hydrocarbons in older deposits.

Generations of hydrocarbons is likely in the deep-sea basins and obviously, it would be more effective in the basins with a high rate of burial and high geothermal gradient. The latter type are those located in a back-arc situation where the magmas are known to well-up. The older sediments, of continental origin underlying the recent deep-sea basin can generate and yield hydrocarbons as the evolution of the organic matter is known to be at the mature to overmature stage.

Potential Traps (Fig. 8)

Most of the infill of deep-sea basins consists of recent to very recent sediments as the basins are controlled by recent tectonics, often still active. The paroxymal tectonic event took place late middle Miocene time and older sediments generally underwent strong tectonic deformation. In the case of the melange or of the imbricate wedge they are often lumped into the economic basement. Principal structural features to be seen are thrust faults and even nappes along the collision zone (Timor), lateral shear faults controlling the subsiding zones and bounding the basins (South Sula Basin), and step faulting or block faulting in the foredeeps. They are generally of large amplitude, but they are found in a not-too-intense fracture environment.

In the post-middle Miocene sediments, sometimes called post tectonic for convenience, structural deformation occurred, but to a much lesser degree. Some large and regional fault zones have been rejuvenated up to the present and are even visible on the sea floor (Sula Basin). Anticlines resulting from simple compression (Kepala Burung foredeep) or drag folds created along wrench faults (Spermonde Basin) are known in the recent series in most of the basins. Even some overthrusts are present (south border of Sawu Basin). Other traps are controlled by the pre-middle Miocene structural configuration. They are basement highs with draping, or roll-over along growth faults, often rooted in the underlying series. In these recent series, traps related to deep-seated fault complexes and other structural traps can be considered as favorable for large accumulations. Shale diapirs also constitute interesting potential traps where they created domal structures or traps related to secondary features like turtle bakcs.

The presence of reefs, although localized on subtle highs, is mainly controlled by the water-depth and restricted to the basin margins. Stratigraphic traps are likely as the turbiditic environment corresponds to a very complex arrangement of sand bodies, but delineation of these would be difficult, particularly as the general tendency is for shalingout in the down-dip direction.

CONCLUSION

Except in basins related to an extremely complex melange or in case of extensive volcaniclastic deposits, objectives of exploration do exist in deep-sea basins. From the reconnaissance data presently available, the deep-sea basins seem to provide the basic ingredients for generation,

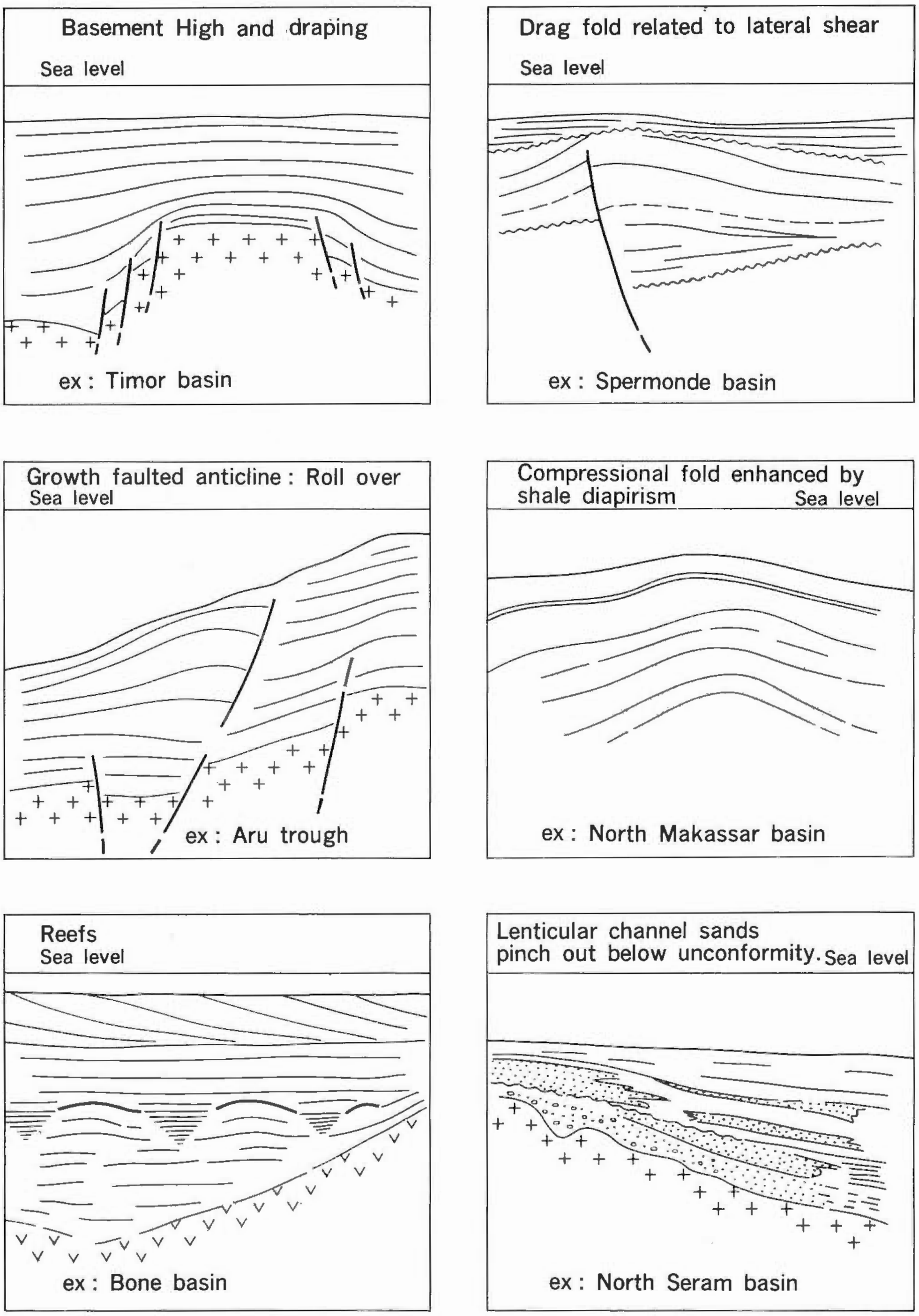

Fig. 8. Examples of traps in deep sea basins.

migration and accumulation of hydrocarbons.

In zones between 200 m and 1000 m of water depth, exploration has already started, and much more effort needs to be devoted to this area. Technology is available, which overcomes the logistic contraints of the moderate deep-sea basins. For the longer term period, in water depths greater than 1000 m, the risks and hazards of exploration must be weighed against the potentially favourable geological characteristics of the vast frontier deep-sea basins.

In the future, when intense exploration of the deep-sea basins is undertaken, the new information will hopefully unlock many secrets and help to solve the geological puzzle of the numerous islands and seas making up the Indonesian Archipelago.

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The idea to make such a study on the deep-sea basins in Indonesia came and was later developed during the preparation of the manuscript for the "Petroleum Potential of Eastern Indonesia", a multiclient study conducted by PERTAMINA and BEICIP.

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Preliminary Report on Characteristics of Coal in Some Continental and Island Arc Region

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ABSTRACT

Interpretation of the coal petrographic results assists preliminary geological and economical evaluation of coal deposits. An attempt is made to infer the coal-forming environment by utilization of coal petrological analyses and to make comparison of coal petrographic analyses with ultimate and proximate analyses throughout the island arc region including Japan, Indonesia and Philippines and continental region including USA, Canada and Australia.

As a result, upper Permian Australian coal was formed under dry conditions or lower water table, and characterized by lower calorific value, volatile matter content and H/C atomic ratio. On the other hand, Pennsylvanian American and Canadian coals were formed under comparatively dry conditions or high water table, and characterized by medium calorific value, volatile matter content and H/C atomic ratio.

Tertiary coals of Australia were formed under little more wet conditions or somewhat higher water table than the upper Permian ones. They show nearly the same properties as the Pennsylvanian North American type within same coal rank. However, Paleogene coals of North America were formed under little more dry conditions than the Pennsylvanian ones. They show nearly the same properties as the Pennsylvanian North American type within same coal rank.

On the other hand, Tertiary coals of the island arcs are quite different from those of both Australia and North America. They were formed under more wet conditions or higher water table, characterized by higher calorific value, volatile matter content and H/C atomic ratio.

INTRODUCTION

During the last few decades, coal petrology, coal science and coal technology developed into independent branches of coal research with both scientific and practical significance. One of the major discovery of coal petrology was that all coals were composed of three major maceral groups. They are vitrinite, exinite and inertinite groups. These groups differ distinctively in both physical properties and chemical composition.

Vitrinite group is the coalification products of humic substances. They are derived essentially from the lignin and cellulose of cell wall. This group is characterized by relatively high contents of aromatic and aliphatic compounds and oxygen. Consequently, vitrinite group is relatively high in volatile matter content and calorific value.

Exinite group is derived from plant remains with relatively high hydrogen content such as sporopollenin, resin, waxes and fats. They are distinguished by higher contents of aliphatic fraction. Consequently, this group is higher in volatile matter content, calorific value and hydrogen content.

Inertinite group is mostly derived from the same original plant substances as vitrinite, but most of the macerals experience a different primary decomposition process. This group is characterized by relatively high carbon, very low hydrogen contents and very high level of aromatization. Consequently, inertinite group is characterized by lower volatile matter content and calorific value.

Special attention should be paid to degradinite. Degradinite is not classified as independent

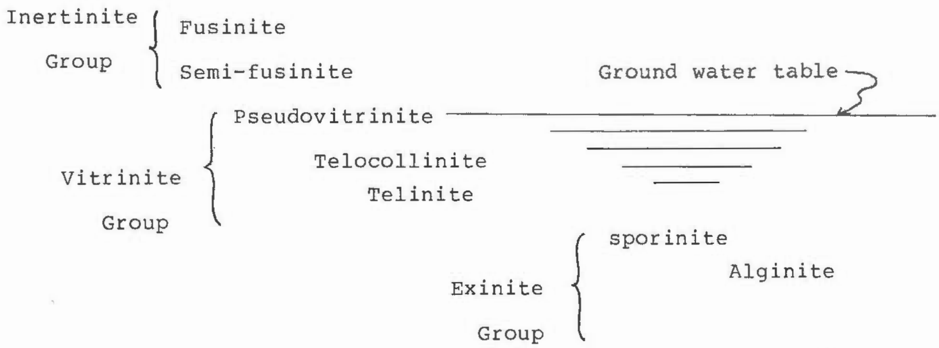

Fig. 1. Relation between dominant maceral type and relative level of water table.

maceral, but it is considered to be a variety of the vitrinite group (STACH *et al.*, 1982). Degradinite is finely dispersed and characterized by low reflectivity, colorful fluorescence, higher H/C atomic ratio, higher alkane content, higher calorific value and volatile matter content compared with other vitrinite macerals. It would be logical to classify degradinite in the exinite group rather than to the vitrinite group (FUJII *et al.*, 1978; FUJII *et al.*, 1982). In this paper the writer will treat degradinite as a variety of macerals of exinite group such as liptodetrinite.

In addition to these chemical properties, it has been pointed out that certain macerals of maceral groups are related to the depositional environment, particularly the water depth which governs the condition for the preservation or existence of original plant substances (TASCH, 1960; TEICHMÜLLER, 1962; HAQUEBARD *et al.*, 1967; SMYTH, 1970; SHIBAOKA and SMYTH, 1975; SPACKMAN *et al.*, 1976; STRAUS *et al.*, 1976; MARCHIONI, 1980; SMYTH and CAMERON, 1982; STACH *et al.*, 1982).

The relation between dominant maceral type and the relative level of water table can be reconstructed as shown in Figure 1 on the basis of the depositional sites of various type of maceral inferred by TEICHMÜLLER (1962) and STACH *et al.* (1982), and study of recent peat deposits by STYAN and BUSTIN (1983).

During various geologic periods, it is expected that each region had unique coal-forming environment. These differences of environment are reflected on the coal properties.

During the Carboniferous period, significant coking coal seams were formed in North America and Eurasia, but not in Australia. During the Permian period, important coking bituminous coal basins were formed throughout Gondowanaland. Mesozoic coals were deposited within each continent in smaller and fewer basins than during the Paleozoic. Significant brown coal and sub-bituminous coal seams of Tertiary period were formed in North America, Australia, Europe and the island arc. Especially, throughout the island arc systems of the West Pacific region such as Japan, Philippines and Indonesia, bituminous coal was mostly formed in Paleogene and brown coal was formed in Neogene.

Based on these facts, this work is an attempt to reconstruct the coal-forming environment and to clarify the relationship between maceral composition and coal properties. It is intended that these results will provide the basis for comparing the characteristcs of island arc coals including Japan, Philippines and Indonesia with those of continental coals including USA, Canada and Australia.

RELATIONSHIP BETWEEN COAL PETROGRAPHY AND COAL PROPERTIES

The auther has studied the Tertiary coals of the island arc system including Japan, Indonesia and Philippines. Also during the past few decades, research on Paleozoic and Tertiary materials was mainly carried out in USA, Canada and Australia (SWARTZMAN, 1953; HACQUEBARD *et al.*, 1967; SMYTH, 1970; SHIBAOKA and SMYTH, 1975; GIVEN *et al.*, 1975; TRAVES and KING, 1975; GUYOT and CUDMORE, 1975; SPACKMAN *et al.*, 1976; DAVIS *et al.*, 1976; MITCHELL *et al.*, 1977; GIVEN *et al.*, 1980; MARCHIONI, 1980; FLEMING, 1982; SAPPAL, 1982 and CHAO *et al.*, 1982).

MACERAL COMPOSITION AND COAL-FORMING ENVIRONMENT

The results of maceral analyses are plotted on ternary diagram, vitrinite, exinite and inertinite, as shown in Figure 2.

There is a definite separation of areas for the continental and island arc coals. Also, concerning continental coals, there is a reasonable degree of separation of the area between Pennsylvanian North American and upper Permian Australian coals with area of overlap at the extremities as was partly pointed out by STRAUSS *et al.* (1976).

But the area of maceral composition of Tertiary brown coals in North America and Australia is included in the area of the Paleozoic coals in North America.

In the light of the maceral composition, the coal-forming environment can be reconstructed as follows. Maceral composition of the upper Permian Australian coals which are rich in inertinite and very poor in exinite indicates that these coals were formed under dry conditions or low water table (SHIBAOKA and SMYTH, 1975; STRAUSS *et al.*, 1976; STACH *et al.*, 1982).

The Pennsylvanian coals in USA and Canada are characterized by lower content of inertinite and higher content of virtinite with some amount of exinite (KULWEIN and HOFFMAN, 1952 in STACH *et al.*, 1982). The coals were formed under higher water table or rather wet conditions compared with the conditions of the upper Permian coals in Australia.

Tertiary brown coals in Australia have higher vitrinite content and lower inertinite content than upper Permian coals. This indicates that the Tertiary coals were formed under wetter conditions or higher water table than the upper Permian coals. Paleogene coals of North America are characterized by the lower exinite content than the Pennsylvanian coals. This indicates that the Paleogene coals were formed under drier conditions or lower water table than the Pennsylvanian material.

On the other hand, Tertiary coals in island arc are characterized by the highest vitrinite

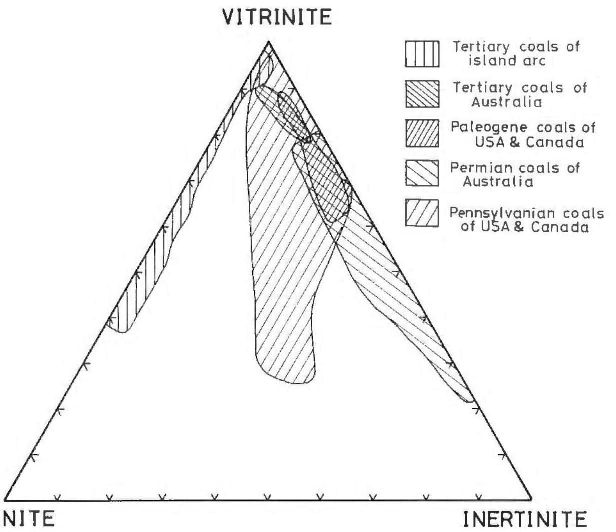

Fig. 2. Maceral composition of coal in island arc region and continental region.

content with some degradinite or exinite and extremely small amount of inertinite. In terms of coal-forming environment, such coals were formed under very wet conditions or high water table.

MACERAL COMPOSITION AND CHEMICAL PROPERTIES

The relationship between maceral composition and two coal properties of practical importance, i.e., volatile matter content and calorific value, is given first because they are important parameters for coal classification by dry-ash free basis. Thus, it is convenient to use volatile matter content versus calorific value diagram for comparison of coal properties.

Usually the volatile matter content decreases with increasing coal rank, in other words, increasing vitrinite reflectance. But the calorific value increases with increasing coal rank (STACH *et al.*, 1982).

In volatile matter content versus calorific value diagram as shown in Figure 3, the theoretical path of change of both volatile matter content and calorific value of coals crosses virtinite reflectance lines diagonally from the bottom of the left to the top of right during the advance of coalification. Coals of the same coal rank are along or parallel to a constant vitrinite reflectance line.

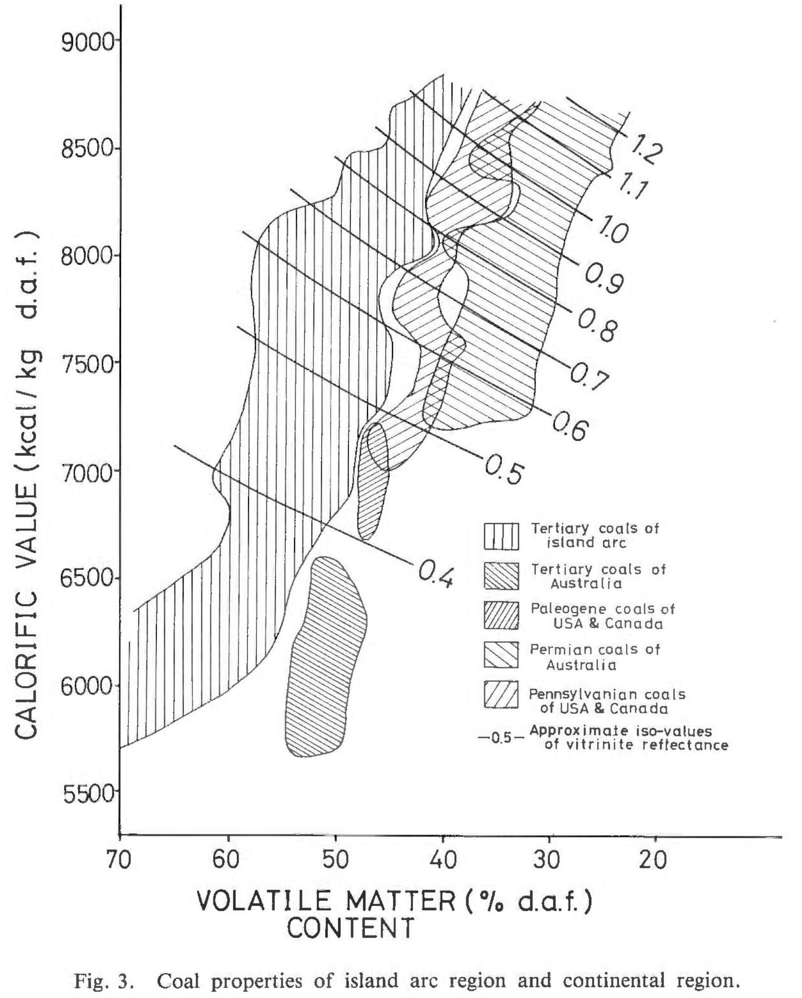

Fig. 3. Coal properties of island arc region and continental region.

First of all, there are five recognozable groups which are well separated from each other with some areas of overlap (Fig. 3).

Among coals with the same rank, the upper Permian coals in Australia have the lowest volatile matter content and calorific value because their maceral composition is characterized by higher inertinite content. On the other hand, island arc coals have the highest volatile matter content and calorific value which reflect the larger amount of degradinite or exinite. Pennsylvanian American and Canadian coals have intermediate volatile matter content and calorific value due to the higher vitrinite and lower inertinite contents.

Paleogene North American coals show the same tendency as the Pennsylvanian coals, but the area of Tertiary coals in Figure 3 partly overlaps that of the Pennsylvanian coals. Also the calorific value and volatile matter content of Pennsylvanian and the upper Permian Australian coals partly overlap in the above diagram. This reflects the fact that maceral composition of the Pennsylvanian coals partly overlaps the upper Permian Australian coals area.

RELATIONSHIP BETWEEN MACERAL ANALYSES AND CHEMICAL PROPERTIES

A very simple and rapid method for clarifying the chemical reaction during coalification is to use H/C-O/C atomic ratio diagram. This plot was first used by van Krevelen (1961) to characterize coals and their coalification paths.

In this diagram (Fig. 4), five groups are recognizable. The upper Permian Australian coals are characterized by lower H/C atomic ratio due to the higher inertinite content. On the hand, Pennsylvanian North American coals are characterized by intermediate H/C atomic ratio due to the mixture of vitrinite and inertinite with smaller amount of exinite.

Island arc coals are characterized by the highest H/C atomic ratio due to the largest amount of vitrinite and some degradinite or exinite. Brown coals of both North America and Australia are chemically similar to the Pennsylvanian North American coals due to their similar maceral

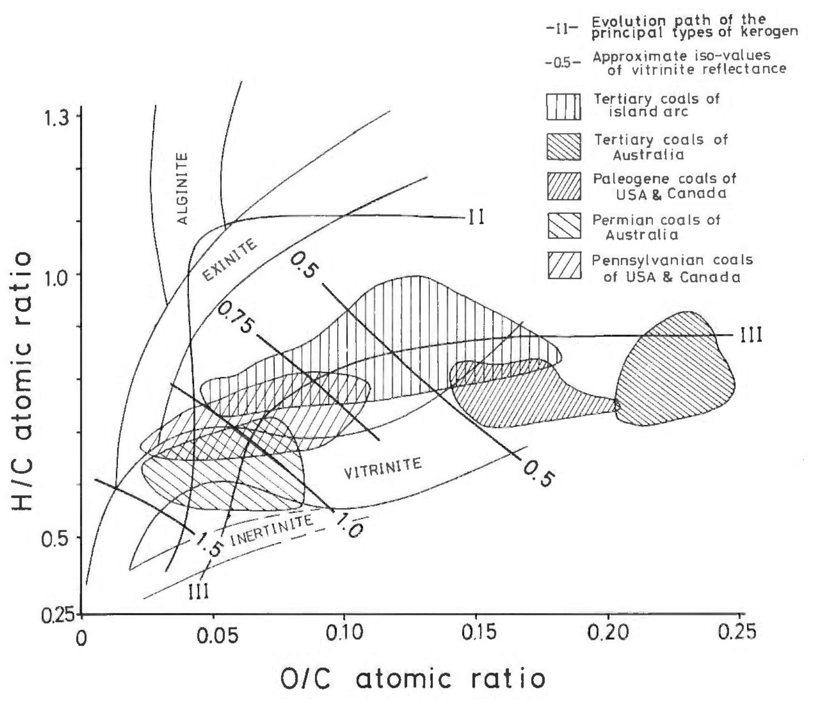

Fig. 4. Chemical properties of coal of various ages in island arc region and continental region.

composition, but advanced coalification of the Pennsylvanian coals compared with the brown coals results in a slight decrease of H/C and a marked decrease of O/C atomic ratios.

SUMMARY AND CONCLUSION

Maceral or maceral group is closely related to the coal-forming environment and has its own specific chemical and physical properties.

The result of maceral analyses were examined to reconstruct the coal-forming environment and to compare the maceral composition with coal properties throughout the island arc region including Japan, Indonesia and Philippines, and the continental region including USA, Canada and Australia.

The upper Permian Australian coals are rich in inertinite and very poor in exinite. This indicates that they were formed under dry conditions or in areas of lower water table. This accounts for the lower calorific value, volatile matter content and H/C atomic ratio.

The Pennsylvanian American and Canadian coals are lower in inertinite and higher in vitrinite content with some exinite. This indicates that they were formed in areas with higher water table or under rather wet conditions which accounts for intermediate calorific value, volatile matter content and H/C atomic ratio.

Tertiary brown coals in USA, Canada and Australia are higher in vitrinite and lower in inertinite content. This indicates that they were formed under slightly wetter conditions or in areas of higher water table than the upper Permian Australian coals. This accounts for nearly the same coal properties as the Pennsylvanian North American coals.

The Tertiary coals of island arcs have the highest vitrinite content and are extremely poor in inertinite. This shows that they were formed under wet conditions or in areas of higher water table and accounts for higher calorific value, volatile matter content and H/C atomic ratio.

As for areas of future research it will be very important to clarify the physical and chemical properties, and genesis of degradinite. Degradinite has not been internationally classified as an independent maceral. It has been considered to be peculiar to the Japanese coals, but it was discovered in the Philippines and Indonesian coals.

As is evident from the preceding discussion, the Japanese coals shows higher calorific value and volatile matter content due to the comparatively high content of degradinite which is chemically and physically close to the exinite group (FUJII *et al.*, 1978; FUJII *et al.*, 1982). Whereas genesis of degradinite has not been clarified.

Thus, it is considered that the study of the relationship between maceral composition and coal properties and the clarification of the properties and genesis of degradinite of the coals of the island arc region will provide important basic data for the understanding and efficient utilization of coal.

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IV. Mineral Resources

Chairman T. SATO

1. Granitoid Series and Mo/W-Sn Mineralization in East Asia.
2. Geology and Tectonic Setting of Copper and Chromite Deposits of the Philippines.
3. The Geology and Economic Significance of Tin Deposits in East Malaysia.
4. Tungsten and Molybdenum Ore Deposits in South Korea.
5. Carbonatites and Associated Mineral Deposits in Brazil.

Geological Survey of Japan Report, No. 263, 1984, p. 173–208.

Granitoid Series and Mo/W–Sn Mineralization in East Asia

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ABSTRACT

Classification and genesis of magnetite-series/ilmenite-series granitoids are reviewed and applied to Mesozoic and Cenozoic granitic terranes of eastern China, southern Korea, southern Sikhote Alin and Japanese Islands. Age of the granitic activities becomes younger in this order from early Mesozoic to late Cenozoic.

In eastern China, the main granitoids of the Yanshanian cycle (190–70 Ma) are different regionally and tectonically. Those in the south are mostly ilmenite-series in the Caledonian folded zone but are largely magnetite-series in the coastal fracture zone. Related magmatic-hydrothermal ore deposits contain characteristically tungsten and tin in the ilmenite-series granitic terranes but lead-zinc and magnetite in the magnetite-series terranes. In the Lower Yangtze area, mafic, K-rich magnetite-series granitoids occur locally associated with deep lineaments of N-S and E-W directions. Characteristic mineralizations are magnetite and copper. In the north, Yanshanian granitoids occur widely. They seem to be largely magnetite-series including K-poor granitoids. Molybdenum is diagonostic mineralization. The Climax-type porphyry molybdenum may be expected with subalkaline granites along the Qiling Suture. In southern Korea, the main granitic activities and related mineralizations are similar to those of southern China, but tin is almost absent, and tungsten and molybdenum coexist together in the ore deposits. Unilateral variation across the major granitic terranes in these continental margin environments appears to be not as clear as that observed in island arc environment.

In southern Sikhote Alin, the magmatism reveals narrow zoning of magnetite-series/ilmenite-series granitoids and has similarity of island arc setting. Tungsten disappears and subvolcanic tin deposits are present. In the Japanese Islands, magnetite-series/ilmenite-series paired belts are clearly seen. The southwestern block has continental but the northeastern block has intra-oceanic island arc characteritics (ISHIHARA, 1978b). Some detailed reviewing is given to subvolcanic tin deposits of the Akenobe-type in relation to plutonic W-Sn deposits.

Granitic magmatism of the studied region is divided into (i) Jurassic-Early Cretaceous, (ii) Cretaceous-Paleogene, and (iii) Neogene cycles. Each set is constituted by frontal ilmenite-series and back-arc magnetite-series granitic belts. The paired belts are considered as characteristic products of granitic magmatism associated with development of marginal basins. The frontal ilmenite-series granitoids are formed under compressional tectonic setting due to oceanward migration of continental blocks. The back-arc magnetite-series granitoids, on the other hand, are formed by deep-seated magmas ascent through tensional fractures developed along the continental margin of East Asia. Some of the fractured zones may be evolved to marginal basins such as Japan Sea and East China Sea. Based on the analyses of the Mesozoic-Cenozoic granitoids, several stages of opening can be assumed on the present marginal basins, even on inland basins of Northeast China.

Throughout the whole region, tin-tungsten and molybdenum appear to be heterogeneously distributed in the basement, hence the continental crust. The

heterogeneity to meet with ilmenite-series granitic belt defines regionally Sn-W metallogenic provinces. Molybdenum, on the other hand, seems to have diversity of the source from the lower continental crust to the upper mantle, although a majority are considered to be from the crust.

INTRODUCTION

Metallic ore deposits consisting of a wide range of the Archean BIF (banded iron formation) to Quaternary sulfur and gold-silver deposits are known to occur in the vast region of East Asia including eastern China, Korean Peninsula, Sikhote Alin and the Japanese Islands. This region is characterized by extensive plutonism and volcanism of felsic composition of mid-Mesozoic to Cenozoic ages, which generally become younger in age from the continent oceanwards. Thus important mineralizations are related to the igenous activites, as shown in Table 1.

Magmatic-hydrothermal ore deposits have shown characteristic metal variation in connection with nearby granitoid series, as classified in terms of fO_2 of granitic magmas, namely magnetite-series and ilmenite-series granitoids (ISHIHARA, 1977). In the Japanese Islands, mineral commodities of the magnetite-series affiliation are S, Mn, Hg, Au, Cu, Pb, Zn, Mo and magnetite, while those related to the ilmenite-series granitoids are W, Sn, Be, F, Li and pegmatite.

WANG *et al.* (1983) recognized two series of granitoids in the southern part of eastern China; namely, Series I (Nanling series) consisting mainly of biotite granite accompanied by mineralization sequence of REE→Nb, Ta (Li, Rb, Cs), Be, Sn, W, Mo, Bi, As→Cu, Zn, Pb→Sb, Hg, U; Series II (Yangtze series) initiated with dioritic magma and ended with alkaline granite, whereby strong concentration of porphyrite iron ores (magnetite and hematite) is followed by Cu (Au)→Mo (W)→Zn, Pb→Pb (Ag) mineralizations. The metals such as Mo, Cu, Pb and Zn are described in both series. It is interesting to know of concentration factor of these metals and also the total amout of the metals contained in given ore deposits. Besides the quantative examination of the ore deposits, we also need to examine Fe_2O_3/FeO ratios and

Table 1 Type of metallic mineralizations in East Asia.

AGE		E. CHINA (Gue et al. 1982)	S. KOREA (Park 1981)	JAPAN (Ishihara 1978b), Philippines
CENOZOIC	LATE			Au-Ag, Cu-Pb-Zn vein and porphyry types (m MT)
				Sn, W, Cu, Hg skarn and vein (IL)
	EARLY			Mo, Pb-Zn skarn and vein (f MT)
MESOZOIC	LATE	Fe-Cu skarn, porphyry (m MT)	Fe, Cu, W breccia pipe (f MT)	W, Cu, (Sn) skarn and vein (IL)
		Pb-Zn, Au skarn & vein (f MT)	W, Mo, Pb-Zn skarn and vein (f MT)	Cu-Fe skarn, W-Au vein (m MT)
	MIDDLE	W, Sn, REE, Hg, Sb vein & skarn (IL)	Mo-(W) skarn & vein (f MT?)	
	EARLY	Cu, Mo porphyry (f MT) Minor Pb-Zn skarn (do.)	Au vein (IL)	
PALEOZOIC	LATE	V-Ti-Fe, Cu-Ni, Cr etc (mafic rock related)		Basalt hosted $Cu-FeS_2$ (Besshi type)
		Minor porphyry Cu-Mo, Fe-Cu, Pb-Zn skarn & Miss.Valley type		
	EARLY	Basalt hosted(?) $Cu-FeS_2$	Sedimentary U and V	
		Cu-Ni (mafic rock related)	BIF (hematite)	
PROTEROZOIC		Stratabound Cu, Pb-Zn	Graphite, BIF (hematite)	
ARCHEAN		BIF, Algoma type		

Notes: m MT, mafic magnetite series; f MT, felsic magnetite series; IL, ilmenite series opaque mineralogy of the granitoids in those terranes.

The study of the magnetite-series and ilmenite-series granitoids was initiated by finding of a distinct Mo and W metal zonation parallel to the island arc in southwestern Japan. Since these ore deposits occur mostly in granitoids, the host and surrounding granitoids were studied, then distinct difference of Fe_2O_3/FeO ratio and modal opaque minerals were found (ISHIHARA, 1971b). In eastern China, molybdenum deposits occur mostly in the northern half of the continental interior (ISHIHARA, 1978a), but tungsten deposits are strongly concentrated in the southern part. The zonation appears to be unclear in southern Korean Peninsula.

With the above mineralization patterns in mind, Mesozoic-Cenozoic granitoids and related ore deposits of proximal types such as Mo and W (-Sn) deposits are revisited regionally in this communication. Let us review at first, the current thinking of the writer on the genesis of the magnetite-series and ilmenite-series granitoids.

GENESIS OF MAGNETITE-SERIES AND ILMENITE-SERIES GRANITOIDS

The two series of granitoids are easily classified by the bulk Fe_2O_3/FeO ratio (at about 0.5 at granodiorite composition) and the magnetic susceptibility (at about 100×10^{-6} emu/g at granite composition). An intermediate series exists locally (ISHIHARA *et al.*, 1984b). The two series of granitoids in terms of fO_2 of the solidifying magmas can be separated at 10^{-16} at 800°C (CZAMENSKE *et al.*, 1981).

Oxygen fugacity of granitic magmas depend greatly upon their original Fe_2O_3/FeO value, and then on its change during the emplacement. A deep origin magmas from unaltered upper mantle should have a low Fe_2O_3/FeO ratio, but an oxidized upper mantle could exist if we

Table 2 Geneses of the magnetite-series and ilmenite-series granitoids (modified from ISHIHARA, 1982a).

Source and materials	Factors controlling fO_2	Examples
Magnetite-series		
(1) Intrincic oxidized magma Altered oceanic slab, stack of altered volcanics in continental crust	Originally high Fe^{+3}/Fe^{+2} ratio Absence of crustal carbon	Green Tuff, Sanin, Chile, Philippine, Gyeongsang basin
(2) Moderate fO_2 magma Older magnetite-series igneous rocks, C-poor graywacke	Preferential loss of H_2 at high level	Kitakami, (Sanin) Small high-level plutons at many places
Ilmenite-series		
(3) Intrincic reduced magma Upper mantle materials	Originally low Fe^{+3}/Fe^{+2} ratio	Gabbro in Sanin and Hidaka (?)
(4) ditto, Ilmenite-series igneous rocks and/or mixture of igneous and C-bearing sedimentary rocks in continental crust	Originally low Fe^{+3}/Fe^{+2} ratio and reduction by crustal carbon	Ryoke, Sanyo, Hidaka, SW Outer zone (I-type), southern China, Malay peninsula
(5) ditto, Carbon-bearing sedimentary rocks	Reduction by crustal carbon	SW Outer zone (S-type), Australian S-type
(6) Drop-off of roof or wall rocks at high level	Local reduction by crustal carbon	Many places at margin of magnetite-series plutons

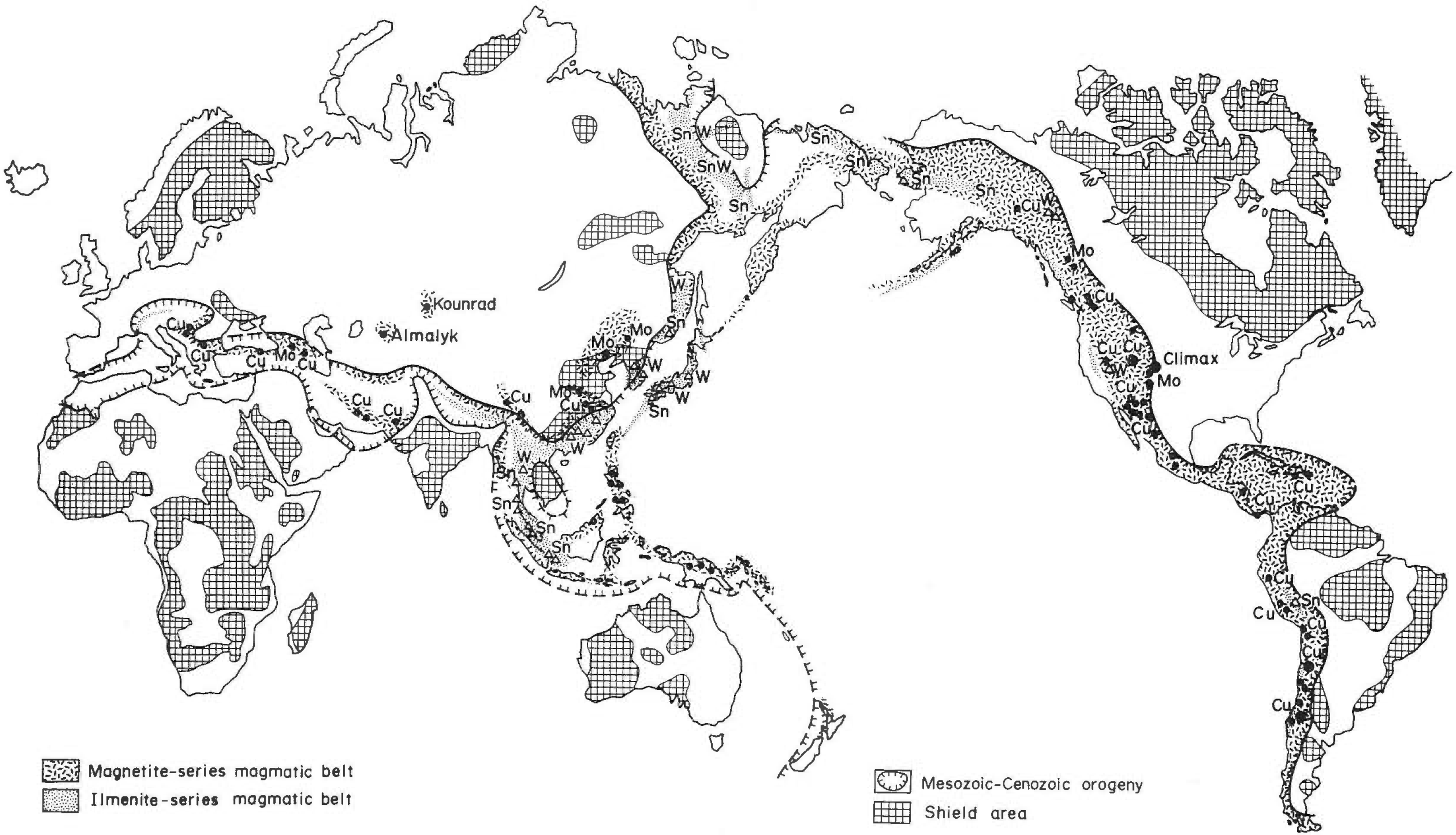

Fig. 1. Distribution of magnetite-series and ilmenite-series plutonic terranes in Mesozoic-Cenozoic orogeny. • Major porphyry-type Cu and Mo deposits; ▵ Sn-W deposits related to ilmenite series, ▴, W deposits associated with magnetite-series granitoids. Two Paleozoic porphyry copper deposits in USSR are also shown.

assume the involvement of altered oceanic slab through subduction processes. Thus even the deep origin magma could sometimes have various fO_2, depending upon the tectonic setting of given magmatic belts (Table 2).

Continental source magmas may have even more variety in the original Fe_2O_3/FeO ratio. Altered volcanic pyroclastics are highly oxidized; andesite and dacite of Tanzawa Mountain, for example, averages Fe_2O_3/FeO ratio of 0.8, whereas black slates containing carbonaceous materials are very much reduced everywhere and the carbon contents are not uniform in the sedimentary rocks (TERASHIMA *et al.*, 1981).

A given magma may change its Fe_2O_3/FeO ratio during the ascent by interaction with sedimentary wall rocks (ISHIHARA, 1977). The magmas emplaced during collision of two continents that contain pelitic rocks or intruded into accretional prism under the compressional tectonic setting appear to have better opportunity to react with the wall rocks; thus reduced, whereas the magmas ascending along fracture zones developed under a tensional tectonic setting may have less opportunity to interact with the wall rocks; thus providing magnetite-series magmatic belts.

Oxygen fugacity of intruded magmas may also change at the final stage of the solidification by drop-off of C-bearing pelitic rocks (10–20%) into the magma chamber (SATO and ISHIHARA, 1983), or preferential loss of H_2 after the liberation of water from the silicate melts and dissociation of the water (CZAMENSKE and WONES, 1973). The former case of reduction of magmas may be local except for katazonal granitoids. The latter case of oxidation is not clearly observed on high-level plutons of the ilmenite series but is sometimes seen on those of the magnetite series (e.g., mineralized stocks of the Green Tuff belt, Japan and Ninwu Basin, China, and Masanite in southern Korea). This case may be also local oxidation phenomenon at the top of small plutons. Individual examples are listed in Table 2.

TYPE EXAMPLES OF MINERALIZATION

Mineralization control of the magnetite-series/ilmenite-series granitoids is quite obvious world wide, especially along the Circum-Pacific orogenic belts (Fig. 1). Porphyry copper deposits with trace amount of Mo or Au are representative of the magnetite-series granitic terranes. Magmatic-hydrothermal magnetite deposits such as porphyrite iron ores in the lower Yangtze River area (Ninwu Research Group, 1978), manto-type iron deposits and El Laco magnetite flow in northern Chile (OYARZÚN and FRUTOS, 1984), magnetite skarn at Kamaishi, Japan,

Table 3 Environmental characteristics of the two representative, magmatic-hydrothermal ore depsoits (after ISHIHARA, 1982a).

Selected items	Cu-Mo deposits	Sn-W deposits
Related granitoids	Magnetite-series	Ilmenite-series
Rock composition	Tonalite-granite	Granite
Breccia pipe	Common	Rare-none
Pegmatite cap	None	Common("Stockscheider")
Orebody	Large vertical extent (1-3 km)	Small vertical extent (100-300 m)
Vertical-lateral zoning	Clear	Unclear
Phyllic alteration	F-Li poor (sericite-quartz-pyrite)	F-Li rich (zinnwaldite-topaz-quartz)
Environment	Shallow and violent	Deep and quiet

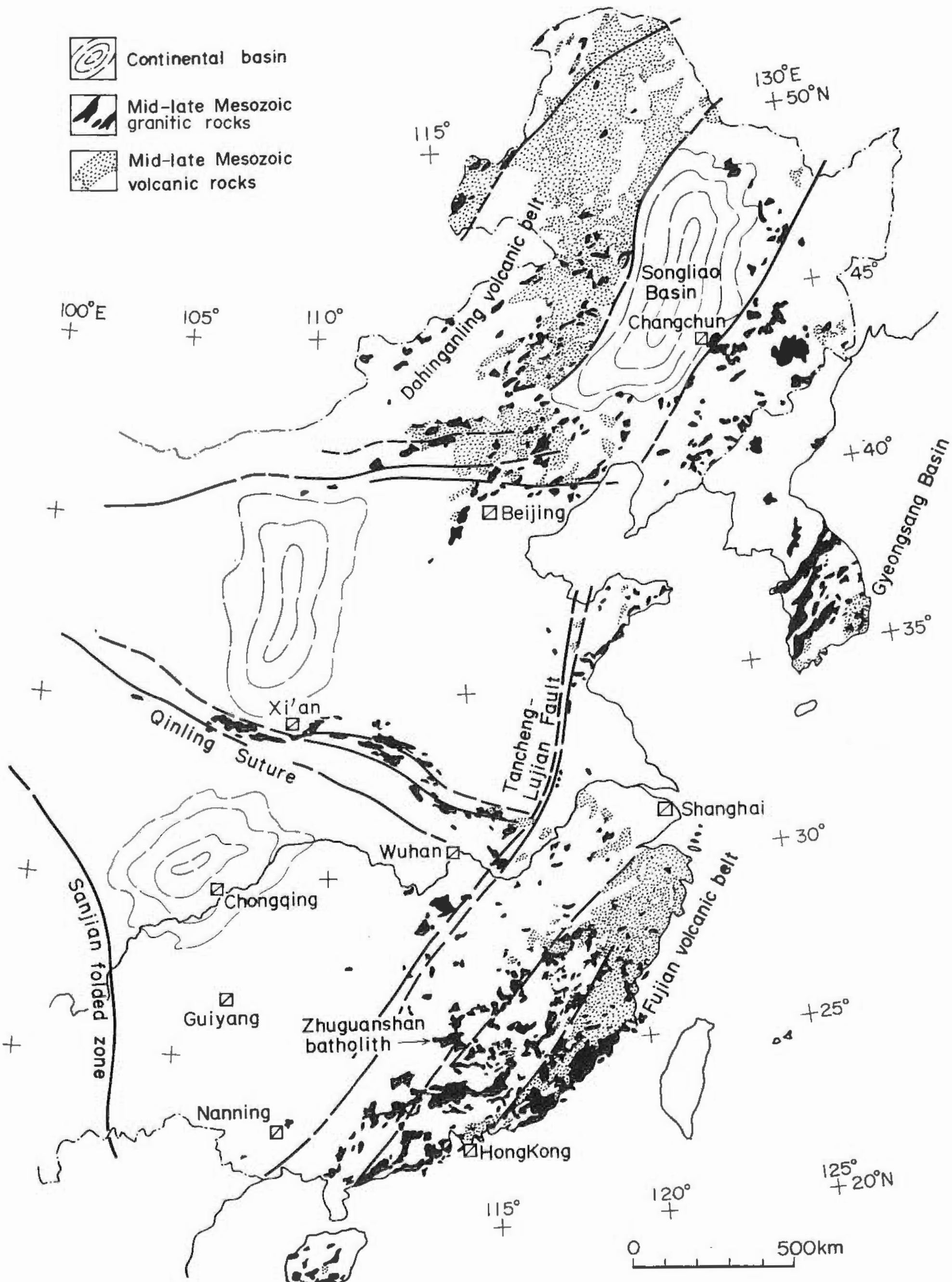

Fig. 2A. Distribution of the Yanshanian volcanic and plutonic rocks and major faults in the eastern China and Korean Peninaula (simplified from HUANG edited 1979 and LEE, 1979).

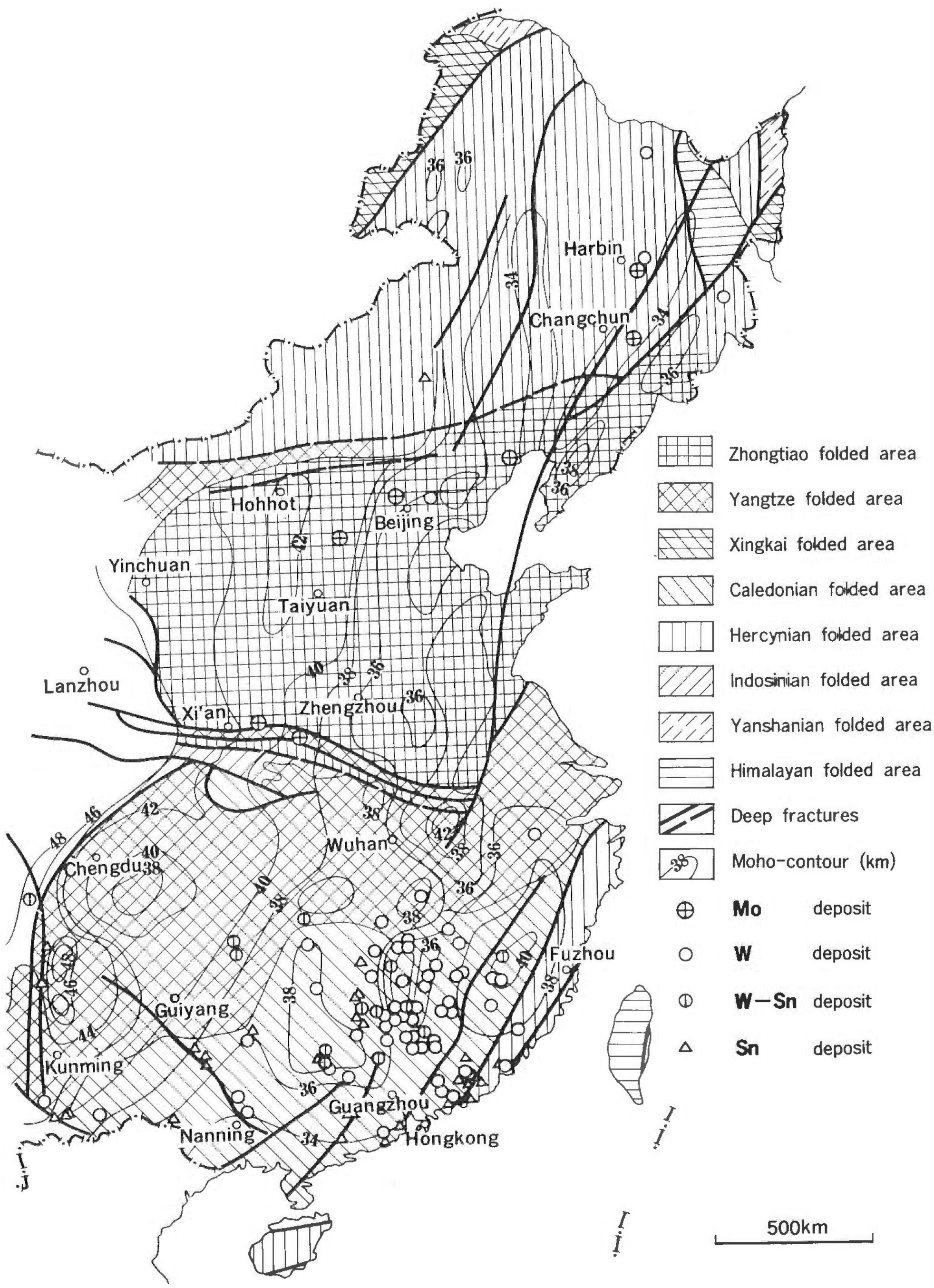

Fig. 2B. Major geologic units and molybdenum, tungsten and tin deposits of the eastern China (after GUO, 1982).

as a matter of fact, all occur associated with the magnetite-series plutonic and volcanic rocks. Porphyry molybdenum deposit is also in this category but the Climax type has an intermediate nature for the high contents of F, W and Sn.

Typical ore deposits related to the ilmenite-series granitoids are plutonic-type Sn-W deposits, which are commonly associated with greisenization. Subvolcanic-type Sn deposits in Bolivia, Akenobe, Japan and Sikhote Alin, USSR, occur in areas where the two series of granitoids are present together. Tin-free tungsten deposits are found in both magnetite-series and ilmenite-series granitic terranes (SATO, 1982; ISHIHARA, 1982b). As far as the past production and remaining ore reserves are concerned, however, ilmenite-series wolframite and scheelite deposits are the most important tungsten resources. Some large ore deposits also occur in the magnetite-series granitic terranes (SATO, 1980, KWAK and WHITE, 1982).

Representative examples of the two series of mineralization are given in Table 3. This characteristic difference between the two series is the result of different original chemistry and different mode of emplacement of the magnetite-series and ilmenite-series granitic magmas.

EASTERN CHINA

Geotectonic units of China is largely controlled by E-W faulted-fold system parallel to the Himalayan suture and NE-rift or fractures (GUO *et al.*, 1982). Eastern China here is defined as the eastern coastal area where the NE-lineaments prevail. Mesozoic granitoids and cogenetic volcanic rocks are widely distributed in the area (Fig. 2), and its southern half is well studied (Guiyang Institute of Geochemistry 1979, MO, YE *et al.*, 1980; Nanjing University, 1981).

The granitic activities of the southern part, south of the Yangtze River, are seen since Precambrian but mainly from mid-Paleozoic onward, and are divided into several cycles as Early and Late Caledonian, Hercynian, Indo-Sinian (Triassic), Early Yanshanian (Jurassic) and Late Yanshanian (Cretaceous). Although the activities become younger oceanward very generally, overlapping of granitic activities appear to be characteristic of the area, as compared with that in the island arc setting such as Japan and Chile (ISHIHARA *et al.*, 1984c).

Precambrian, Sipu (1550–1695 Ma) and Xuefengian (830–990 Ma) granitoids are mainly granodiorite (HSU *et al.*, 1980) and mineral separation study of Guiyang Institute of Geochemistry (1980) indicates less than 110 ppm of magnetite, thus they appear to be all ilmenite-series but generally I type of CHAPPELL and WHITE (1974). These granitoids are distributed in the continental interior. Caledonian (350–170 Ma) granitoids are mainly granite associated with migmatitic granite and are largely of the ilmenite series. Hercynian (230–280 Ma) and Indo-Sinian (200–230 Ma) granitoids are also composed mainly of ilmenite-series granite. Several chemical parameters of the granitoids are given in Fig. 3. Typical S-type ilmenite-series granite occurs in Darongshan area, while typical I-type magnetite-series granitoids may be seen in the Lower Yangtze area.

Hercynian Darongshan granite

According to MO, YE *et al.* (1980), the Darongshan granitic complex, located in the southeastern part of the Guangxi Zhuang Autonomous Region, occurs as a large batholith of 6450 km^2 in area, stretching in NE-SW direction. Four intrusive stages are recognized: I, Cordierite-biotite granite; II, Fine-grained garnet-cordierite-biotite granite; III, Hypersthene granite porphyry; IV, Hypersthene granophyre.

Common ferromagnesian minerals are biotite (2–20% by volume), cordierite (generally 1–5%, 5–10% close to the wall rocks or xenolith), garnet (up to 3%), hypersthene (up to 10%) and muscovite (up to 2%). Sillimanite and andalusite occur rarely. The biotite has $Z \doteqdot Y$

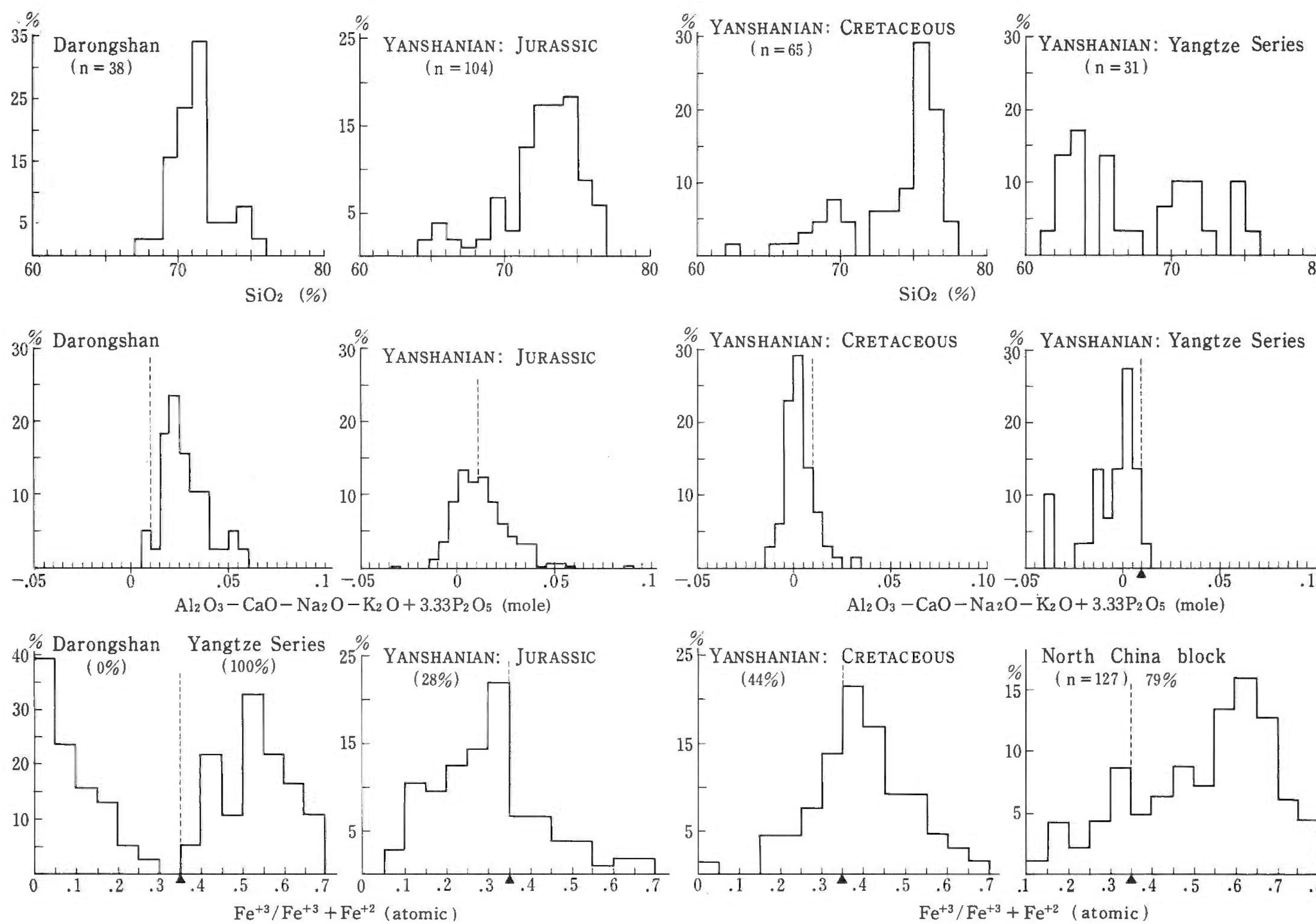

Fig. 3. Selected petrochemical data for the Mesozoic granitoids of the eastern China (compiled from ISHIHARA and SATO, 1982). Triangle (▲) with vertical broken line in the $Fe^{+3}/Fe^{+3}+Fe^{+2}$ (atomic) diagram is the separation of ilmenite-series and magnetite-series granitoids. Percentage of the magnetite-series by number of analyses is also shown. Data of the North China block from GUO (1982).

color of reddish brown with high refractive index and low $Fe_2O_3/(Fe_2O_3+FeO)$ and $MgO/(MaO+FeO)$ ratios. The bulk magnetite contents are less than 100 ppm.

These granites are typical S-type ilmenite series and are probably originated from upper continental crust including the surrounding Paleozoic sedimentary and metamorphic rocks. No mineralization is associated with the granites.

Yanshanian Granitoids in the South

Yanshanian (195–70 Ma) granitoids are most widely distributed in the southern part of eastern China. Their tectonic setting can be briefly divided into two as follows. In and around the famous Nanling Range, Early Yanshanian (Jurassic) granitoids occur mainly in the Caledonian folded zone of lower Paleozoic sedimentary rocks. They seem to have intruded into a compressional tectonic environment. These granitoids are classified as transformation type (formed by anatexis) by HSU *et al.* (1980) or Nanling series by WANG *et al.* (1983), and are associated with the famed W-veins at Xihuashan and other localities, and with huge W-skarn at Shizhuyuan (see HEPWORTH and YU eds., 1982).

Late Yanshanian (Cretaceous) granitoids occur mainly in the coastal, Fujian volcanic belt, where late Mesozoic volcanism and plutonism were preceded by the development of sedimentary basins. Thus the magmatism occurred in a tensional environment. It is said that the granitoids are more mafic than those of the Nanling series (HSU *et al.*, 1980). They are of the syntexis type (mixed magmas from the upper mantle and continental crust) of HSU *et al.* (1980) or the Yangtze series of WANG *et al.* (1983). Some Pb-Zn and Fe (Makeng type) ore deposits are distinct here but mineralization is rather weak associated with this magmatism (GUO *et al.*, 1982; KOUDA, 1983).

MO, YE *et al.* (1980) described the above-mentioned granitoids distributed in lat. 22–27°N in detail. They divided the Yanshanian granitoids into 8 substages as listed in Table 4. Substage 1 granitoids are widely exposed including the huge batholith of the Zhuganshan South body (more than 3000 km^2 in area). Main rock type of this substage is biotite granite but is partly hornblende-bearing biotite granite. Average magnetite content as determined by weighing after the mineral separation is 414 ppm (Table 4), which is much below the upper limit for ilmenite-series granitoids of 1000 ppm. Major chemical data are available on 16 bodies. Using the bulk $Fe_2O_3/(Fe_2O_3+FeO)$ criteria to classify magnetite-series/ilmenite-series granitoids, 13 bodies fall in the ilmenite-series category. Thus the granitoids of this substage belong mostly to the ilmenite series.

Substage 2 granitoids are usually small in size and occur as stock (less than 100 km^2 in area). Xihuashan (20 km^2) and many other W-mineralized stocks belong to this substage. The main rock type is biotite granite but is partly muscovite (1–3%)-biotite (3–5%) granite. Very small ones (1–5 km^2) are often albitized and contain muscovite and Li-micas (3–30%) and topaz (up to 5%). Granites of this substage appear to be all ilmenite series by the Fe_2O_3/FeO examination (Table 4).

Substage 3 granitoids range from quartz diorite to granite but generally granodiorite. They contain biotite, hornblende and also magnetite (Table 4), and seem to belong to the magnetite series. Substage 4 granitoids occur widely and are best represented by the largest, Fogang batholith (5000 km^2 in area). This batholith is mainly composed of biotite granite and contains hornblende in some parts. Some small plutons (50–200 km^2) are composed of muscovite (1–3%)-biotite (4–5%) granite. Xingluokeng W-veins (155 Ma) and disseminations are products of this substage.

Cretaceous granitoids are small in the exposed area relative to the Jurassic granitoids, but are variable in composition and texture. Besides, the Cretaceous granitoids are associated with voluminous amounts of coeval volcanic rocks. Substage 5 granitoids are hornblende-biotite granodiorite with local quartz diorite. Substage 6 granitoids consist of many small to intermediate plutons (less than 420 km^2) and are mostly biotite granite, which contains hornblende or

Table 4 Yanshanian granitoids of southeastern China between lat. 21–27°N, compiled mostly from Mo, Ye *et al.* (1980).

Age	Stage		Exposed area (km^2)	Number of body	Hb-bt Gd	(Hb-)bt granite	Biotite granite	Two-mica granite	K-feld. granite	Avg. mt content	Mt/Ilm ratio*7
EARLY YANSHANIAN (Jurassic)	Early stage (195–160 Ma)	Substage 1	15277	19	0	0	19	0	0	414	3/13
		2	367	17	0	0	12	2	3*1	n.g.	0/9
	Late stage (160–135 Ma)	Substage 3	2174	24	14	10	0	0	0	4264	8/3
		4	43400	62	0	0	59	3*2	0	934	8/18
			61218	122	14	10	90	5	3		19/43
LATE YANSHANIAN (Cretaceous)	Early stage (135 Ma-	Substage 5	1615	9	9	0	0	0	0	14302	5/1
		6	4650	45	0	11	34	0	0*3	n.g.	19/7
	Late stage -70 Ma)	Substage 7	915	9	0	0	0	0	9*4	2374	13/5
		8	411	10	0	0	7*5	0	3*6	n.g.	8/1
			7591	73	9	11	41	0	12		45/14

*1 Including albitized granite. *2 Including one body of granite porphyry. *3 Some albitized granite
*4 Including 6 bodies of drusy granite. *5 Porphyry. *6 Including one body of quartz syenite. *7 Ratio of magnetite-series/ilmenite-series granitoids by number of granitic bodies, as identified by the bulk Fe_2O_3/FeO ratio by the writer.
Abbreviation: Hb, hornblende; (Hb-), hornblende bearing; Bt, biotite; Gd, granodiorite; K-feld., K-feldspar; Avg, average; Mt, magnetite; Ilm, ilmenite; n.g., not given.

muscovite in some parts. Muscovite (less than 3%)-biotite (1–5%) granite is present in the apical part of the biotite granite. The granite may be albitized and contain topaz up to 1.5%. Some W ore deposits (e.g., Daqishan) are associated with the albitized granite.

Substage 7 granitoids are characterized by drusy, alkaline granite. This granite is leucocratic (biotite less than 2%) and may contain alkali amphiboles. Substage 8 granitoids are small in exposure (less than 90 km^2) and are alkaline granite porphyry. Thus the granites of the last two stages are considered to have intruded at very high level.

The Cretaceous granitoids contain abundant magnetite in many cases. They are dominantly high silica rocks similar to the Jurassic granitoids (Fig. 3), but are different because of the general magnetite-series character (Table 4). Iron (Makeng type) and Pb-Zn ore deposits appear to be related to the magnetite-series granite and porphyry.

Yanshanian Yangtze-series Granitoids

Yanshanian igneous activities are seen in limited places along the E-W trending Yangtze folded belt. The plutonism is most severe in volcanic basins where the depression began since Triassic time. The individual basins are controlled generally by NE-fracture system parallel to the Tancheng-Lujian Deep Fault (Fig. 2). High-K andesite erupted in early Cretaceous and, with increasing K_2O content or decreasing Peacocks' alkali-lime index from 55 to 48, the volcanism ended by eruption of phonolite and alkali trachyte (Ninwu Research Group, 1978). Thus the volcanic rocks are more potassic than those of the Fujian volcanic belt.

Plutonic rocks are associated with each phase of the volcanism. They are small stocks ranging in composition from diorite to alkaline granite. The granitoids have a broad peak on the SiO_2 content (Fig. 3), which is quite different from a sharp symmetrical peak of the Darongshan S-type ilmenite-series granite and asymmetrical peaks of the Yanshanian granitoids of the Nanling Range region and Fujian volcanic belt. The Yangtze-series granitoids are considered also as the syntexis type by Hsu *et al.* (1980) and are type example of Series II granitoids of Wang *et al.* (1983).

The Yangtze-series granitoids have high Fe_2O_3/FeO ratios, which correspond to those of the magnetite-series granitoids (Fig. 3). The magnetic susceptibility goes up to 500×10^{-6} emu/g (Ishihara, 1982c). An oxidized type of the magmatism is obvious from these data and also hematitized magnetite and sulfate occurring in the related ore deposits. These rocks belong to typical I-type magnetite series.

The Yangtze-series magmatism provided fruitful mineralization. Porphyrite iron ore deposits

(Ninwu Research Group, 1978) are large hematitized magnetite deposits occurring in and around apical zone of very fine-grained diorite, which is called porphyrite iron ore deposit in Chinese literature. Copper is another important mineral commodity occurring as bedded, skarn or porphyry type (LI *et al.*, 1980; LI, 1983). However, most of the copper may be recycled through the plutonic and volcanic activities from sedimentary copper beds of Devonian Wutong Group (ISHIHARA, 1982d).

In the southern margin of the Yangtze folded zone, small Jurassic intrusives are associated with a large porphyry copper (-Mo) deposits at Dexing and Pb-Zn skarn orebodies at Suikuoshan. The associated granitoids are magnetite-series granodiorite of calc-alkaline series and are different from the alkaline-series rocks of the Lower Yangtze volcanic basins (ISHIHARA, 1980b). The Yanchuling porphyry-type tungsten (-Mo) deposits and many small W-Cu deposits occur associated with the same intrusive bodies in northern Jiangxi Province (LIU and SHEN, 1982).

Type of Tungsten Deposits in Southern China

Tungsten ore deposits in southern China are classified into many ways by different authors. XU *et al.* (1982) recognized five genetic groups as (1) high-temperature wolframite quartz vein, (2) contact metasomatic scheelite skarn, (3) stratabound scheelite-stibnite-gold deposits, (4) W-absorbed hematite beds of exhalative origin, and (5) porphyry tungsten deposits.

LI and XU (1982) classified tungsten deposits into (1) those of sedimentary-derived magmatic affiliation, (2) those of igneous mixed fusion magmatic affliation, and (3) stratabound tungsten deposit. The first two groups may correspond respectively to the granite-tunsgten series and porphyry-tungsten series of LIU and SHEN (1982). LIU and SHEN examined accessory minerals of the related granitoids and found that those of granite series have ilmenite-monazite or monazite-xenotime-zircon assemblage, whereas those of the porphyry series have magnetite-apatite-zircon or sphene-zircon-apatite assemblage. Thus they seem to correspond respectivley to the ilmenite series and magnetite series of the writer. However, bulk Fe_2O_3/FeO ratio of the granodiorite porphyry and also $Mg/(Mg+Fe)$ ratio of the biotite at Yangchuling deposit, which is type example for the porphyry tungsten series are intermediate between typical magnetite-series and ilmenite-series granitoids. Thus this series is less oxidized than the Yangtze series in volcanic basins of the Lower Yangtze area. Tungsten ore deposits of southern China are reclassified in Table 5.

Economically speaking, wolframite-quartz vein type may be most significant. The past production of China during 1905–1980, about 400,000 tons in W metal, is mostly from this type. Scheelite skarn type is also important, because the ore reserves of the Shizhuyuan ore deposits are reported to reach *ca.* 1 million tons in W metal. Among other types, Damingshan stratabound deposits are in the 1 million ton WO_3 class, including low-grade ores (WAN, 1982).

Wolframite-quartz vein type is widespread in southern China. This type consists of endo- and exogranitic veins. LIN (1983) classifies them into (1) thick vein type (e.g., Xihuashan, Dangping), (2) narrow vein type (e.g., Piotang) and (3) veinlet-dissemination (e.g., Xingluoken and Dajishan). Characteristic associated minerals of the ilmenite-series vein and skarn at recoverable level are cassiterite, beryl, Bi-minerals and very locally molybdenite and base metals. Cassiterite of the endogranitic veins in Jiangxi Province was recovered from 6 mines out of 15 mines between 1918 and 1935 (Jiangxi Geological Survey, 1936). The ilmenite-series tungsten deposits were formed by high temperature, magmatic-hydrothermal ore solution, and can be called simply as W-Sn type.

At distances from ilmenite-series granitic bodies, there occur low temperature-type tungsten mineralizations in SE Asia (e.g., Khao Soon, ISHIHARA *et al.*, 1980) including southern China. They have simple ore mineralogy with weak wall-rock alteration. The tungsten minerals are ferberite and scheelite with or without heubnerite. Stibnite, gold and marcasite are accessories. They occur in Paleozoic sedimentary rocks with or without intercalated volcanic rocks and/or porphyries of later periods, so that their geneses are often controversial as to syngenetic or

Table 5 Classification of tungsten deposits in East Asia.

Type and Characetristics		Southern China	Southern Korea	Japan
Magnetite-series related plutonic type				
W-Mo type (or Cu-W) Magmatic H_2O	Stockwork and disseminated, skarn and replacement, and explosive pipe with Mo-scheelite, wolframite, molybdenite and chalcopyrite	Some small ones	Many middle-size ones (Sangdong?)	Minor W-Au type
Ilmenite-series related plutonic type				
W-Sn type Magmatic H_2O	(1) Wolframite-quartz veins with cassiterite, beryl, Bi-minerals, molybdenite and greisenization (zinnwaldite, (Li-) micas, topaz, quartz)	Many large ones	Some middle-size ones	Some middle size ones
	(2) Scheelite skarn with wolframite, cassiterite, Bi-minerals, molybdenite, magnetite, Cu-Pb-Zn sulfides and garnet-diopside skarn	One large one (Shizhuyuan)	None	Some middle-size ones
Subvolcanic type Meteoric H_2O	Ferberite-bearing cassiterite quartz vein with abundant sulfides and weak wall-rock alteration	None	None	Two large ones
Volcanic type Meteoric H_2O	(1) Tungsten-hematite bed (2) Scheelite-stibnite-gold bed	Minor	None	None
Sedimentary type	Fossiled placer, ferberite and scheelite	One large one	None	None

epigenetic nature.

Scheelite-stibnite-gold beds at Woxi is considered as volcano-sedimentary type (Li and Xu, 1982). Tungsten-absorbed siliceous hematite bed at Fenglin is also considered syngenetic to the underlying dacitic-rhyolitic rocks, which intercalate several cupriferous pyrite beds (Zhu and Zhang, 1981). However, ferberite disseminates in nearby granodiorite porphyry. Stratabound ferberite-scheelite deposits with the mineral ratio 2:1 of the Damingshan mine have similar geological setting, but are most probably fossiled placer-type sedimentary deposits (Wan, 1982). The volcanic and sedimentary type deposits have not been found in southern Korea and Japanese Islands (Table 5).

Source of Tungsten

Major tungsten deposits of southeastern China were formed by the ilmenite-series granitic activities. The granitoids have both S and I type characters, so that they are considered to have originated in sedimentary and igneous source materials in the continental crust. Thus tungsten content of the basement rocks needs to be examined.

Trace amounts of tungsten in the intruded wall-rocks have been reported by several authors. Wan (1982) described anomalous tungsten contents of 50–620 ppm of the Lower Paleozoic sandstone at just north of the Damingshan mine, Guangxi Zhuang Autonomous Region, which strongly support the fossiled-placer origin of the stratabound deposits. The other Paleozoic sediments of mainly sandstone at 7 km to 30 km from the mine are also rich in tungsten, 4–72 ppm on their average (Table 6). Most of the sedimentary rocks are eroded-out clastics from the north, the Jiangnan massif where some tungsten mineralization is known in the Precambrian strata.

Table 6 Tungsten contents of sedimentary rocks in the Damingshan mine area (WAN, 1982).

Locality	Age		Rock type	Number of analysis	Range (ppm)	Average (ppm)
Littoral sediments						
7 km SE	Devonian	D_1y	Sandstone, shale	64	0.5–92	14
ditto		D_1n	Shale	62	5.8–79	21
ditto		D_1l	Sandstone	50	3.8–56	17
10 km SE		D	Sandstone	50	0.5–100	34
30 km SE		D	Sandstone, shale	60	0.5–17	9
Just north		D	Sandstone	25	50–620	193
ditto	Cambrian	E	Sandstone	20	100–400	194
10 km SE		E	Sandstone	22	40–160	72
30 km NE		E	Sandstone	59	0.5–12	6
Marine sediments						
20 km S	Middle Triassic		Sandstone, shale	34	1.8–7.6	5.0
ditto	Upper Permian		Sandstone, shale	37	0.1–21.8	4.4
15 km S	Carboniferous		Carbonate rock	50	0.1–1.3	0.4
10 km N	Middle Devonian		*ditto*	61	0.1–0.8	0.3
TUREKIAN and WEDEPOHL (1961)			Shale			1.8
ditto			Sandstone			1.6

In the Huangsha, Jiangxi Province, on the other hand, sandstones are slightly anomalous (3–4 ppm W) but pelitic rocks contain anomalous tungsten of 16–42 ppm. Besides, Cambrian flysh-type sediments are rich in the element (22–28 ppm W) throughout the rock types. WU *et al.* (1982) also noted 7 to over 100 ppm W from the Sinian-Cambrian strata of tungsten mining areas and 1 to 6 ppm W from those at some distances from the mining areas.

Sedimentary and metamorphic rocks prior to the Early Yanshanian granitoids appear to be rich in tungsten in southeatern China. The ultimate origin of the tungsten may be due to hetrogeneity of the upper mantle for a few anomalous values found in ultramafic and mafic rocks in that region (XU *et al.*, 1982). Trace amount of tungsten thus contained in the basement was recycled through the ilmenite-series granitic activities. Granitoids of the famed Nanling geochemical province have the highest average value as 5.2 ppm W, the eastern Guangdong province as 5.1 ppm W and the Hunan province as 4.0 ppm W, while other provinces are as low as 2 to 3 ppm W (LIU *et al.*, 1982).

LIU *et al.* (1982) also reported average content of various rock types. The tungsten contents of major granitic bodies which appear to be largely the Early Yanshanian ilmenite-series

Table 7 Average tungsten contents of major granitic bodies in southeastern China (LIU *et al.*, 1982).

Rock type	Nomber of pluton	Number of sample	Exposed area (km^2)	Average W (ppm)
Granodiorite	27	46	8084	1.3
Monzonitic granite	31	49	6336	4.6
Biotite granite	97	293	47739	8.2
Two-mica granite	6	17	1155	13.7
Albite granite	19	52	579	106.9
Low-Ca granite (TUREKIAN and WEDEPOHL, 1961)				2.2
Average of 10 geochemical reference samples*				1.1

*Granite (n = 5), G-2, GA, GH, NIM-G, JG-1; Syenite (n = 4), NIM-S, SY-1, 2, 3; Granodiorite (n = 1), GSP-1 (TERASHIMA, 1980).

granitoids are listed in Table 7. The biotite granite of 8.2 ppm W is much higher than the world average (2.2 ppm W) of low-Ca granite by TUREKIAN and WEDEPOHL (1961). Secondly, the tungsten contents increase as the granitoids differentiate; albite granite gives the highest 107 ppm W. Tungsten in these magmas thus concentrated may be released in the magmatic fluid phase when they reached the upper part of the continental crust, then formed the ore deposits. Available isotopic data (e.g., MU *et al.*, 1982) indicate that an external source of tungsten (e.g., intruded wall-rocks) concentrated in the ore deposits by meteoric hydrothermal circulation system may be unrealistic.

Yanshanian Granitoids and Molybdenum Deposits in the North

The northern half of the eastern China may be divided into North China Block and Northeast China Block (GUO *et al.*, 1982). In the North China, the Yanshanian magmatism is shown by sporadic distribution of batholith and stock, while the Northeast Block is characterized by extensive volcanic rocks, especially in the Daxinganling folded belt (Fig. 2). The Yanshanian granitoids appear to be largely biotite granite and granodiorite, and seem to belong mostly to magnetite series (Fig. 3) and I type (GUO *et al.*, 1982). Molybdenum ore deposits are scattered in these regions. They are dominantly of porphyry type.

Along the Qinling folded belt, many small stocks, less than 3 km^2 in area, intrude into Precambrian metamorphic rocks at intersections between E-W and NNE lineaments (SHENG *et al.*, 1980). At Nannihu, Jurassic (162 Ma), biotite (5%) granite porphyry crops out as small plug (0.1 km^2 in area), which becomes bigger (1.5 km^2 in area) at -600m from the surface. The granite porphyry is cored by more mafic and holocrystalline, biotite (10–15%) granite. Molybdenite occurs mainly as veinlet in hornfels and as skarn in carbonate horizons in the wall rocks, and partly in granites.

All ranges of alteration, from potassic silicate to propylitic association, is observed and molybdenite mineralization is divided into the following 6 stages (SHENG *et al.*, 1980).

(1) K-feldspar-quartz veinlets (barren).
(2) Molybdenite film.
(3) Pyrite-molybdenite-quartz veinlets (main stage) and minor dissemination. Some K-feldspar, purple fluorite, scheelite and sulfides (mainly pyrite).
(4) Pyrite-quartz veinlets. No molybdenite but little fluorite.
(5) Calcite-molybdenite-zeolite veinlets. Some pyrite.
(6) Carbonate veinlets, mainly calcite.

The Jinzhuicheng deposit is associated with aplitic granite, which intrudes into Precambrian andesite. Molybdenite is seen around the tip of flat-lying tongue-like intrusion. The mineral occurs as veinlets and dissemination, and potassic silicate alteration is distinct. Pyrite is dominant and chalcopyrite is very minor in the associated minerals.

In the Northeast Block, the famed Yangjizhangzi deposits are seen at the southern flank of biotite granite stock which intrudes into lower Paleozoic sedimentary rocks during the Early Yanshanian time (183 Ma, ISHIHARA and SHIBATA, 1980). Molybdenite occurs in several skarn layers (E-W, 45°S) around aplitic plug (500 m in diameter), which is an apophysis of the biotite granite. Diopside skarn is dominant close to the granite, while garnet skarn is well developed far from the contact. Magnetite is concentrated around the southern fringe of the biotite granite. Sphalerite and galena are locally concentrated at some distances from the contact. In the aplitic plug quartz veinlet is well developed without molybdenite. Thus, the ore deposits are more or less porphyry type.

The Daheishan molybdenum deposits in Qiling Province are associated with plagiogranite which intrude into lower Paleozoic sedimentary rocks. The intrusion is controlled by NE faults. Molybdenite occurs as veinlets and dissemination in aplitic part of the plagiogranite. The host rock is silicified, sericitized and kaolinitized. Molybdenite-quartz veinlets contain subordinate amount of pyrite and chalcopyrite.

Table 8 Average chemical composition of Mo-related leucogranites in China and Japan

	Nannihu (1) Gb	Nannihu (2) GP	Yechangping (3) K-Gp	Jinzhuicheng (4) Gb	Yangjizhangzi (5) Gb	Seikyu (6) Gb	Hirase (7) Gb
SiO_2 (%)	69.58	73.26 %	73.26 %	76.82 %	74.63 %	75.37 %	75.84 %
TiO_2	0.41	0.15	0.10	0.09	0.21	0.21	0.11
Al_2O_3	14.61	12.80	12.73	12.44	13.94	12.90	13.54
Fe_2O_3	1.72	1.63	0.45	0.69	0.88	0.78	0.42
FeO	1.22	0.47	0.20	0.72	0.50	0.60	0.41
MnO	0.04	0.02	0.08	0.02	0.06	0.04	0.04
MgO	0.93	0.32	0.33	0.13	0.31	0.44	0.26
CaO	1.92	1.28	0.31	0.56	0.84	0.93	0.56
Na_2O	4.18	1.98	0.88	2.48	4.01	3.02	3.63
K_2O	4.93	5.95	9.84	5.31	4.21	4.60	4.20
P_2O_5	0.17	0.06	0.06	n.g.	0.07	0.02	0.04
H_2O (+)	n.g.	n.g.	n.g.	n.g.	0.04	0.54	0.38
H_2O (−)	n.g.	n.g.	n.g.	n.g.	0.04	0.31	0.30
Total	99.71	97.92	98.24	99.26	99.74	99.76	99.73
Cl (ppm)	n.g.	n.g.	n.g.	n.g.	55	83	45
F (ppm)	n.g.	n.g.	n.g.	n.g.	780	300	240
$\delta^{18}O$ (‰)	n.g.	n.g.	n.g.	n.g.	+7.6	+6.9	+7.7
$\chi(\times 10^{-6})$	n.g.	n.g.	n.g.	n.g.	265	300	170

Notes: (1) Biotite granite, (2) Biotite granite porphyry (from FENG and ZHU, 1978) (3) K-rich granite porphyry, (4) Biotite granite (from SHENG et al., 1980), (5) Pink biotite granite, (6) and (7) Aplitic biotite granite; (5–7) are analyzed at the Geological Survey of Japan. Cl, F and $\delta^{18}O$ analyzed by S. TERASHIMA and Y. MATSUHISA. n.g., no given.

Related granites to the above molybdenite deposits are highly fractionated. Available chemical data indicate that they are highly oxidized magnetite series, having $Fe_2O_3/(Fe_2O_3+FeO)$ ratios (atomic) from 0.46 to 0.76 (Table 8). In the Qinling area, granites are potassic having high K_2O/Na_2O ratios (2–20). Fluorine can also be enriched for the presence of fluorite in the mineralized veinlets. Thus the granites can be interpreted to be similar to those related to the Climax-type molybdenum deposits. On the other hand, the related granites in the Northeast Block are more sodic having K_2O/Na_2O ratio of about unity. Their initial strontium ratios are as low as 0.7042–0.7047 (ISHIHARA *et al.*, 1985) and fluorine contents are also low, below 780 ppm. Chemistry of these granites is more close to that of the island arc types, such as Seikyu and Hirase mine areas of southwestern Japan (Table 8).

SOUTHERN KOREA

Granitic activities in Korean Peninsula, which occur essentially in the Precambrian metamorphic terranes, are seen in three major cycles; Triassic, Jurassic (Daebo) and Late Cretaceous (Bulgugsa). The Triassic granitoids are seen only in the northern part (KIM, 1967), and the Cretaceous ones occur dominantly in the southern part of the peninsula. The three cycles of the granitic activities may be correlated with the Indosinian, Early Yanshanian, and Late Yanshanian cycles in southeastern China. But the absolute time scale are different (Fig. 4).

On the K-Ar age bases of correlation, the southeastern China granitoids are divided into 190–160 Ma and 160–135 Ma for the Early Yanshanian cycle, and 135–100 Ma and 100–70 Ma for the Late Yanshanian cycle. Most of the Daebo granitoids have the age between 180 and 140 Ma, which correspond to the Early Yanshanian in China but some give the ages of early stage of the Late Yanshanian. Similarly, K-Ar ages of the Bulgugsa granitoids range

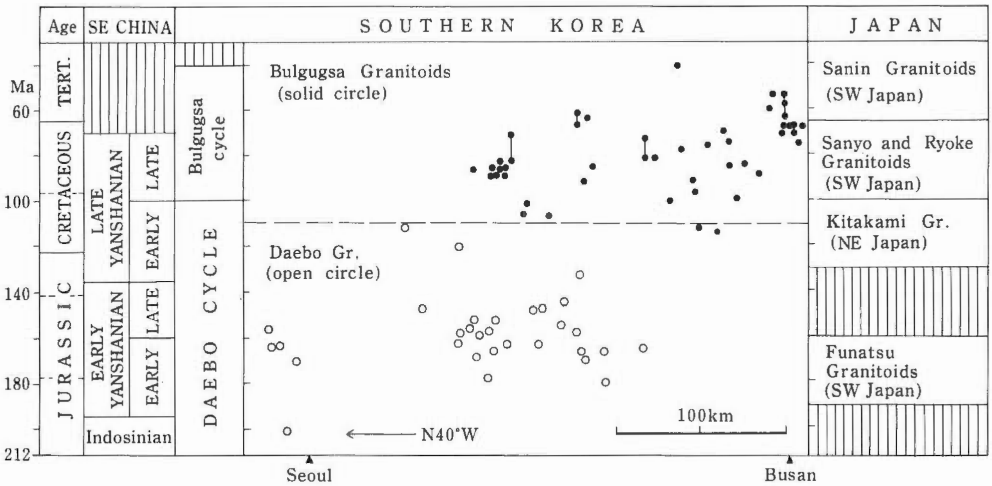

Fig. 4. Correlation of granitic activities in East Asia and NW-SE plot of the K-Ar ages of the southern Korean granitoids. The age data are taken from the compiled data of KIM and LEE (1983), ISHIHARA *et al.* (1981a), and SHIBATA *et al.* (1983).

from those of late stage of the Late Yanshanian to Paleogene. Thus the Korean granitoids are relatively younger than the Chinese ones. As a whole the ages become younger toward the marginal sea side (Fig. 4); the magnetic susceptibility increases also in the same direction (see Fig. 2 of ISHIHARA *et al.*, 1981a).

The Jurassic Daebo granitoids (strictly middle Jurassic to early Cretaceous) are distributed in Precambrian massifs and the Ogcheon folded zone, which is subdivided into (1) SE (southeast), C (central) and NW (northwest) subzone (KIM and LEE, 1983). Granitoids of the SE subzone are foliated or migmatitic granodiorite and granite, which grade into the surrounding Precambrian metamorphic rocks. Some of the foliated granitoids may be late Paleozoic in age.

Granitoids of the NW subzone include large batholiths of granodiorite and granite with some gabbro and tonalite; thus forming complex bodies alligned parallel to the general trend of the Ogcheon zone. Tonalite is limited to the southeastern margin of this subzone. Two-mica granite may occur locally. Granitoids of C subzone are limited in exposure because thick limestone sequence of lower Paleozoic still remains. They are dominantly granodiorite and locally granite in composition. The Daebo granitoids are largely ilmenite series (ISHIHARA *et al.*, 1981a), but are mostly of I type (SHIMAZAKI and LI, 1982). Pink granite at north of Seoul is generally magnetite series, and the oldest ages around 200 Ma are known in the plutons. These granitoids possibly belong to a different substage among the Daebo plutonic activities.

Contrary to the Daebo granitoids, the Bulgugsa Cretaceous granitoids (strictly late Cretaceous to Paleogene) occur widely in Cretaceous volcanic basin of the Gyeongsang Basin (Fig. 5). They are high level granitoids of largely granodiorite and granite, but some mafic rocks (gabbro to tonalite) are also present (JIN, 1981). They are largely magnetite series (JIN, 1981; ISHIHARA *et al.*, 1981a). Granophyric variety of the Bulgugsa granitoids is called Masanite in which magnetite is formd in the late stage of crystallization (IIYAMA and FONTEILLES, 1981).

Cretaceous granitoids, together with cogenetic volcanic rocks, occur also in the C subzone of the Ogcheon Zone. Thus the Ogcheon Zone was reopened during the late Cretaceous time. They are mostly fine-grained leucocratic biotite granite with miarolitic cavities in many places. They are also high level granite. The granitoids have lower magnetic susceptibility than those of the Gyeongsang Basin for more felsic composition.

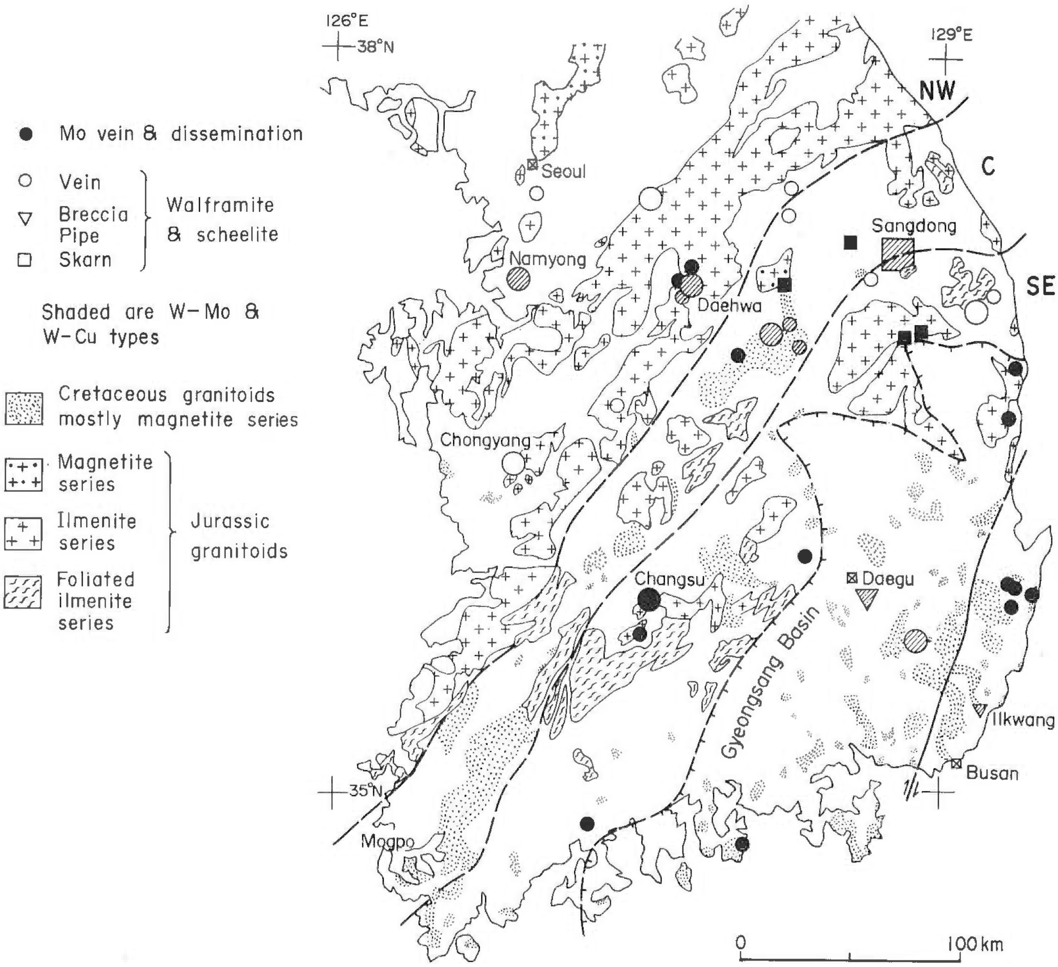

Fig. 5. Mesozoic granitoids and Mo and W deposits of the southern Korean Peninsula (compiled from PARK, 1981 and ISHIHARA *et al.*, 1981a).

With regard to Mo/W-Sn metallogeny of Korean Peninsula, characteristic is almost Sn-free feature in the tungsten ore deposits. The granitoids are also depleted in trace amount of Sn which may be resulted from Sn-poor character of the continental crust (ISHIHARA *et al.*, 1981b). On the other hand, molybdenum is often associated with tungsten in this metallogenic province and also in single ore deposit. However, production figures of tungsten and molybdenum in southern Korea between 1946 and 1980 (123, 493 t, WO_3 70%: 5,542 t MoS_2 90%, KIM, 1984, this volume) indicate that the W/Mo ratio (metal) is about 23, and thus the country is essentially a tungsten province.

Tungsten ore deposits in the Gyeongsang Basin must be related to the magnetite-series granitoids of the Bulgugsa cycle and may belong to the W-Mo or Cu-W type in southern China. They are W-Mo vein at Sannae and Cu-W breccia pipe at Dalsung and Ilkwang, CHUNG, 1975; FLETCHER, 1977). The Sannae W-Mo veins occur in magnetite-series biotite granite but the Ilkwang Cu-W-bearing tourmaline breccia pipe occurs in granitic stock of the intermediate series (ISHIHARA *et al.*, 1981a). Ages of these mineralizations are 65 and 69 Ma, respectively (FLETCHER and RUNDLE, 1977).

Table 9 Ore constituents of molybdenum and tungsten deposits in southern Korea.

Ore deposit, host rock & age	Qz	Kf	Li-mica	Fl	Be	Sn	Wo	Sch	Mt	Mo	Po	Bi-min.	As	Cp	Py	Sp	Gn
Gyeongsang Basin																	
Dalsung: Breccia pipe in andesite	○						◎	◯	○		–	–		◯	○	–	
Ilkwang: Breccia pipe in granitoids, 69 Ma	◯						◯	○			◯	–	○	◎	–	–	–
Sannae: Vein type in biotite granite, 65 Ma	◎		–				◎	◯	◯	◎				○	○		
C subzone of Ogcheon Zone																	
Sangdong: Skarn and stockwork types, 81-84 Ma	◯	–		–			–	◎	○	◯	○	◯	–	○	–	–	–
Wolak: Vein type in granite & hornfels	◎						◎	–		◯		–		○	○	–	–
Daehwa: Vein type in gneiss, 89 Ma	◎	◯	◯	–	–	–	◎	◯		◎				○	○		
SE subzone of Ogcheon Zone																	
Ogbang: Peg. lens in gneiss & granite P€?	◎	◎		◯			–	◎			○				○		
Changsu: Vein type in granite	◎	◯	◎	–			–			◎				–			
NW subzone of Ogcheon Zone																	
Chungyang: Vein type in granite porphyry	◎		◯		◯		◎	○		◯	–	○	–	○	–	–	–
Namyong: Vuggy vein in brecciated gneiss	◎						◎	○		◯				○	○		–

◎ ◯ ○ – : Relative abundance in decreasing order. The Sangdong includes recently discovered stockworked molybdenite orebody at depth. Abbreviations: P€, Precambrian; Qz, quartz, Kf, K-feldspars; Li-mica, Li-bearing mica minerals; Fl, fluorite; Be, beryl; Sn, cassiterite; Wo, wolframite; Sch, scheelite; Mt, magnetite; Mo, molybdenite; Po, pyrrhotite; Bi-min., bismuthinite and native bismuth; As, arsenopyrite; Cp, chalcopyrite; Py, pyrite; Sp, sphalerite; Gn, galena. Arranged from Gallagher (1963), Chung (1975) and others.

Sangdong Mo-scheelite skarn and Wolag molybdenite-woframite veins occur in Cretaceous granitic terrane of the C-subzone of the Ogcheon zone. Daehwa wolframite-scheelite and molybdenite quartz veins are located in the Daebo granitic terrane, and are recently found to have late Cretaceous age (88.6 Ma, SHIBATA *et al.*, 1983). All of the above-mentioned deposits are of the W-Mo type but their mineralization ages are older (81–89 Ma) than those of the W-Mo and Cu-W types in the Gyeongsang Basin.

Although the Daebo cycle of W-Mo mineralizations is definitely present (e.g., Keumseong Mo-skarn, SHIBATA *et al.*, 1983), the main mineralizations appear to be related to the Bulgugsa, magnetite-series granitic activity. This may be chief reason for the unclear separation of W and Mo in the Korean metallogeny. SATO *et al.* (1981) supported this view in finding positive $\delta^{34}S$ values of ore sulfur in many ore deposits outside of the Gyeongsang Basin. TSUSUE *et al.* (1981) proposed higher capability of mineralization of the Bulgugsa granitoids than the Daebo granitoids by Cl-contents in the rock-forming apatite.

As far as ore metal assemblage is concerned (Table 9), Chungyang wolframite-quartz vein deposit has the possibility of being associated with the Daebo ilmenite-series granitic activity. Okbang ore deposit is nothing but fluorite-scheelite pegmatite and thus may not belong to the Bulgugsa cycle. In order to confirm this speculation, radiometric dating needs to be done on vein-forming minerals. On the contrary to the tungsten ore deposits in southern China, the major tungsten ore deposits of southern Korea are the W-Mo type.

SOUTHERN SIKHOTE ALIN

In the southern part of the Sikhote Alin, USSR, volcano-plutonic belt similarly zoned to those of the southern Korea and Fujian Volcanic belt is seen (Fig. 6). Here, the oldest Khanka massif is surrounded by late Paleozoic and Mesozoic sedimentary rocks, and ages of these rocks become younder toward the Japan Sea side. Late Cretaceous to Paleogene volcanic rocks occur dominantly along the coastal region (Fig. 6). Tectonically, this region is more disturbed than southern Korea, as shown by stronger folding and faulting.

Granitic activities are divided into four cycles. Mid-Paleozoic tonalite occurs locally along the central fractured zone. The late Paleozoic activity is seen in the western part and consists of biotite granite and two-mica granite. Some W and Sn ore deposits are related to this granitic

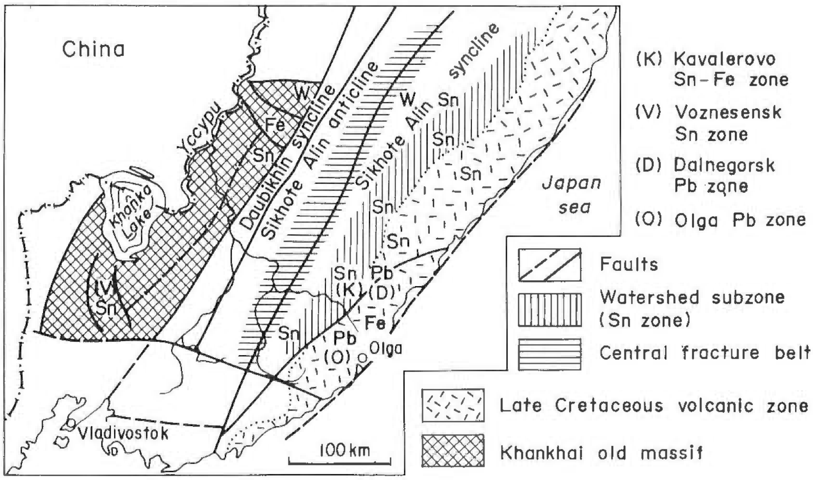

Fig. 6. Zoned structures and main ore deposits of the southernmost part of Sikhote Alin, USSR (after RADKEVICH, 1977).

Table 10 Ore constituents of major subvolcanic and plutonic-type Mo and W-Sn vein deposits in Sikhote Alin and Japan.

Ore deposit, host rock, mineraliz. age	Altered minerals					Vein-forming minerals																
	Bt	Tu	Chl	Ser	Qz	Kf	Fl	Cc	Ka	Sn	Wo	Sch	Mt	Mo	Po	Bi	As	Cp	Py	Sp	Gn	Ag
Sikhote Alin																						
Sn Dubrovsky: J-K sandstone & shale, K		◎	◎		○			–		◎					◎		○	–	○	–	–	
Sn Silinsky: ditto K		–	◎	–	◎		∘	∘		◎					○		○	–	–	○	◎	
Sn Arsenyev: K sandstone & shale K		◎	○	○	◎		∘	∘		◎					◎		○	○	–	○	∘	
Japan: Subvolcanic type veins																						
Sn Ikuno : K volcanic rocks 75 Ma			○	○	◎		∘	∘	–	○	∘				–	–	∘	◎	○	◎	○	○
Sn Akenobe: P-M mafic tuff & slate, 69 Ma II stage					◎		∘	–		◎	○	∘	∘	–				◎	∘	∘	–	
I stage			○	∘	○			–	∘	∘			◎		–	–	○	◎	∘	◎	∘	
Japan: Plutonic type veins																						
W Takatori: P-M slate & sandstone 69	∘		∘	◎	◎		○	∘	–	○	◎					–	∘	○	∘	–	–	
W Ebisu : K rhyolitic tuff 64	○		–	◎	◎		○			∘	◎	–		∘		○	◎	–	∘	–	–	
W Kaneuchi: P-M slate & sandstone 91	∘	○	∘	◎	◎	∘		–		○	◎	◎			○	–	∘	○	∘	–	–	
W Otani : Biotite granodiorite 91	∘		∘	◎	◎	∘	∘	∘		○	○	◎			○	∘	○	○	∘	∘		
Sn Obira : Miocene granite 14		◎	∘	◎	◎		○		∘	◎	∘			–	◎		◎	◎	∘	○	–	○
Mo Hirase : Paleogene granite 60			○	○	◎	–		∘	–					◎					–	–	–	
Mo Seikyu : ditto 48			○	◎	◎	–		–	○				∘	◎				–	○	–	–	
Mo Daito : Tonalite-granite 48	◎		○	◎	◎	○		∘	○				○	◎				–	○	–	–	

Abbreviations: P-M, Late Paleozoic-early Mesozoic; J, Jurassic; K, Cretaceous; Bt, hydrothermal biotite; Tu, tourmaline; Chl, chlorite; Ser, sericite including greisen muscovite which may contain Li; Cc, calcite; Ka, kaolinite; Ag, Ag-minerals. For the others, see Table 7. Andalusite is common in the altered wall-rock of the Daito-Hinotani Mo deposits.

activity. Jurassic granitoids are present only locally and have wide variation in silica contents but are somewhat alkaline. Late Cretaceous to Paleogene granitoids occur widely but mainly in the eastern zone. They constitute high level plutons with diorite to granite composition, and belong generally to magnetite series, as far as the writer's study in Kavalerovo area is concerned. This area is well known for Sn mineralization. Genetically related granitoids for the Sn ore deposits are only seen underneath Dubrovksy mine where leucocratic biotite granite of ilmenite series occurs as hidden mass. This granite is similar to that observed everywhere in Sn-W-mineralized, ilmenite-series granitic terranes in East Asia. Predominance of pyrrhotite in Sn deposits also supports that the granite genetically related to the mineralization is in a reduced state.

The final cycle is mafic, I-type, magnetite-series igneous activity of mid-Tertiary age which is seen very locally along the Japan Sea coast (ISHIHARA, 1980a).

Major Mo-W-Sn mineralization in southern Sikhote Alin is vein-type cassiterite deposits related to the late Cretaceous to Paleogene granitic activities. They occur generally in the anticlinal zones of Jurassic and Cretaceous sedimentary rocks. (e.g., Dubrovsky, Silinsky and Arsenyev mines) and rarely in granitoids (Mt. Tjomnaya prospect, RADKEVICH, 1979). Cassiterite, tourmaline and chlorite, besides quartz, are characteristic of these ore deposits (Table 10), and wolframite and molybdenite occur only locally as trace minerals in endogranitic veins. Sulfide minerals are rather abundant in these deposits occurring as separate veins or overlapping over cassiterite mineralization forming composite veins.

A number of felsic to intermediate dikes are seen in and around the major exogranitic ore deposits. At Arsenyev, ore veins occur associated with breccia pipe within a small caldera (2 by 5 km) and are composed of the early stage of quartz-sulfide-sulfosalts vein (N80°E) and the later stage of the main veins (N30°W) with cassiterite, quartz and sulfides. Thus the mineralization sequence is reversed. Together with the overall mixed occurrence of cassiterite and low temperature-type sulfide minerals (Table 10), these tin deposits, the Arsenyev in particular, are considered to have subvolcanic character.

JAPANESE ISLANDS

Japanese Mo-W-Sn ore deposits are arranged in distinct zones parallel to the island arc direction, in which fundamental pattern is paired zoning of Mo province in the back arc side and W-Sn province in the fore arc side (e.g., Inner Zone of southwestern Japan, Fig. 7). The metallogenic provinces are well correlated to the magnetite-series and ilmenite-series granitic belts (ISHIHARA, 1978b). Molybdenite deposits occur associated with the magnetite-series granitoids, while cassiterite, wolframite and scheelite deposits are present in the ilmenite-series granitic terranes. Small gold-scheelite type deposits in the Kitakami Mountains are related to magnetite-series and intermediate-series granitoids (see ISHIHARA, 1982b for detail). Thus tin appears to be concentrated with the most reduced type of granitic magmatism, whereas an oxidized magma is necessary to form molybdenum deposit. Tungsten has both characters, although the majority are concentrated with ilmenite-series granitic magma.

Ore mineral assemblages of these deposits are also correlated with the granitoid series. In plutonic type of ore deposits, to which almost all of the producing molybdenum deposits and most of the producing tungsten deposits belong, molybdenum deposits contain no pyrrhotite but often hematitized magnetite. Pyrrhotite, on the other hand, is very common in tungsten and tin deposits (Table 10). Other characteristics of the tungsten and tin deposits are common occurrence of As-sulfides (arsenopyrite and löllingite), Bi-minerals (bismuthinite and native bismuth), topaz and fluorite and Li-bearing micas; these minerals are absent in molybdenum deposits. Since plutonic-type deposits have been described in the previous papers of the writer (ISHIHARA, 1971a, 1982b), subvolcanic type W-Sn veins, which share more than half of the tin production of the country will be described in the following paragraphs.

Subvolcanic Sn-polymetallic Deposits

Cassiterite and wolframite-bearing polymetallic veins of Akenobe mine have an overall composition of 0.37% Sn, 1.09% Cu and 2.0% Zn, which are an average tennor of the total ores mined out between 1947 and 1980 (SATO and AKIYAMA, 1980). Besides these, substantial amount of wolframite, gold, silver and lead have been recovered. Similar veins of Ikuno mine are less in tin and tungsten.

The Akenobe mine is located in the Maizuru tectonic zone which is 30 km wide with an ENE trend in the Inner Zone of southwestern Japan. The ore veins are widespread in an area 5 km (N-S) by 7 km (E-W) where late Paleozoic to early Mesozoic Maizuru Group consisting of basaltic tuff and lava and pelitic and psammitic rocks is folded and metamorphosed up

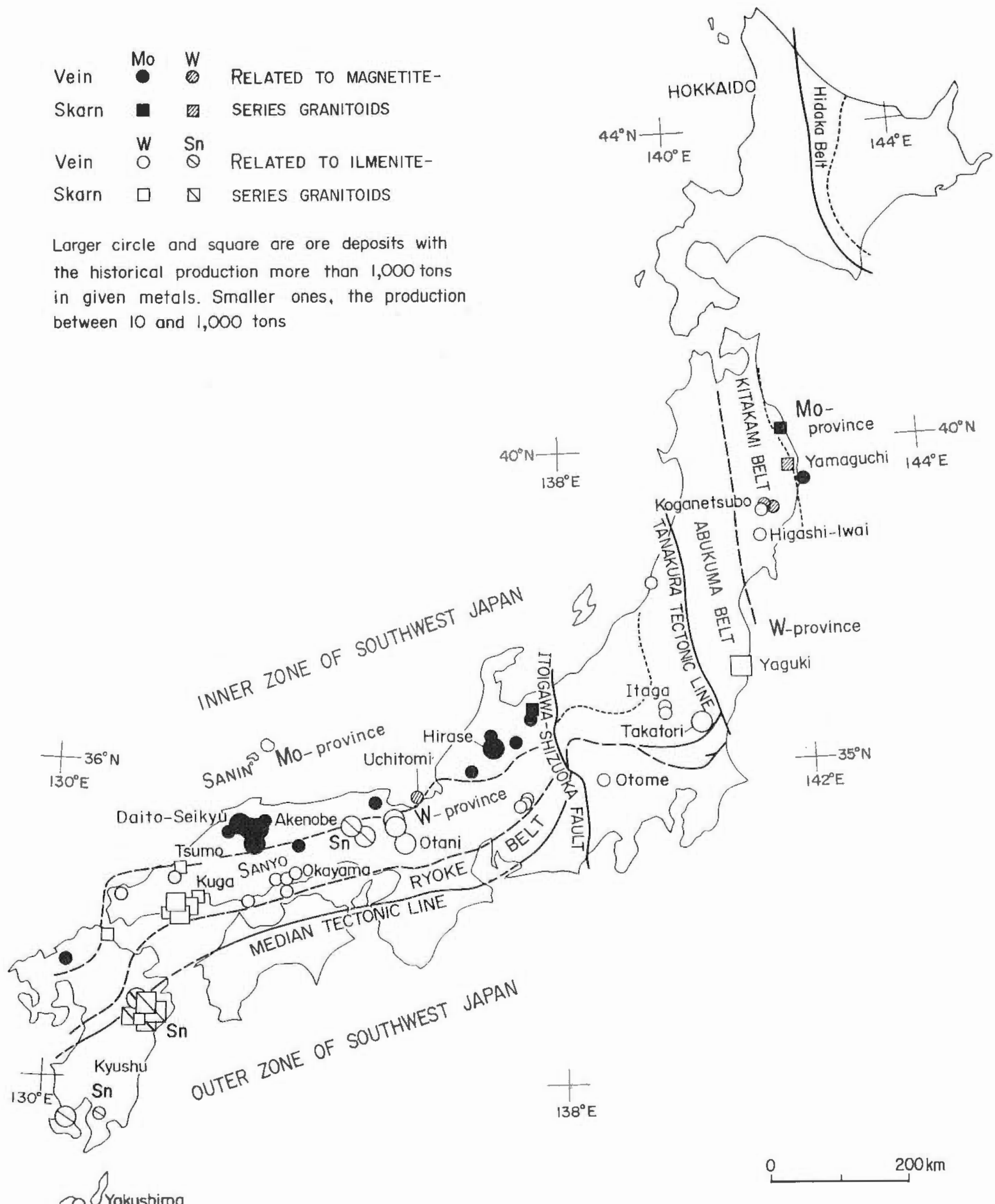

Fig. 7. Mo and W-Sn metallogenic zoning of the Japanese Islands.

to a green schist facies, and is intruded permissively by the Yakuno mafic igneous complex consisting of sheared gabbro-plagiogranite (Fig. 8).

The Akenobe-Ikuno area is extensively covered by late Cretaceous andesitic pyroclastics and lava and rhyolitic welded tuff of Ikuno and Arima Groups. A number of dikes with similar composition are known to occur in especially well fractured, Akenobe and Ikuno mines areas. Cogenetic granitoids with the andesitic rocks, which are named as the Shiso granitic

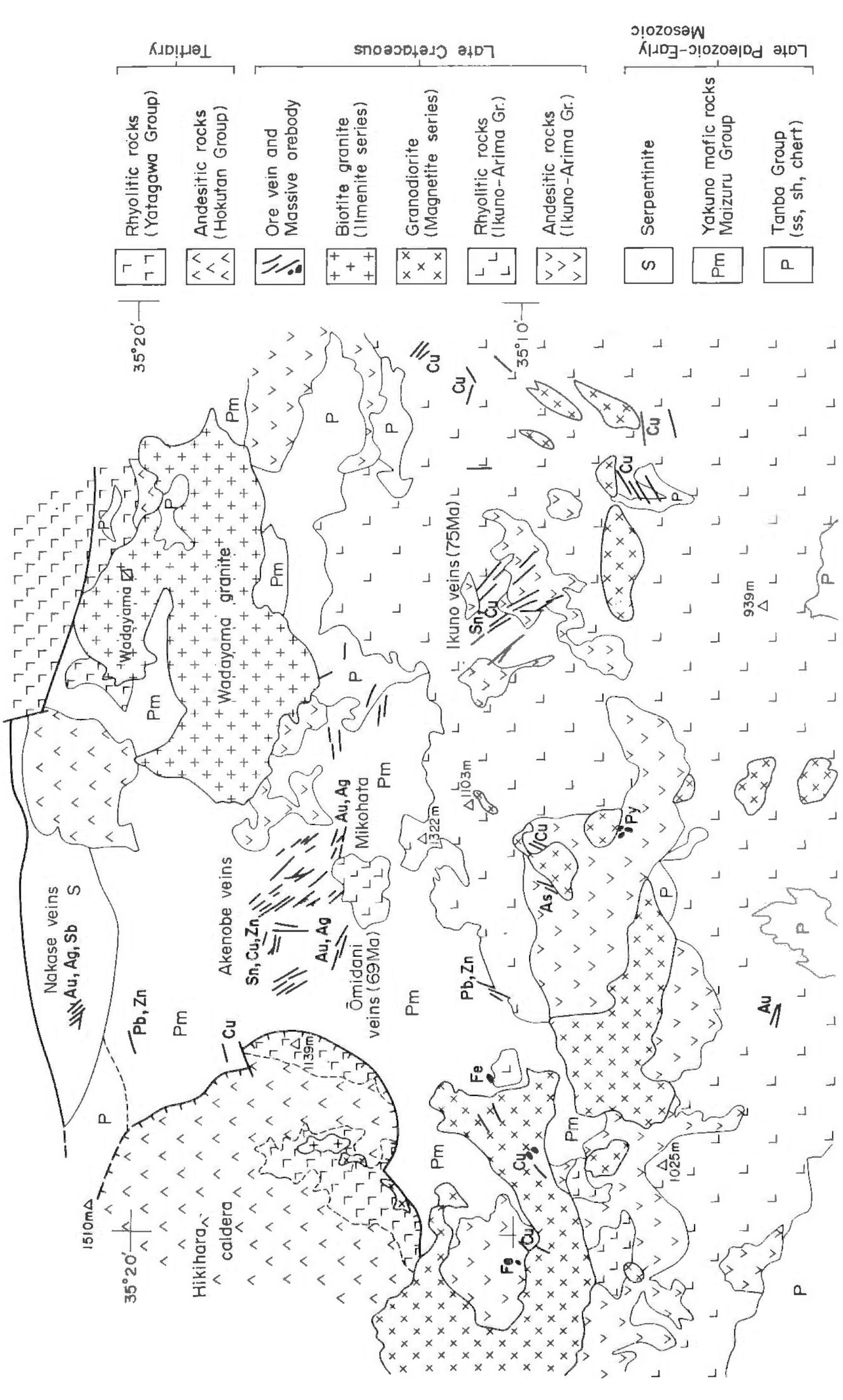

Fig. 8. Simplified geologic map of the Akenobe-Ikuno mine area. Compiled mainly from MMAJ (1974).

complex, occur in the southern part closely associated with the andesites. Both intrusive and extrusive rocks are calcic in composition and contain abundant accessory magnetite; thus both belonging to I-type magnetite-series (ISHIHARA *et al.*, 1981c). Minor mineralization of vein and replacement types includes chalcopyrite, magnetite, arsenopyrite and pyrite (Fig. 8), which are also characteristic mineral commodity of the magnetite-series granitic activity.

Plutonic equivalent of the rhyolitic rocks may be the Wadayama, pink granite. This is an ilmenite-series, biotite granite and has significant bearing on the Akenobe tin mineralization, because the fresh rocks contain an average of 6.0 ppm Sn, but the majority of altered facies including small body occurring to the west of the Akenobe mine in the middle of the Hikihara caldera are depleted in tin down to 1.7 ppm (TERASHIMA and ISHIHARA, 1982). The Akenobe vein system is situated above the intrusion axis of an E-W trending pink granite (Fig. 8).

More than one hundred independent veins are known to occur in the Akenobe mine area. They generally have a northwest strike and steep northward dip, while the others have E-W and rarely northeast strikes. SATO and AKIYAMA (1980) reconstructed the original vein system and concluded that major faults of northeast trends served as conduit for the mineralizing solution.

The tin-polymetallic veins show distinct two stages of mineralization; an early sulfide stage (or Cu-Zn stage) and later oxide stage (or Cu-Sn stage). The early stage veins are composed of abundant sulfides such as sphalerite, chalcopyrite, galena and magnetite, while the later stage veins are dominantly quartz containing chalcopyrite, cassiterite and wolframite. The two stage of veins occur generally in a single fissure system in a parallel manner. The sulfide stage veins are at the wall-rock side and the oxide stage veins are in the central part. This zonal arrangement was the cause of controversy as to the mineralization sequence in the past. In the Chiemon vein group, however, NW-trending sulfide veins are cut obliquely by WNW-trending oxide vein (AKIYAMA *et al.*, 1980). Assay values for the ore-reserve calculation indicate clear separation of the veins of the two stages in the Zn/Sn ratio (Fig. 9). Thus, at least two stages of mineralization occurred in the Akenobe mine, each of which may have been related to different igneous activity.

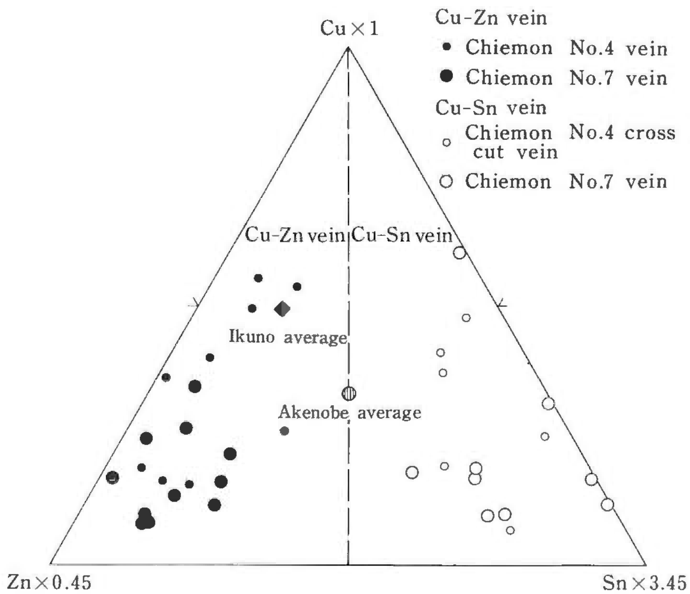

Fig. 9. Sn-Cu-Zn ratios of the two stages of ore veins at the Akenobe mine (after ISHIHARA *et al.*, 1981c).

Genetic Scheme

Within the Akenobe vein swarm, more than 90 dikes of basaltic, andesitic and rhyolitic compositions are known. Andesite and felsite are most common and they generally have NE trends, which are the same direction as the assumed fractures for the ascending ore solution. Oxygen isotopic study indicates meteoric water origin of the ore solution (MATSUHISA *et al.*, 1980). Hence it is inferred that base metals and sulfur of the early, sulfide stage mineralization is brought up by the andesitic activities, whereas the late stage mineralization is related to felsite activities, through which Sn, W and F of hidden pink granite are leached out by circulating groundwater (Fig. 10A). Leaching of the ore components from the direct wall rocks can not be considered for the very weak wall-rock alteration in these vein system including the veins of the Ikuno mine.

Among the plutonic Mo and W-Sn provinces over the whole Japanese Islands, Mo-province is situated in the magnetite-series volcano-plutonic belt. This is very clear in minor Mo/Au-W provinces of the Kitakami Mountains, northern Honshu (Fig. 7), where comagmatic volcanic rocks dominantly occur along the Pacific coast but granitoids of Au-W province do not accompany volcanic equivalents. In the major province of the Inner Zone of southwestern Japan, comagmatic volcanics are abundant in the Mo province. In the W province, there also occur thick pile of rhyolitic welded tuffs as seen even in the Ikuno-Arima area (Fig. 8). However, ages of the major tungsten mineralization such as in the Otani-Kaneuchi and Kuga mining areas are 92–96 Ma (SHIBATA and ISHIHARA, 1974), and no volcanic rocks of similar ages are known to occur around the W-mineralized areas.

As far as the depth of formation is concerned, molybdenum deposits of the Mo province appear to be next to the subvolcanic veins (Fig. 10D). This shallow level of mineralization is related to the high-level of granitic intrusion, which was assumed by finer grain size of the granitoids in addition to the volcanic/plutonic rock ratio of the province (ISHIHARA, 1971a). Oxygen isotopic study indicates no involvement of meteoric water (ISHIHARA and MATSUHISA, 1975), so that all the ore components are considered to be originated in the

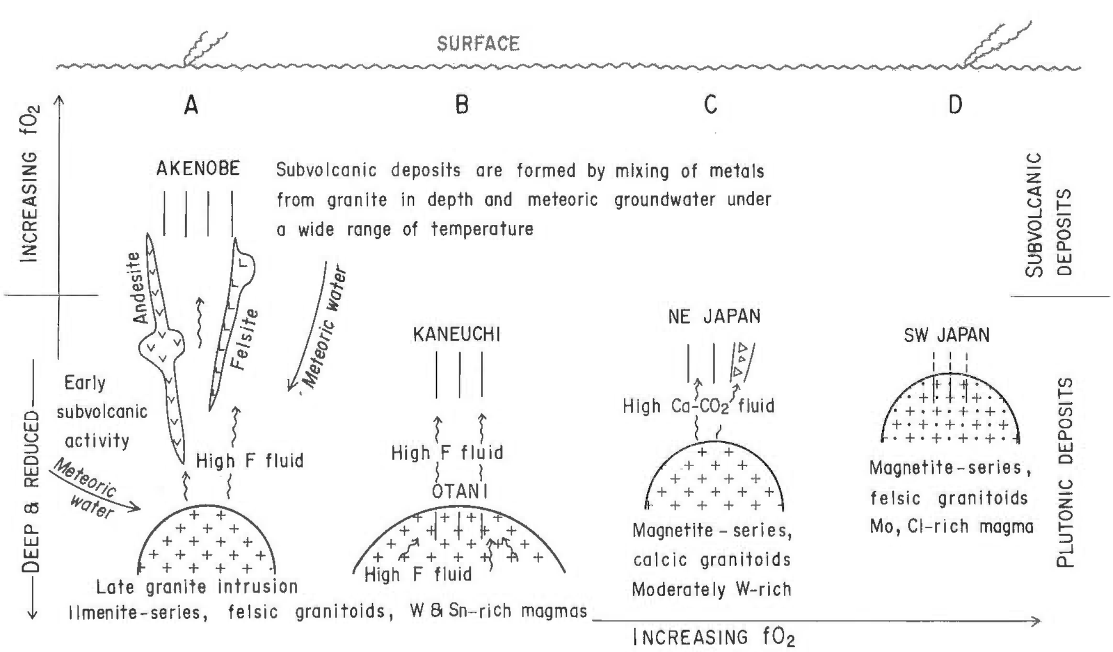

Fig. 10. Schematic model for the plutonic-type Mo and W and subvolcanic-type Sn deposits in Japan (modified from ISHIHARA, 1982b).

magnetite-series granitic magmas. The magmas probably were rich in Mo, Cl and H_2O, as indicated, respectively, by molybdenite occurrence as a rock-forming mineral in well fractionated aplitic rocks (ISHIHARA, 1971a), by high Cl content in the bulk samples (ISHIHARA and TERASHIMA, 1977) and in apatite (CZAMANSKE *et al.*, 1981), and by wide contact-type hydrothermal alteration around the Mo-mineralized granitic plutons (ISHIHARA, 1971a).

Plutonic-type tungsten deposits may have been formed at the deepest level among the three types discussed here (Fig. 10B). Because the related granitic magmas are originated from older granitic rocks rich in F and W, such as we have seen in southeastern China, and older meta-sedimentary rocks, they are rich in W and F originally. These magmas usually form wolframite in contact with non-carbonate host rocks. In the case of the Otani veins, however, workable mineral is exceptionally large amounts of scheelite, although they are hosted in granitoid. The host rock is granodiorite higher in CaO than that of normal granite, and greisen bands adjacent to the ore veins are much depleted in CaO. The scheelite is considered to have formed there by hydrothermal activity consuming calcium of the wall rock.

DISCUSSION AND CONCLUSION—PAIRED MAGNETITE-SERIES/ ILMENITE-SERIES BELTS

As described in the previous chapters, Mo and W-Sn mineralizations are related to granitic provinces as classified in terms of granitoid series. The Mesozoic-Cenozoic granitoids in East Asia were recently grouped into the following five categories by their geologic setting, alkali contents and their ratios (TAKAHASHI, 1983):

Types	K_2O, K_2O+Na_2O, K_2O/Na_2O	Examples
A) Island arc	Low	Kitakami, NE Japan
B) Continental margin	Moderate-high	Almost all the granitoids discussed here
C) Intra-continental	High	Daxinganling, Shandong
D) Collision	Moderate-high	Qinling
E) Predominantly alkaline	Trachybasalt-syenite	Middle-Lower Yangtze, Shangdong

The wide area of the magmatism from Mongolia to the Japanese Island was examined to explain by oblique subduction and strike-slip movement of the Paleo-Pacific plates, especially subduction of hot oceanic ridges of the Farallon-Kula Ridge and of the Kula-Pacific Ridge, which had been subducted at the latest Jurassic and latest Cretaceous, respectively. In this paper, the granitoid series are primarily concerned, because alkali contents and their ratio of the ilmenite-series granitoids are much dependent upon those of the continental crust whereby the magmas were emplaced. Moreover, paired plutonic belts (ISHIHARA, 1979b) of the outer or frontal ilmenite-series terrane and the inner or back-arc magnetite-series terrane are considered essential to the granitic activities that occurred in the continental margin environment associated with the development of marginal basins.

Jurassic-Early Cretaceous Magmatism

The Jurassic to Early Cretaceous magmatism, which is known as the Early Yanshanian cycle in China and the Daebo cycle in southern Korea, is characterized by a mesozonal, ilmenite-series granitoids accompanying no coeval volcanism. Along the oceanic side of these granitic belts, there occur narrow zones of foliated granitoids (e.g., southern Korea) or high-temperature-type metamorphic rocks and migmatites (e.g., Fujian coast, China, LI *et al.*, 1982). These Jurassic granitoids are felsic in composition and the major part was possibly originated in sedimentary and igneous mixed source materials within the continental crust. Characteristic mineralizations are either tungsten or tin reflecting the original concentration of those elements in the continental crust.

Toward the interior, magnetite-series granitoids occur sporadically along tectonically weak zones. The plutonism accompanies extensive effusive facies, especially in the Daxinganling. Thus the granitoids are epizonal. They are also felsic in composition, and are therefore considered to have been derived from igneous source rocks of an intermediate composition within the continental crust. Characteristic mineralization is molybdenum. Thus a paired W-Sn/Mo province is seen regionally (Fig. 11A).

Magnetite-series granitoids associated with voluminous volcanism tend to occur in a tensional tectonic setting; the best example may be seen around the Japan Sea during the Tertiary

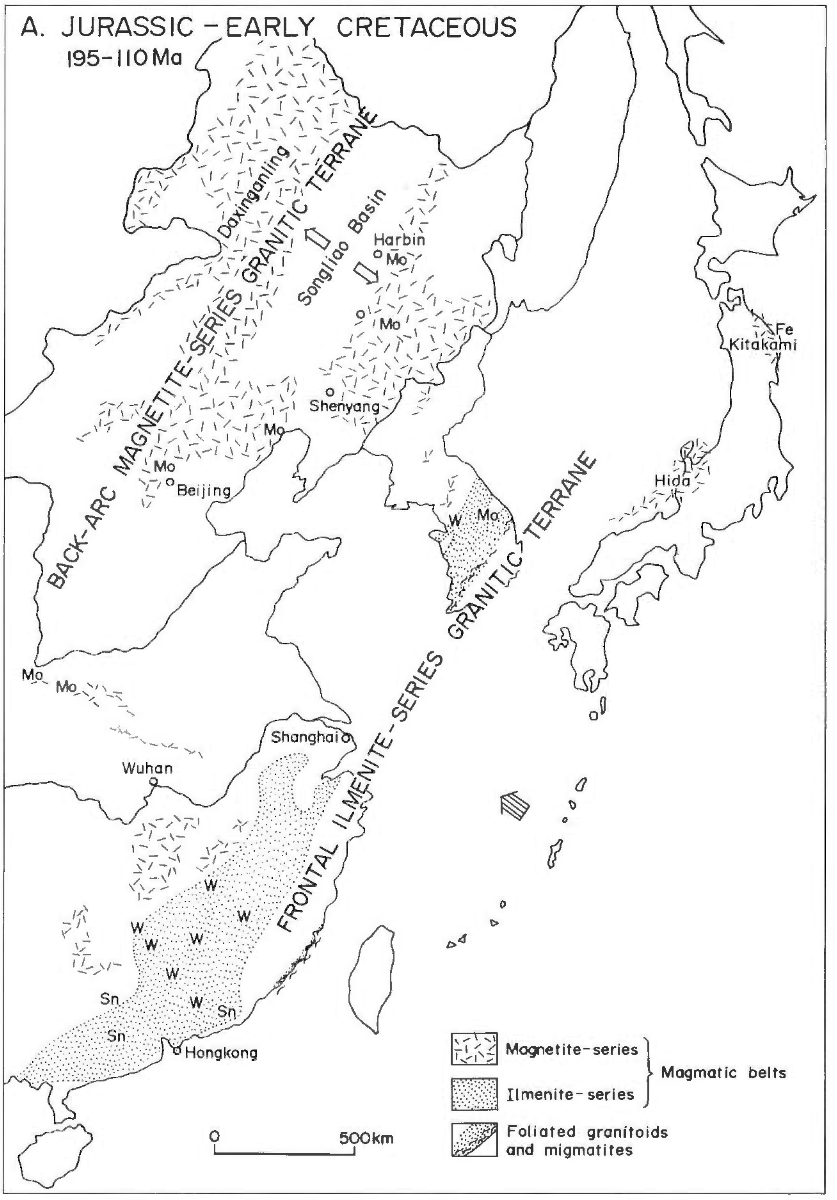

Fig. 11. Evolution of the paired magnetite-series/ilmenite-series granitic belts in East Asia. Main magmatic-hydrothermal ore deposits are shown by chemical symbols.

time which will be described later. The magnetite-series magmatism of Northeast China may have occurred in such a tectonic environment. That is, the lowest unit of upper Jurassic volcanic rocks and successive sedimentary sequence which includes the Daqing petroleum horizons in the Songliao sedimentary basin (CHENG *et al.*, 1982) are considered as accumulated volcanoclastics in an aborted marginal basin where tensional fracturing was developed before the depression. Similar fracturing may have also occurred locally behind the Nanling ilmenite-series granitic terrane where small magnetite-series granitic plutons are seen sporadically, but the stretching out was much weaker than in Northeast China.

Jurassic granitoids in the Japanese Islands are magnetite-series, Funatsu granitoids of

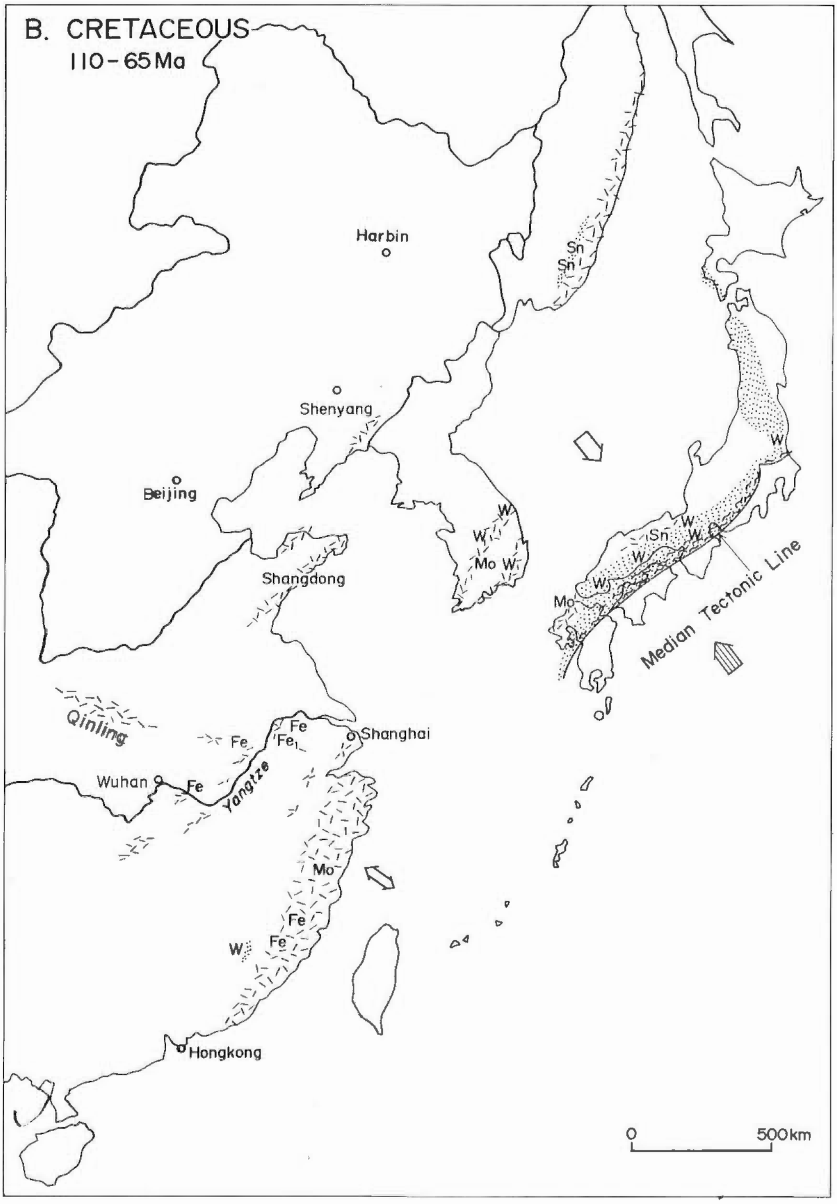

Fig. 11. Continued.

southwestern Japan. This block has no associated ilmenite-series counterpart, and can therefore be considered a continental fragment of northern Korea, which was drifted to the southeast after the emplacement of granitoids. On the other hand, early Cretaceous magnetite-series granitoids of the Kitakami block, northeastern Japan, is independant island arc drifted from the east (ISHIHARA, 1978b).

Cretaceous-Paleogene Magmatism

Cretaceous magmatic activities are more clearly controlled by NE-fracture systems than the Jurassic ones, and are seen mainly in China and locally in southern Korea and southwestern

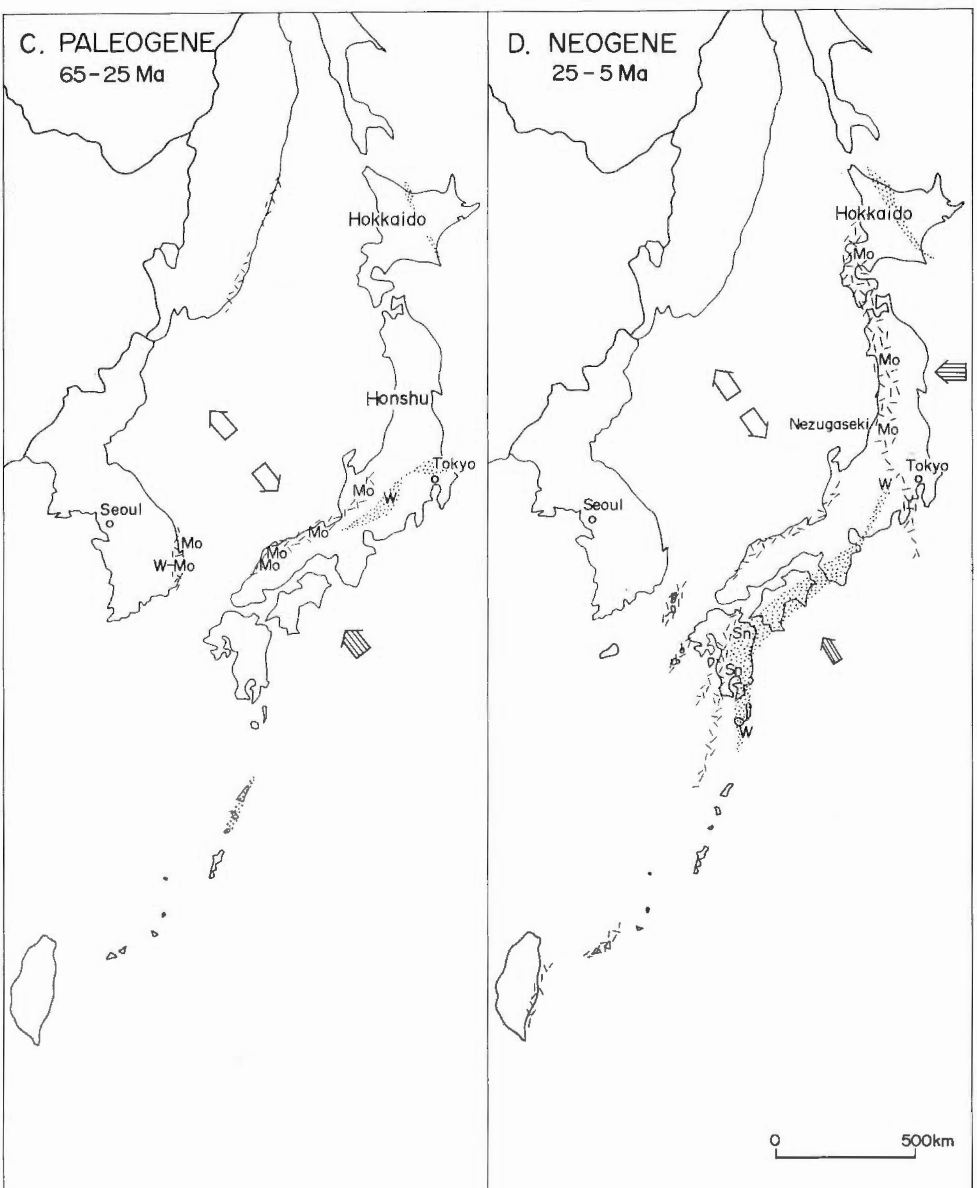

Fig. 11. Continued.

Japan (Fig. 11B). The magmatism of the latter two regions started principally in late Cretaceous and continued to Paleogene (Fig. 11C). The frontal ilmenite-series granitic belt is known as the Ryoke foliated granitoids in high temperature-type metamorphic terrane in southwestern Japan, where the composition is more mafic than that of the Early Yanshanian ilmenite-series granitoids, due possibly to involvement of mafic magmas from the depth into the continental crust where a majority of the magmas are generated from sedimentary and igneous source rocks.

Toward the continental side of southwestern Japan, there occur W-Sn province associated with massive ilmenite-series granitoids; then to the further north, highly oxidized, magnetite-series granitic and volcanic rocks and related Mo deposits of Paleogene age. The Cretaceous to Paleogene granitoids of the southernmost Korea and Fujian volcano-plutonic belt are also magnetite-series ones. Tungsten is more predominant than molybdenum in the Korean Peninsula and some tungsten and molybdenum and many magnetite deposits are konwn to occur in the Fujian Province. Lead-zinc mineralization is common feature throughout the coastal magmatic belts. The magnetite-series granitoids of the above-mentioned three regions are felsic in composition containing some diorite and gabbro. They are considered to have derived from an oxidized igneous rock of an intermediate composition of the continental crust by mixing of mafic magmas from the depth.

On the contrary to the NE-trending magmatic belts just mentioned, Cretaceous magmatism of the continental interior is different. Jurassic to Cretaceous magmatism along the Qinling Suture, which was referred as collision type by TAKAHASHI (1983), post-dates the main collision event and seems to be composed of magnetite-series granite and rhyolite, unlike ilmenite-series, garnet-tourmaline leucogranites in the core of the Himalayan Suture (TU *et al.*, 1982). The Qinling magmatism may have occurred when the N-S compressional force was released by remelting of felsic to intermediate igneous source rocks of the continental crust.

On the other hand, the predominantly alkaline type of TAKAHASHI (1983), which is seen locally in the Lower Yangtze area and Shangdong Province, tends to occur along the deep fracture systems related to the Tancheng-Lujian Fault. Thus, this magma is considered to have a deep origin.

Neogene Magmatism

The Neogene magmatism is only seen in the Japanese Island (Fig. 11D). The major magmatic belt is the Green Tuff belt of northeastern Honshu to Hokkaido where voluminous volcanic rocks occur associated with Miocene plutonic rocks. They range in composition from gabbro to granite including low-K tonalite, but the majority are tonalite and granodiorite. They belong to magnetite series.

The Green Tuff magmatism occurred in a tensional tectonic setting for most periods of the activities since *ca.* 40 Ma ago. Many rift zones, through which the I-type magnetite-series magmas were bought up, are considered during the Miocene (CATHLES *et al.*, 1984). Source of the magmas may largely be of the altered oceanic slab subducted along the Japan Trench (SASAKI and ISHIHARA, 1979).

The magmatism provides fruitful mineralizations of Kuroko and vein types. The mineral commodity includes Au, Ag, Cu, Pb, Zn, Mn, hematite, barite and gypsum. Tungsten and tin are negligible, but recently a porphyry-type molybdenum deposit at Nezugaseki was found to have a Miocene age. This mineralization is seen in small circular stock (1 km wide) of fine-grained, magnetite-series granodiorite and granodiorite porphyry. Molybdenite occurs mainly in pyrite-sericite-quartz veinlets and partly as film with chlorite-clay veinlets (ISHIHARA *et al.*, 1983). There are only two molybdenum mines with any production in the Green Tuff belt, but molybdenite showing is known at seven localities associated with volcanic and subvolcanic rocks and at six localities related to plutonic rocks (ISHIHARA and MORISHITA, 1983). Thus, this belt an also be called as Mo-province.

In central Hokkaido, Miocene ilmenite-series granitoids occur in N-S direction without coeval volcanism (Fig. 11D). They are granodiorite and granite with subordinate amount of tonalite, and are mostly of I type. No mineralization is known associated with the plutonism.

In southwestern Japan, there occurs similar paired magmatic belt; magnetite-series igneous rocks are seen along the marginal sea side, but less intense than that of northeastern Japan, whereas ilmenite-series granitic belt is developed widely along the oceanic side (Fig. 11D). Kuroko and vein type mineralizations with Au, Ag, Cu, Pb, Zn and gypsum occur in the magnetite-series volcano-plutonic belt, but W and Sn are absent. Magnetite-series plutonic rocks appear to be present along aborted rifts within the marginal basins of East China Sea (ISHIHARA *et al.*, 1984), and continue to Taiwan.

The frontal ilmenite-series granitic belt of southwestern Japan is composed of granodiorite and granite of both I and S types (TAKAHASHI *et al.*, 1980). Cogenetic volcanic rocks are known at a few places but to a limited extent. Tin mineralization characteristically occurs as skarn and vein types. Boron silicates and arsenopyrite are also diagnostic in certain areas. Some tungsten and base metal deposits are also present in the ilmenite-series granitic belt.

Tectonic Setting of the Paired Granitic Belts

Plate tectonic models for the Neogene plutonic activities are well presented by many author (e.g., TAKAHASHI, 1980; OHMOTO, 1984). Subduction along the Japan Trench and Nankai Trough are considered the main cause for the Neogene magmatism. Along the oceanic side of southwestern Japan, accretional prism of the Shimanto Supergroup is well developed, and thrusting and faulting are very common in the sedimentary piles. This implies general compressional tectonic setting on the fore arc side from late Mesozoic to Paleogene, due possibly to southeastward migration of southwestern Japan. The frontal ilmenite-series magmatism occurred in Miocene time, and the whole terrane, particularly its southern half as shown by large exposed bodies of the granitoids, was uplifted rapidly by successive regional compression. This magmatism may have been forced to react with rocks of the basement and the accretional prism, thus reduced. If the clastics and its basement materials were rich in tungsten or tin, the ilmenite-series magmatism could form W or Sn ore deposit.

Behind the island arc, on the other hand, many open fractures are developed by spreading of the marginal seas. Magmatism here has less opportunity to interact with continental materials than the fore arc side. Thus the original chemistry of the deep-origin magmas is retained and the back-arc magnetite-series granitic terranes can be formed. This magmatism may not be originated in "fresh" upper mantle materials but those once exposed on near-surface environment, because oxidation is after all a surface phenomenon (WONES, 1981). Fruitful sulfide-forming mineralization with the magnetite-series magmas is principally due to high mobility of the ore constituents with high fO_2 conditions in the magmas (ISHIHARA, 1981).

Cretaceous magnetite-series/ilmenite-series plutonic terranes are considered similarly, in assuming the southwestern Japan was not attached but closely located to the coastal magnetite-series terranes of the Asiatic continent (ISHIHARA *et al.*, 1981a). Here, major difference from the Neogene ones is seen as the Ryoke foliated granitoids and Ryoke metamorphic rocks associated with the Median Tectonic Line. The presence of the Ryoke metamorphic rocks and overlying late Cretaceous sandstones of Izumi Group indicates that the Ryoke granitoids are meso- to katazonal one but uplifted rapidly along the Median Tectonic Line after the emplacement. Thus the tectonic setting may have been similar to that of the Cenozoic paired plutonic terranes.

Similar tectonic situation may be considered during the Jurassic to Early Cretaceous time, because the NW-SE variation in texture and composition of the Daebo granitoids in southern Korea resemble very much with that across the Ryoke belt (ISHIHARA *et al.*, 1981a). Besides, high temperature-type metamorphic rocks and migmatites are recently found along the Fujian coast (LI *et al.*, 1983). The whole rock Rb-Sr ages of 160–200 Ma correspond to the Early Yanshanian cycle. Hence, this belt may be coupled with the ilmenite-series granitic belt of the Nanling Range and sporadic magnetite-series granitoids behind it. The presence of foliated granitoids and migmatites along the ilmenite-series granitic front implies regional shearing during the emplacement, deep levels of their formation and subsequent rapid uplift. All of these are in accord with the compressional tectonic setting assumed from analysis of Neogene ilmenite-series granitic belt in southwestern Japan.

The wide zone of the Jurassic-Early Cretaceous magmatism at the Korea-Daxinganling transect (Fig. 11A) can be explained by subduction of hot oceanic ridge (TAKAHASHI, 1983). Here, the Songliao basin in Northeast China is considered as an aborted marginal basin where many tensional fractures were developed at the initial stage. This tectonic setting could make possible to produce wide but less intense magnetite-series magmatism than that of the Cenozoic circum-Japan Sea region. We need more quantitative data to reconstruct the magmatic history of Northeast China.

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Geology and Tectonic Setting of Copper and Chromite Deposits of the Philippines

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ABSTRACT

The Philippines is an amalgamation of various crustal terranes (magmatic arcs, ophiolites, microcontinents) that have coalesced in response to complex and rapidly changing interaction between converging magaplates since the Mesozoic. Several sets of collided magmatic arcs and trench sutures are interpreted from structural ridges and basins which define the archipelago.

Copper deposits in the Philippines are genertically classified into those of oceanic and island arc origins. The first include the Cyprus-type massive sulfides and the vein-type deposits exclusively found in thrusted/uplifted mafic-ultramafic rocks in ophiolitic terranes. Metamorphosed equivalents of these deposits are the Besshi-type, associated with basic schists.

Island arc copper deposits are the Kuroku, porphyry copper, contact metasomatic and vein-type deposits whose origins are generally related to the intrusion of intermediate calc-alkaline igneous rocks attributed to subduction processes.

Chromite deposits in the Philippines are of podiform type and are exclusively found in ophiolitic terranes where metamorphic harzburgite immediately below gabbro is exposed. The most productive horizon of chromite is within a region extending 1.4 km below the gabbro-peridotite transition.

Differentiating the distribution and ages of mineralization of the various types of copper and chromite deposits on the basis of the evolution of their associated magmatic and ophiolotic terranes is an important step towards the long term exploration of similar deposits.

INTRODUCTION

During the past two decades, the geological sciences have undergone a major revolution brought about by the development of the Plate Tectonic concept. Correspondingly, previous concepts on the geologic evolution of many areas have come under close re-examination and scrutiny in the light of the new framework. The Philippines has been no exception to this. On the contrary, it has become the focus of vigorous researches because of the fact that it lies in a region where primary plate tectonic processes are actively at work or have been recently active. As an island arc-protocontinental complex, it exhibits the tectonic processes and features that characterize the transition stage in the development of simple island arc into continental masses, and is therefore of great value in understanding the development of continents.

Following in the heels of the new tectonic concepts, new interpretations have been developed with regard to the origin, occurrence and distribution of mineral deposits. It has long been recognized that mineral deposits are strictly related to certain domains (BILBIN, 1968; SAWKINS, 1972; MITCHELL and GARSON, 1981; MITCHEL, 1982). Consequently, attempts to define the space-time relationship between mineral deposition and tectonic events/processes have become a major concern in mineral exploration strategies.

This paper proposes a framework for understanding the tectonic evolution of the Philippine islands based on most recent information and concepts. It then attempts to correlate the distribution of copper and chromite deposits with their tectonic setting as imterpreted on the basis of the proposed framework.

TECTONIC EVOLUTION OF THE PHILIPPINE ISLANDS

The Philippines forms part of a very active region caught at the junction between three convergent megaplates: the Eurasian Plate in the west; the Philippine Sea Plate in the east; and the Indo-Australian Plate in the south (Fig. 1). This region is now made up of several small oceanic basins, island arcs, fragments of micro-continental blocks, and proto-continental complexes made up of bits and pieces of various crustal elements. The tectonic history of this region is apparently complex, characterized by rapid shifts in subduction regimes, back-arc spreading, micro-continental block rifting, ocean crust trapping and large scale collisions, and accretion of various crustal elements (HAMILTON, 1979).

The manifestation of these processes is well reflected in the geology and structure of the Philippine archipelago. The archipelago is presently surrounded on almost all sides by several small pieces of oceanic crust whose junctions with the archipelago are characterized by oceanic trenches. Altogether, these trenches define a system of convergent zones that enclose or "sandwich" the archipelago from both flanks. This is a unique tectonic feature of the islands and underscores the apparent importance of subduction processes in the islands' tectonic development.

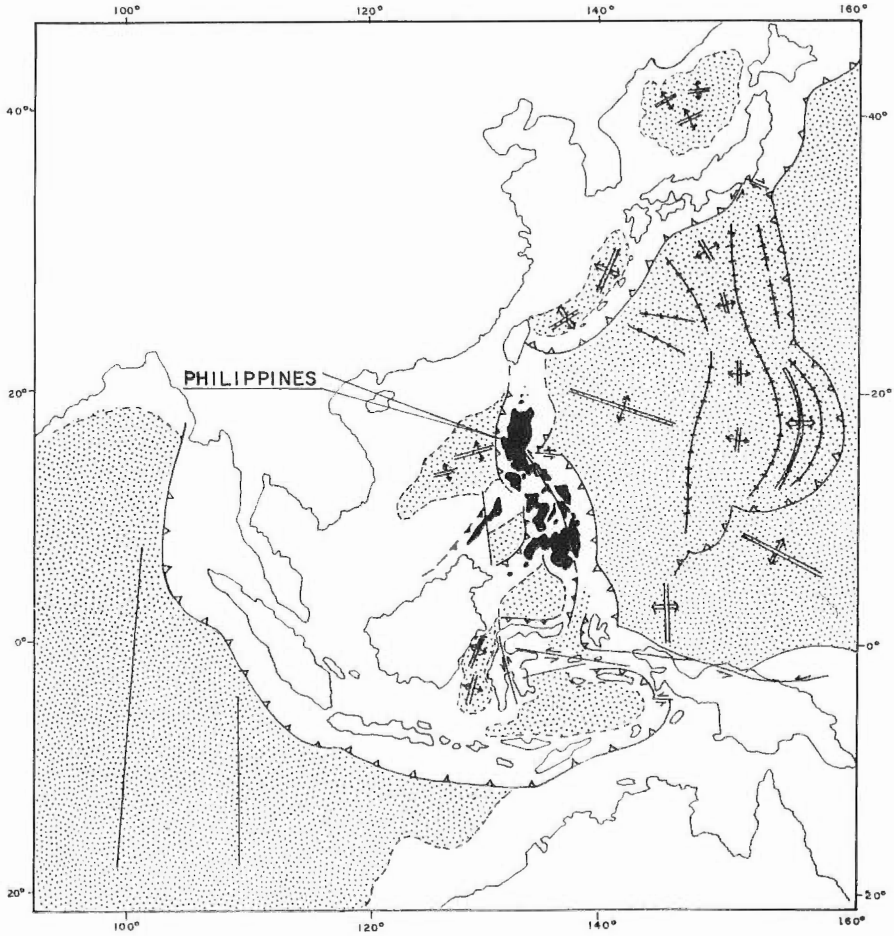

Fig. 1. Generalized tectonic map of East and Southeast Asia.

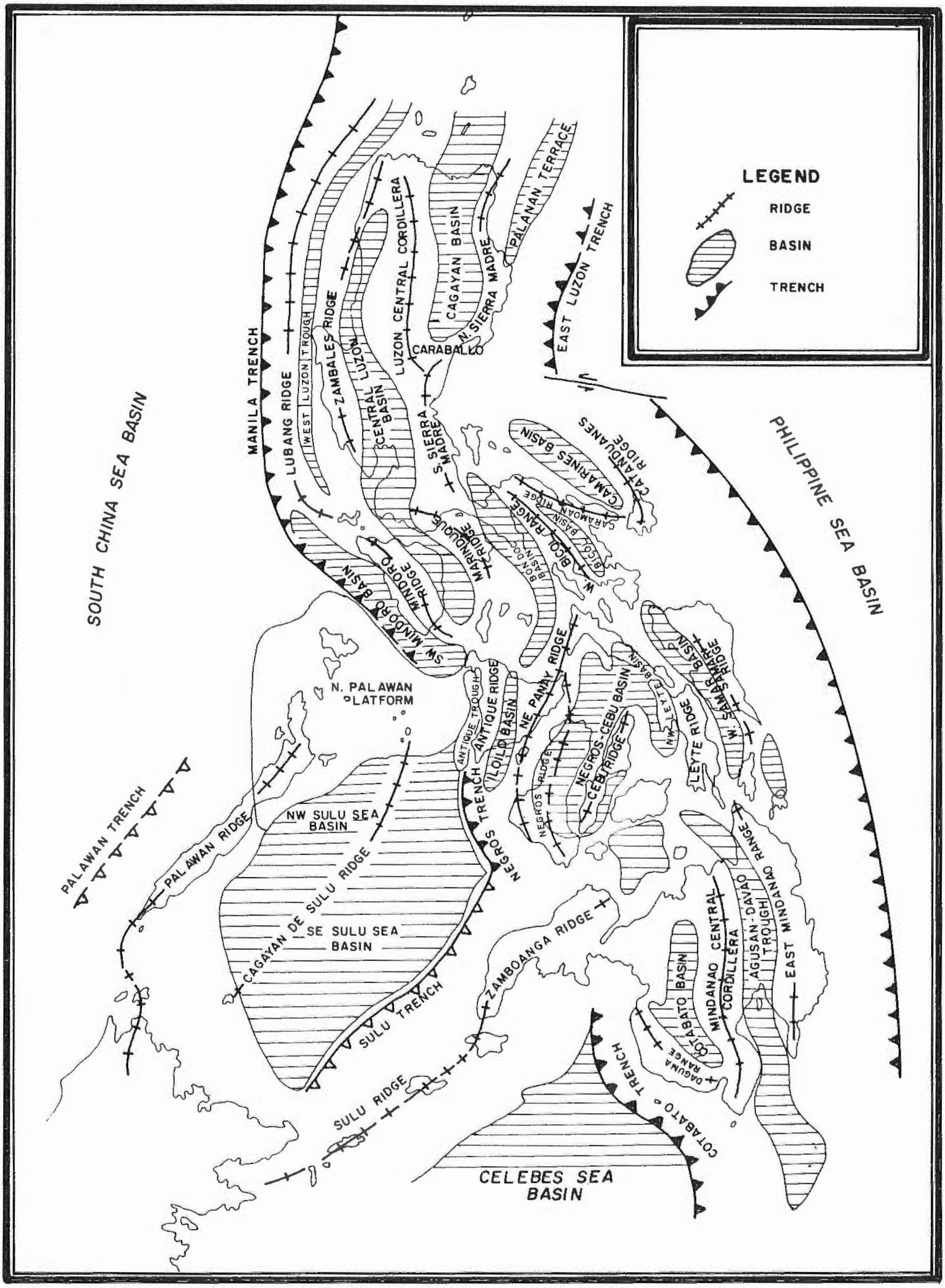

Fig. 2. Ridge and basin structure of the Philippinnes.

The Philippine archipelago is structurally defined by a series of sub-parallel alternating ridges and basins (Fig. 2) that generally follow the trends of adjacent trenches (BALCE and ZANORIA, 1980). The ridges are geologically varied in nature.These are generally made up of: a) Plio-Pleistocene volcanic centers whose origins are attributable to the subduction in the adjacent trenches; b) dioritic stocks and batholiths that have intruded into a generally undifferentiated but predominantly ophiolitic basement; c)ophiolite blocks; d) melange; e) metamorphic massifs and f) folded sediments.

The basins that separate these ridges are commonly elongated in form and thickly sedimented. However, the structural origins of most of these basins, and their relationship to the adjacent ridges are little understood in most cases.

A significant development has been made recently, with respect to the nature of the Agusan-Davao Basin in Mindanao. The Agusan-Davao Basin is a deep (12 km) and narrow, elongated basin bounded by the Mindanao Central Cordillera in the west and the east Mindanao Ridge in the east. Offshore to the east is the active Philippine Trench.

From a study of earthquake profiles, CARDWELL *et al.* (1980) recognized two distinct west-dipping Benioff zones beneath Mindanao. The eastern zone of shallow but very intense seismicity was clearly correlated with the subduction in the Philippine Trench. However, the second Benioff zone in the west was not easy to correlate with known convergence zones. This zone of seismicity extends 700 km below Central Mindanao and its projection to the surface coincides approximately with the trace of the Agusan-Davao Basin.

Several lines of evidence indicate that the Philippine Trench in Mindanao and its associated subduction zone is of a very young origin (KARIG, 1982; HAMILTON, 1979). Bathymetric profiles across the trench are identical to those of known young trenches. Seismic reflection profiles indicate little or no accretionary prism across the trench. Furthermore, a thick lobe of sediments is observed in the abyssal floor east of the trench, which, it is reasoned, could have only derived from the Mindanao landmass in the west prior to the formation of the Philippine Trench (KARIG and SHARMAN, 1975). Thus it seems well-evidenced that the Philip-

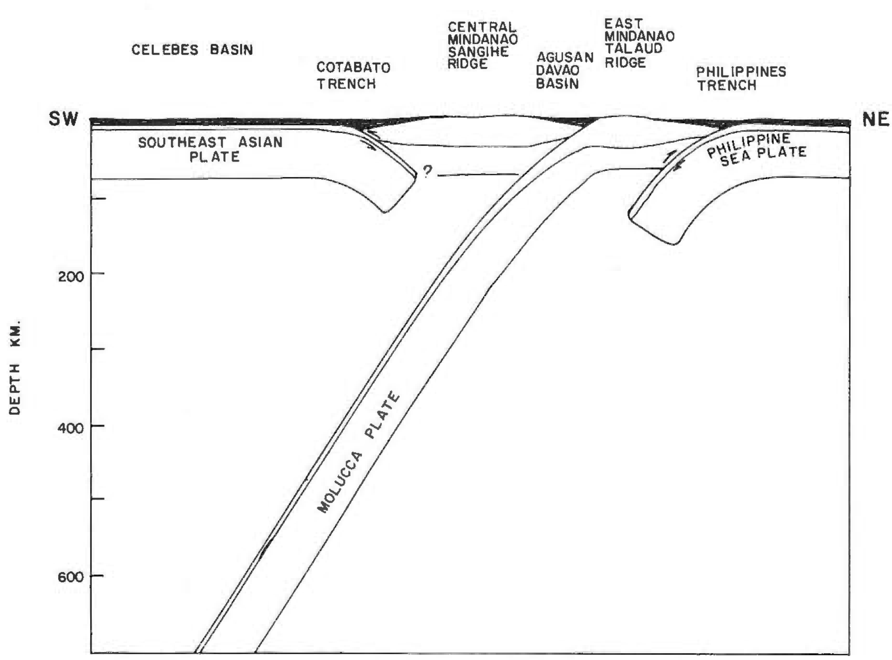

Fig. 3. Inferred plate geometry across East Central Mindanao (Modified after CARDWEL *et al.*, 1980).

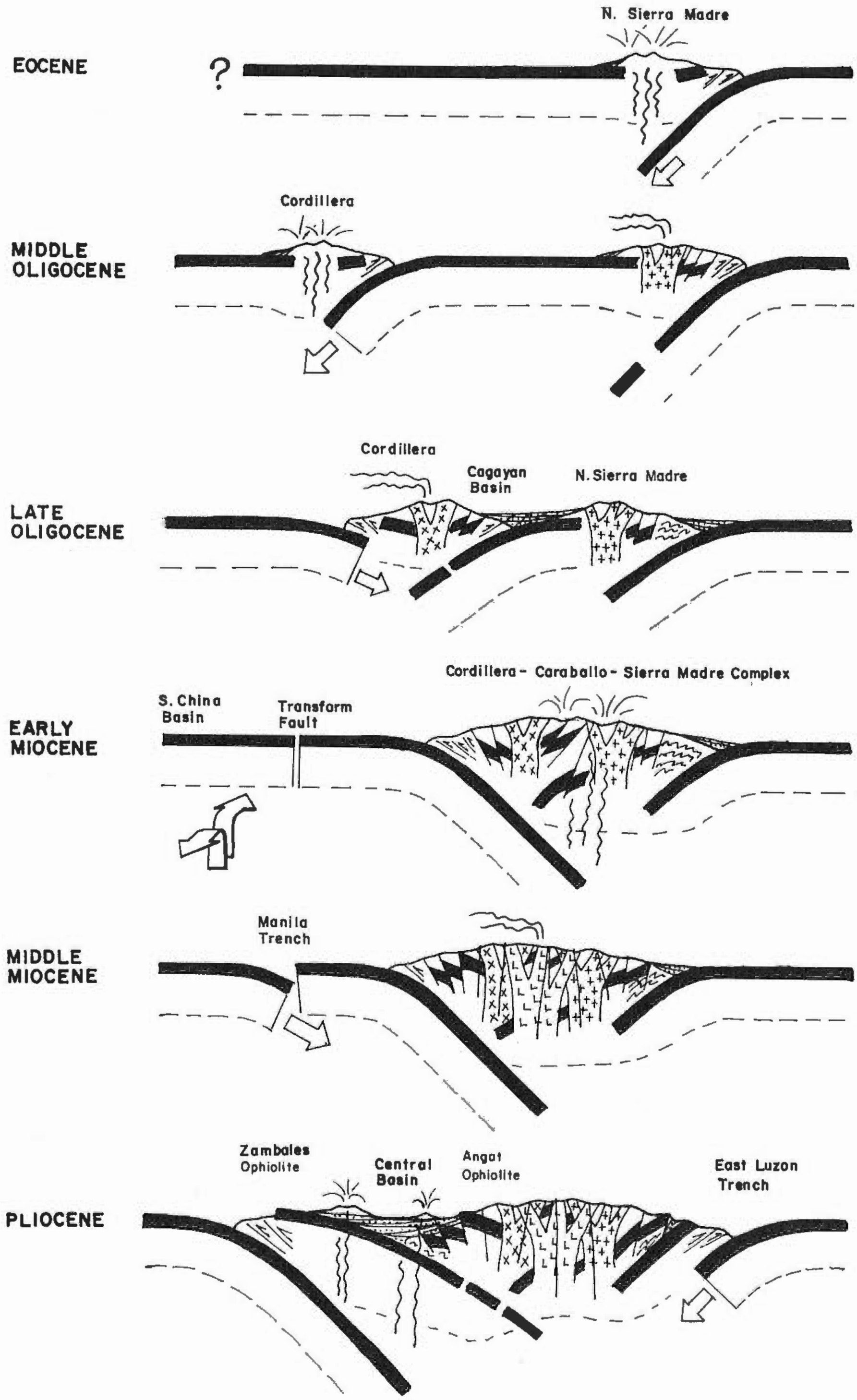

Fig. 4. Schematic model of the tectonic evolution of Luzon.

pine Trench and the subduction along it has a youthful feature, and this view is in harmony with the shallow but very active Benioff Zone beneath Mindanao as well as with the absence of Quaternary volcanism in the east Mindanao Ridge.

CARDWELL *et al.* (1980) then proposed to explain the deep-seated Banioff zone in the west to be a relict of an older subduction system that has since been sutured due to the collision of two arcs. They proposed that prior to the initiation of the Philippine Trench, a west dipping subduction system existed in association with the Central Cordillera arc. However, this subduction came to a close when the Central Cordillera arc collided with a ridge (East Mindanao Ridge) which was riding on the subducting plate. The Agusan Davao Basin now mark the trench suture associated with the collision event. Following the collision, a new trench (the Philippine Trench) developed east of the accreted arcs in response to the continued westward motion of the Philippine Plate (CARDWELL *et al.*, 1980).

The case of Mindanao provides a very unique and compelling illustration of recent arc collision immediately followed by initiation of subduction from a new trench because the relevant two Benioff zones are still recognizable from direct evidence. An important implication of this postulation is the apparent ease by which subduction episodes seem to be capable of terminating and initiating. With the development of the Philippine Trench consequent to the collision, it was apparently machanically easier for the crust to develop a new subduction zone, than to continue convergence and produce extensive collisional features in the suture zone. This well-demonstrated example of a recent arc-arc collision and the development of a successor basin from the suture zone spells significant repercussions on the interpretation of other basins in the Philippine Archipelago.

In reference to the model above-mentioned, it has been recently proposed that the Central Valley Basin of Luzon (Fig. 4) may have evolved in an essentially similar manner (ZANORIA *et al.*, 1982). The Central Valley Basin is a 600 km long and 14 km deep, sediment-filled depression that is bounded by the Luzon Cordillera-Sierra Madre Ridge in the east and the Zambales Ridge in the west. The Cordillera-Sierra Madre Ridge is underlain by a Late-Cretaceous basement, represented by the Angat ophiolite (KARIG, 1982) and intruded by middle Oligocene to Late Miocene dioritic intrusives (WOLFE, 1981). The Zambales Ridge on the other hand is largely underlain by an east-dipping, essentially coherent ophiolite slab of Eocene age (VILLONES, 1980). Through this ophiolite have activated late Miocene to Quaternary volcanoes (WOLFE 1981), whose activities may have been triggered by the subduction of the oceanic crust of South China Basin from the Manila Trench.

Several lines of evidence are cited in support of the view that the Central Valley Basin is the site of a former trench associated with an east dipping subduction zone during the late Oligocene to middle Miocene, that was deactivated in the middle Miocene, and since then, was transformed into a successor basin (the Central Valley Basin) and burried by later sediments:

a) A distinct middle Oligocene to middle Miocene magmatic arc is recognized east of the basin and running parallel with the axis of gravity low. The magmatism of this age is represented by the diorite stocks and batholiths intruding the Luzon Cordillera and Southern Sierra Madre. On the other hand younger igneous activities associated with the subduction from the active Manila Trench cut indiscriminately across all the sedimentary units filling the basin.

b) Lithologic and biostratigraphic characteristics of sedimentary sequences in both edges of the basin indicate that prior to the middle Miocene, the eastern edge had persisted as a shallow, shelf environment while the western edge was a deep marine oceanic environment. The basin became integrated as a single elongated depositional trough only in the middle Miocene (BACHMAN *et al.*, 1982; TAMESIS *et al.*, 1982).

c) The large difference in ages between the two ophiolite basements on each side of the basin suggests a major tectonic boundary between them. Comparison between the respec-

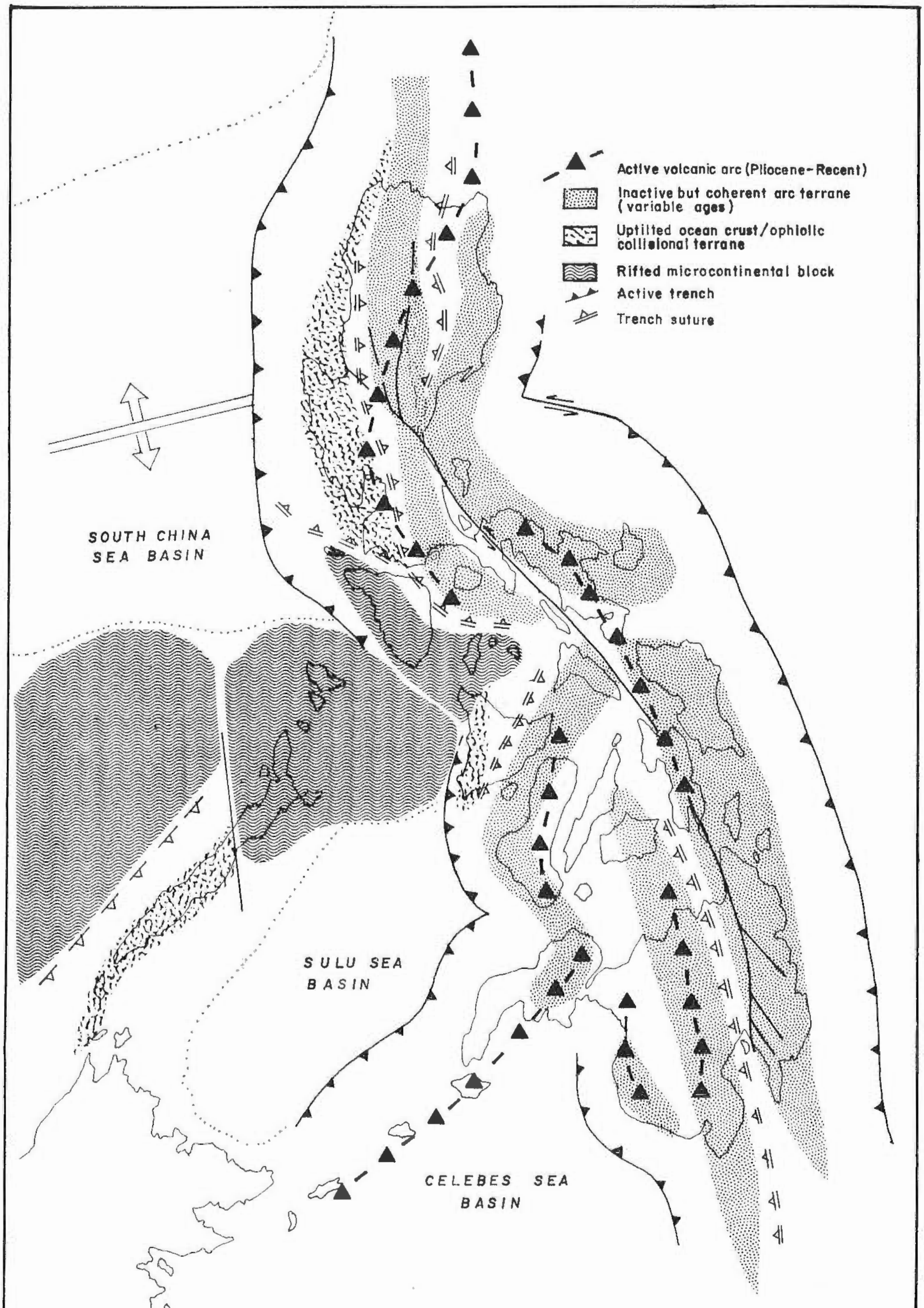

Fig. 5. Tectonic terranes of the Philippines.

tive ages of the ophiolites, in the light of their present separation, further suggests considerable convergence of crustal shortening between them.

d) Seismic sections indicate predominance of east-dipping thrust structures before the late Miocene, followed by continuous and undisturbed sediment-filling thereafter.

These and other lines of evidence were used as basis to speculate that the Central Valley Basin originated from a remnant trench from which east-dipping subduction had caused the middle Oligocene to late Miocene magmatism in the Luzon Cordillera-Southern Sierra Madre Range. This trench became deactivated sometime in the Middle Miocene, when the site of subduction shifted to the young Manila Trench in the west. The Manila Trench is believed to have been initiated from a former N–S transform fault that marked the eastern boundary to the South China Basin Crust. The initiaton of the new trench apparently occurred immediately after the cessation of South China Sea spreading. The Zambales ophiolite is interpreted to be a relict of the subducting slab that became uplifted as a refult of the initiation of subduction from the Manila Trench.

These new postulations on the tectonic development of the east Mindanao region and the west Luzon region illustrate the importance of re-evaluating the tectonic evolution of the Philippines, taking into account the apparently important role of large scale lateral movements of crustal elements related to general convergence in the region. Recent paleomagnetic data (FULLER, *et al.*, 1982) tend to indicate broad contrasts in latitudinal and rotational trajectories among the various terranes and supports the proposition that the archipelago is an agglomeration of terranes (Fig. 5) originating from far and separate origins, that have accreted together into the present proto-continental complex. These terranes generally consist of fragments of ophiolites, microcontinental blocks and various components of island arcs that often serve as matrix to the other units (KARIG, 1982). Apparently, collisions related to plate convergence (subduction) has played a major role in the aglomeration of the various units although lateral motion along major transcurrent faults may also be significant in certain cases. Superimposition of new magmatic arcs over previously accreted terranes commonly provides the matrix in the amalgamation of the various units, and is an important feature in the overall development of the existing island arc-protocontinental complex in the Philippines.

PHILIPPINE TECTONIC TERRANES

Using the above framework of analysis, the major tectonic terranes that make up the Philippines can be differentiated into: 1) ophiolitic terranes; 2) metamorphic terranes; and 3) magmatic arc (dioritic) terranes.

Ophiolitic Terranes

Ophiolitic terranes are interpreted to be the fragments of oceanic crust formed from the magmatic differentiation of upper mantle material at midocean spreading regions. In the Philippines, ophiolites commonly form the primary basement upon which magmatic arcs formed by the subduction process were built up. However, in this setting they are rarely coherent and has generally undergone complex structural deformation and varying degrees of metamorphism. They are commonly referred to as "undifferentiated Cretaceous-Paleogene basement complex" in the literature. The ophiolitic origin of the basement is unmistakable, however, as evidenced by the common association of greenshist-metamorphosed pillow basalts with intercalated deep marine sediments and occasional gabbros and serpentinites. These ophiolitic materials are sometimes tectonically mixed with coarse volcanolithic sediments, pyroclastics and shallow marine clastics that probably represent earlier stages in the development of the island arcs.

A rare example of an essentially coherent oceanic slab exposed on land is the Zambales ophiolite (Fig. 6). A complete and continuous sequence from pillow basalts to metamorphic harzburgite is clearly traceable across the section of the ophiolite (EVANS and HAWKINS, 1982). This extraordinary preservation of the oceanic slab may be attributed to the unique manner of its emplacement related to the suturing of the Cental Basin Trench in the east and the initiation of the Manila Trench in the west. The combined effect of downtilting on one side

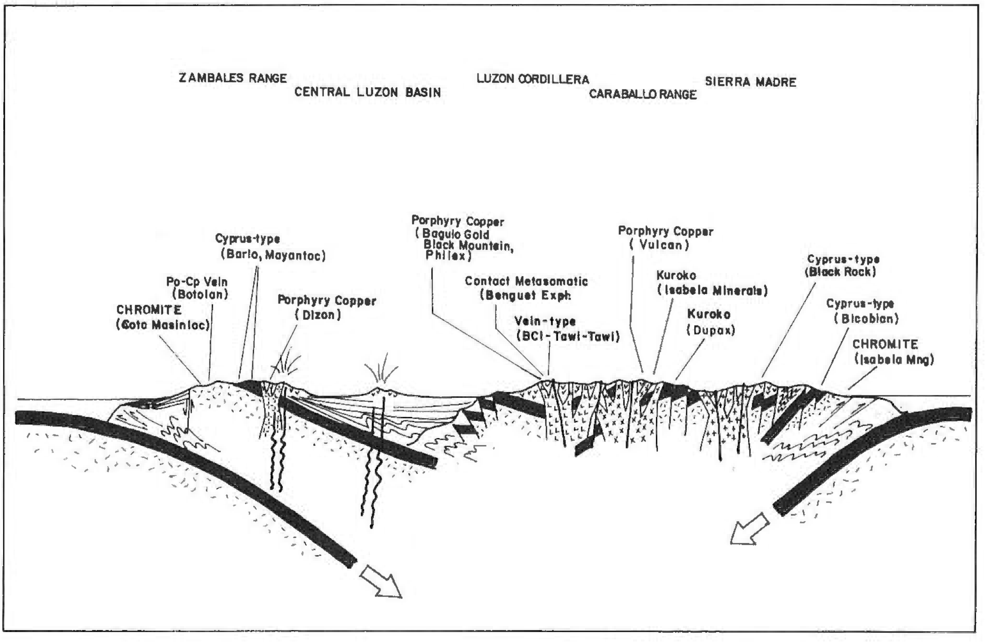

Fig. 6. Tectonic section across Luzon.

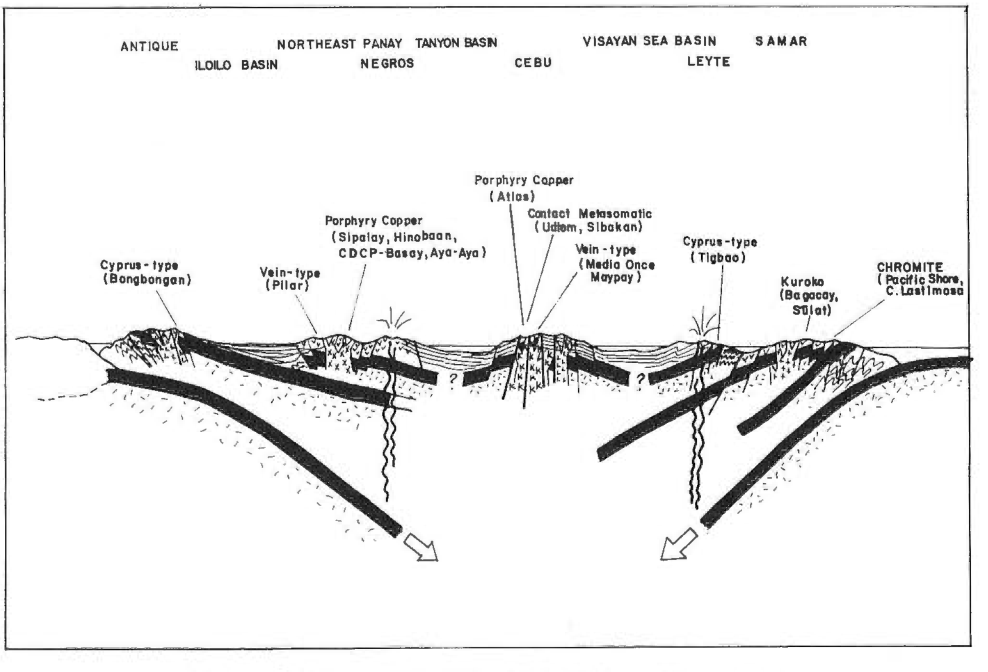

Fig. 7. Tectonic section across North Palawan-Visayas Region.

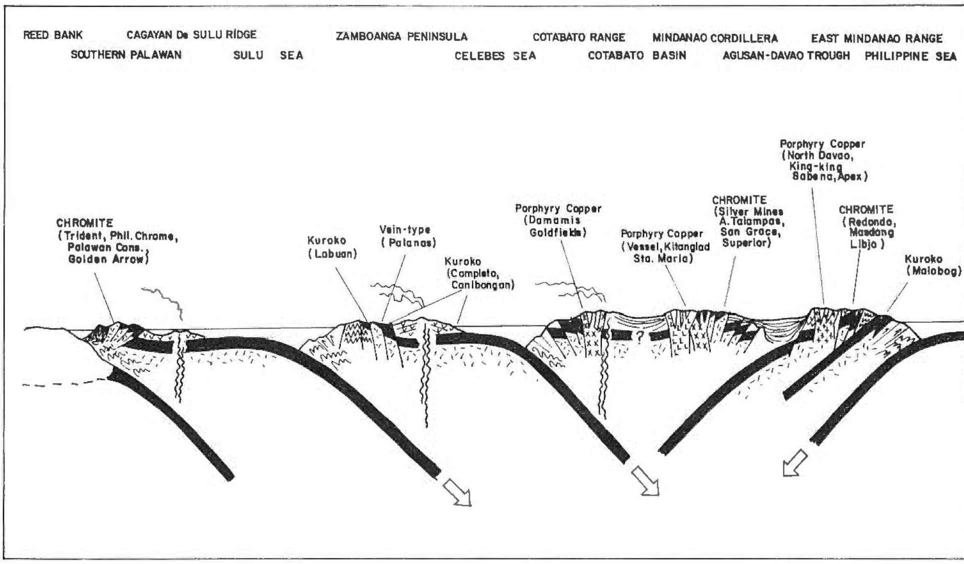

Fig. 8. Tectonic section across South Palawan-Mindanao.

and uplifting on the other may have been a major factor in the unique trapping and preservation of the ophiolite slab.

Another setting for ophiolitic terranes are in the areas of apparently recent collision. The best examples of this are the Southern Palawan and Antique Regions (Fig. 7), both of which are in the zone of collision with the rifted Reed Bank-North Palawan micro-continental blocks (HAMILTON, 1979; McCABE, 1982).

Metamorphic terrances

Metamorphic terranes in the Philippines are differentiated into two types: 1) Pre-Jurassic continental metamorphics, and 2) Post-Jurassic island arc metamorphics (Fig. 9).

The first type is best represented by the metamorphic terranes that make up the Reed Banks, North Palawan and Mindoro. These have been shown to be continental blocks drifted away from mainland Asia during the sea floor spreading of the South China Sea Basin during 32–17 m.y.b.p. (TAYLOR and HAYES, 1980). This type is distinctly characterized by its association with the oldest rocks in the Philippines, its silica-rich composition and its contiguity over a restricted area situated adjacent to the South China Sea Basin.

The second type of metamorphic terrances occur in smaller patches throughout the islands. Their compositions are suggestive of basic to ultrabasic protoliths. Their origin is likely related to deeper sections of old island arcs or to regions of former collision.

Magmatic Arc (Dioritic) Terrances

The occurrence of magmatic arcs that are not correlatable in space or time with the active subduction zones are direct indications that the evolution of the archipelago has involved older island arcs systems that have since coalesced together and upon which new magmatic arcs are superimposed. Based on stratigraphic and available radiometric dating (mostly from Luzon), of these dioritic intrusives, several sets of magmatic arcs have been delineated. The delineation is however generalized in nature and may be highly speculative in some parts because of the weakness of available data. It should be mentioned that since the framework of analysis recognizes that these magmatic arcs may have originated from separate and independent subduction systems before their coalescene into the present geography, their corresponding episodes

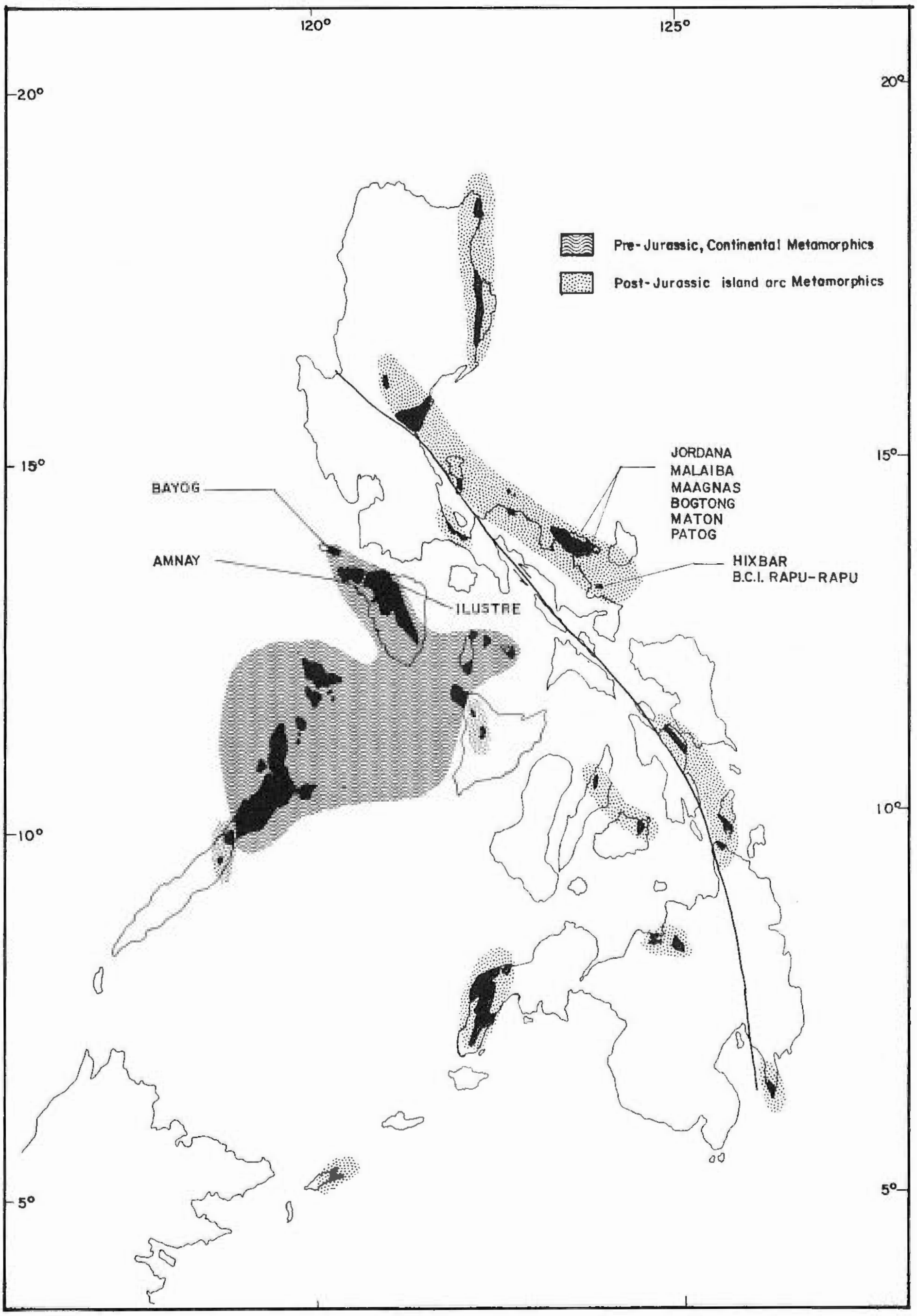

Fig. 9. Metamorphic terranes and associated Besshi-type copper deposits.

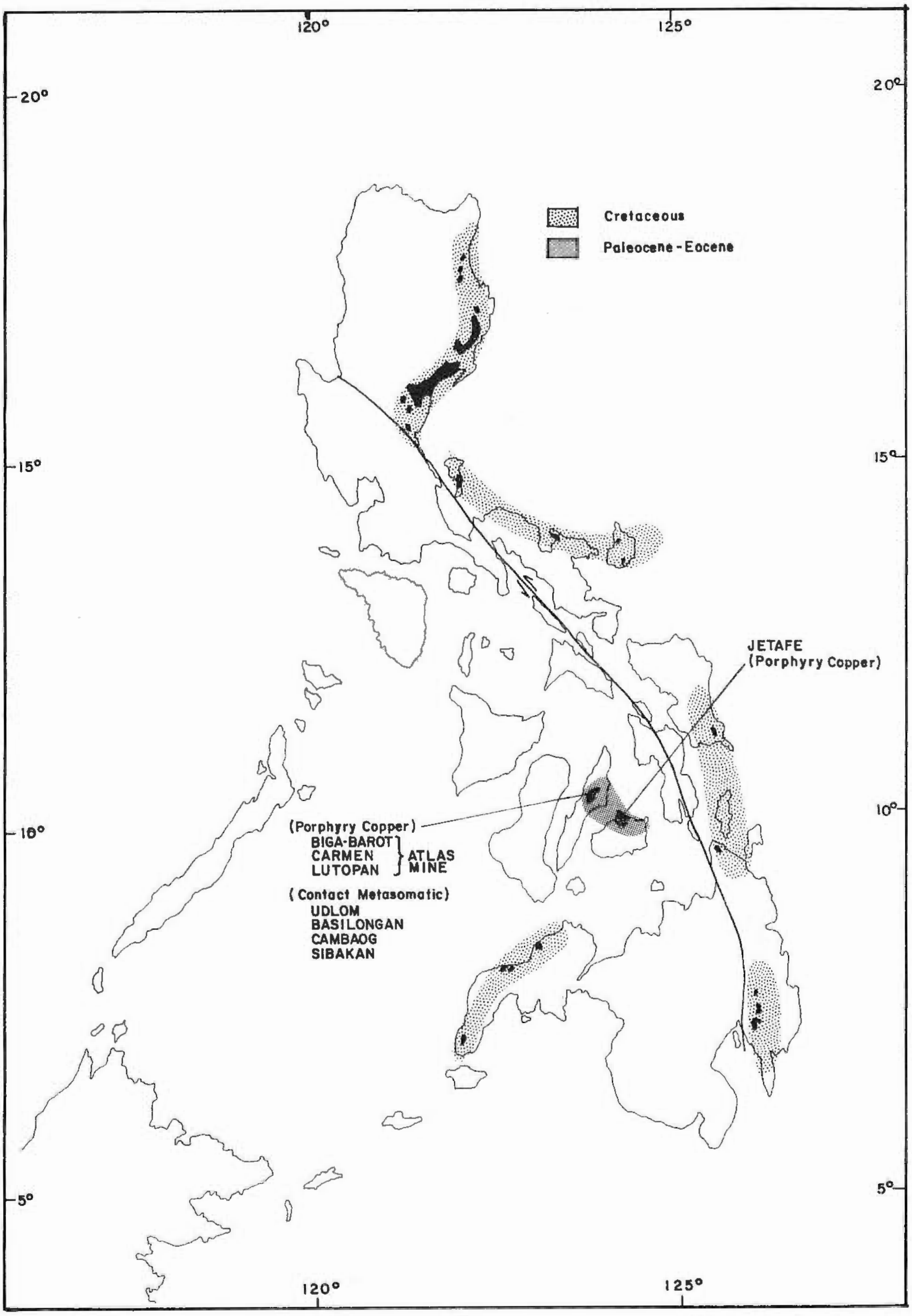

Fig. 10. Cretaceous-Paleogene dioritic intrusives and associated copper deposits.

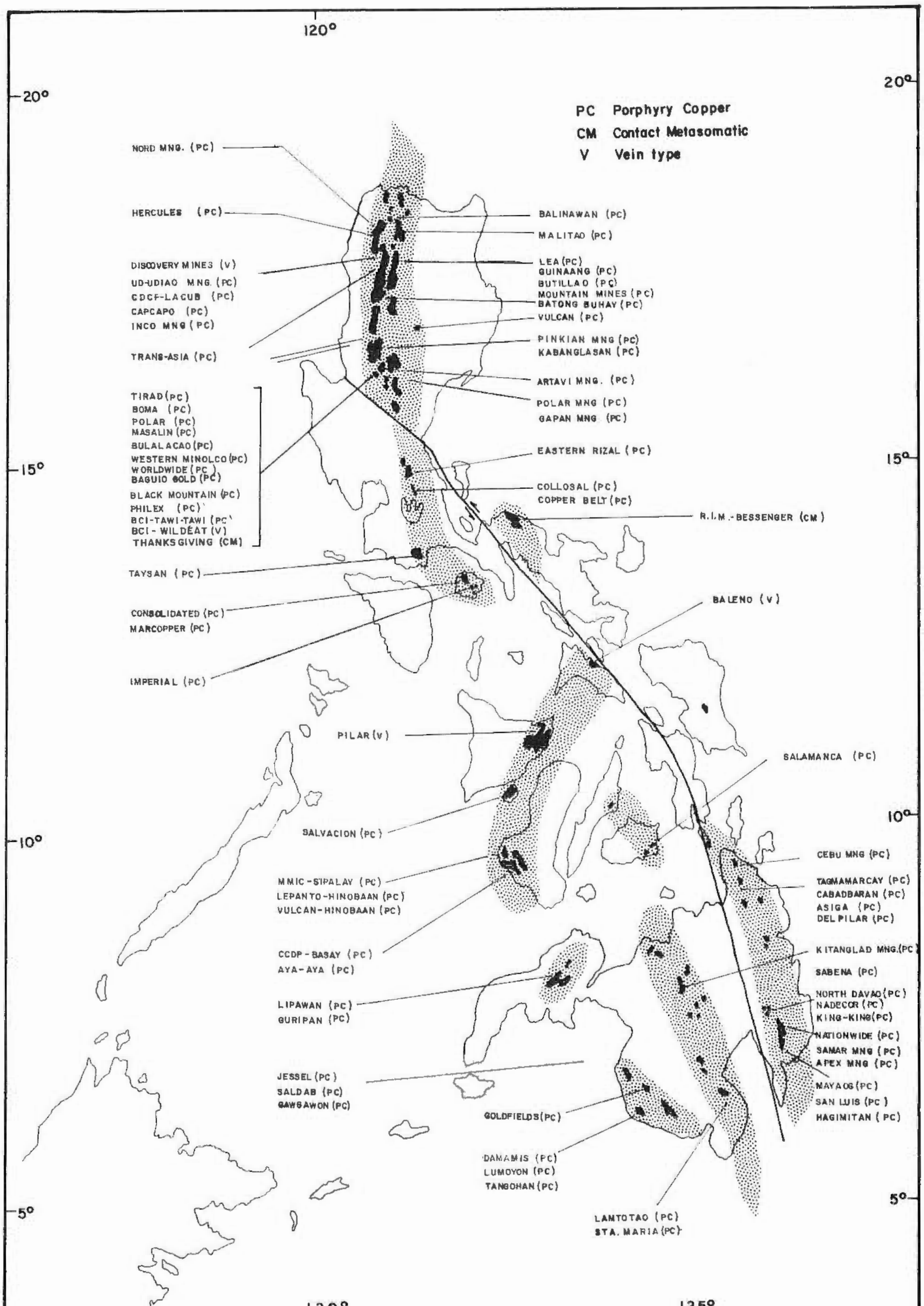

Fig. 11. Oligocene-Miocene dioritic intrusives and associated copper deposits.

of magmatism may be overlapping. There is no need in trying to define distinct time boundaries applicable for the entire archipelago. It is more important to define better the time range of magmatic activity in each locality so that distinct belts can be identified and the effect of overprinting is differentiated.

The oldest dated dioritic intrusive (Fig. 10) is the Lutopan diorite of Cebu which, from most recent radiometric studies, yielded a late Early Cretaceous age (WALTHER *et al.*, 1981). We have correlated this intrusive with similar diorite bodies in northern Bohol. However, the polarity of subduction related to this magmatism is unknown and may be difficult to ascertain due to obliteration of possible indicators. The diorites in northern Sierra Madre have K–Ar ages ranging from early Eocene to early Oligocene (WOLFE, 1981). The age of this terrane makes it distinct from the Luzon Cordillera diorites (Late Oligocene-Middle Miocene) and suggests a possible tectonic boundary in the Cagayan Valley Basin that separates the two arc terranes. In the Southern Sierra Madre, a Cretaceous arc has been postulated by KARIG (1982), behind which the Late Cretaceous Angat Ophiolite is believed to have formed in a back-arc spreading regime.

Oligocene and Miocene dioritic intrusives are more extensive and make up distinct belts throughout the archipelago (Fig. 11). The age of the extensive belt of diorites in the Luzon Cordillera is well constrained by stratigraphic and radiometric evidence to range from middle Oligocene to late Miocene. It continues southward to include the intrusives in the Southern Sierra Madre, Batangas and Marinduque Island (WOLFE, 1981), where it terminates against the nose of the North Palawan-Mindoro continental basement. This arc is correlated with a former east-dipping trench now burried under the present Central Valley Basin. Earlier, this magmatic arc was attributed to subduction from the Manila Trench. However, this idea has become untenable (ZANORIA *et al.*, 1982) in view of the more recent information that the South China Sea Basin had barely started to open during the Oligocene time (TAYLOR and HAYES, 1980).

The diorites in southwestern Negros have been radiometrically determined to be of middle Oligocene age. This correlates with the stratigraphic ages of the diorites in eastern Panay and Masbate, and may continue southward to link up with similarly aged intrusives in northwestern Mindanao. We prefer to correlate this arc with an east-dipping trench whose northern part is now partly buried under the Iloilo Basin and continues southward to connect with the present Negros Trench. This is because the free-air gravity low over the Negros Trench is observed to continue onshore to Panay, following the axis of the Iloilo Basin.

Inasmuch as a similar Oligocene magmatic arc with an east-dipping subduction zone is recognized in Luzon, it is possible to speculate that the two arcs and subduction systems had been contiguous before it collided with the nose of the North Palawan microcontinent in the middle Miocene.

The ages of the diorites in central Mindanao have not been determined. However, bacause of the demonstrated relationship between the Central Mindanao Ridge and a former west-dipping trench in the Agusan-Davao Basin (Fig. 3), the diorites in central Mindanao and considered to belong to a single terrane. These diorites probably relate with small bodies of Middle Miocene diorite intrusives in Cebu and southern Bohol.

The diorites in eastern Mindanao and southern Leyte are considered together as belonging to the terrane which was accreted unto Mindanao (CARDWELL *et al.*, 1980) after the suturing in the Agusan-Davao Basin. The polarity of the subductin associated with this arc is uncertain.

The ages of the diorites in the Cotabato Ridge in Southern Mindanao are also not dear but some of them may be related to the subduction along the Cotabato Trench.

The interrelationship between these various terranes as resault of their coalescence and juxtaposition is illustrated by interpretative tectonic sections across the northern, central and southern portions of the archipelago (Figs. 6, 7, and 8).

COPPER AND CHROMITE DEPOSITS

Cooper deposits in the Philippines, using the plate tectonic framework on the geologic setting of mineral deposits (MITCHELL and GARSON, 1981), are genetically classified into those of oceanic and island arc origins (Table 1). The first genetic types include the Cyprus-type massive sulfides and the vein-type deposits exclusively found in mafic-ultramagic rocks. The second genetic types, associated with island arc magmatism are the Kuroko, porphyry cooper, contact-metasomatic and vein-type deposits. Metamorphosed equivalants of the massive sulfide deposits, associated with schistose rocks, are the Besshi-type.

The chromite deposits, containing both metallurgical and refractory type ores, are of the podiform type exclusively found in the peridotite-dunite-gabbro portion of the ophiolite terranes.

Cyprus-type Copper Deposits

The deposits of this type are found mainly in the ophilotic belts on the eastern and western flanks of the archipelago (Fig. 12). Stratigraphically, the deposits are found at the top of ophiolitic sequences composed of spilitic basaltic flows and pillow lavas, tuffaceous interbeds and cherty sediments. The orebodies, normally occurring as lenses concordant to the primary stratification of the host rocks, are composed of massive fine-grained pyrite-chalcopyrite-sphalerite ores with subordinate amount of bornite, chalcocite and tetrahedrite, and minor amounts of silver and gold.

The Barlo Mine, located in the Zambales ophiolitic suite, is a representative of this type of deposit (Figs. 6 and 12). The area is underlain by a middle Eocene sequence of basalts, spilites and quartz keratophyres overlying a thick pyroxenite-gabbro layer which is believed to be a part of an old island arc root (EVANS and EAWKINS, 1982). The lenticular orebodies

Table 1 Classification of Philippine copper deposits.

GENETIC TYPE	GEOLOGIC SETTING	ORE MINERAL ASSEMBLAGE
A) OCEANIC		
1. CYPRUS-TYPE	Submarine spilitic basalts and pillow. flows in Cretaceous-Paleogene ophiolitic suites	Massive Py.-Cp; subordinate Sp, Bo, Th, Tn; moderate Ag : Au
2. VEIN-TYPE	Gabbroic rocks in Paleogene mafic-ultramafic complex	Po-Cp; subordinate Py; minor Sp
B) ISLAND ARC		
1. KUROKO	Early to Late Miocene felsic volcanic flows and pyroclastics, and intercalated normal sediments	Cp-Sp-Gl-Py; subordinate Bo, Cc, Cv, Th, Tn; moderate to high Ag : Au
2. PORPHYRY COPPER	Cretaceous-Paleogene metavolcanics/metasediments intruded by Cretaceous, Oligecene or Miocene diorite-grano-diorite plutons	Cp-Py-Bo; varying amounts of Sp, Gl, Mo, Mt, Cv, Cc; low Ag : Au
3. CONTACT METASOMATIC	Skarn, Hornfels or Limestone intruded by Miocene dioritic-granodioritic intrusives	Sp-Gl-Cp-Py-Mt; Au-Ag Tellurides moderate Ag : Au
4. VEIN-TYPE		
a) Polymetallic BM Sulfides	Cretaceous-Paleogene metavolcanics/metasediments intruded by Oligecene-Miocene Dioritic-granodioritic plutons.	Cp-Py-Mt-Ht; minor Bo, Co, Cv; low to moderate Ag : Au
b) Copper-Sulfosalt veins	Plio-Pleistocene andesitic-dacitic lava flows and pyroclastics	En-Lu-Th-Tn; varying amounts of CP, Py, Sp, Cc; moderate to high Ag : Au
C) METAMORPHOSED		
1) BESSHI-TYPE	Cretaceous-Paleogene basic and pelitic quartzose Schists	Py-Cp; subordinate to minor amount of Sp, Bo, Cc, Cv; high Ag : Au.

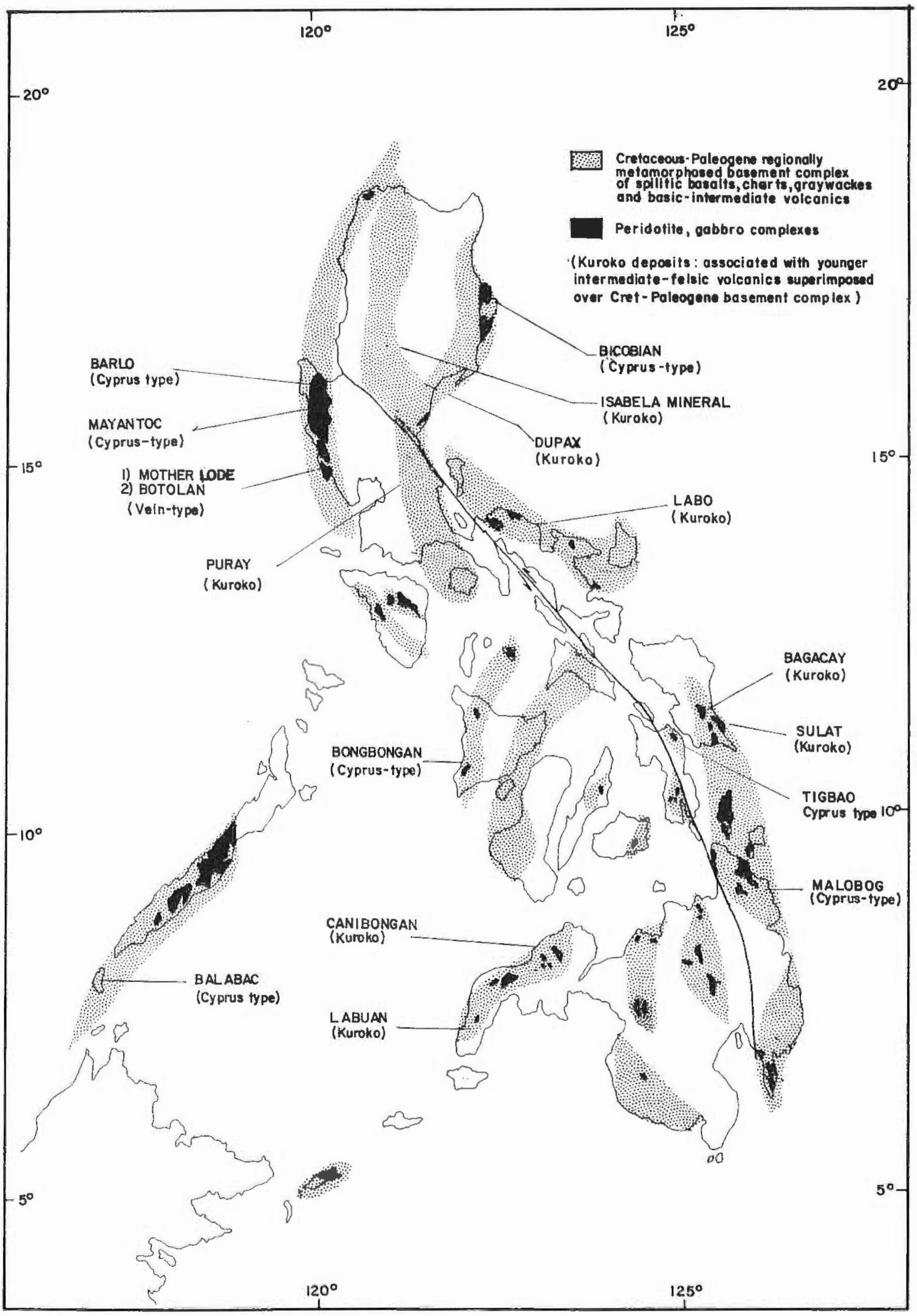

Fig. 12. Ophiolitic terranes and associated copper deposits.

are found in the so-called "boulder gouge", which is probably an altered volcanic breccia (BRYNER, 1969), composed of hydrothermal clay with boulders of silicified volcanic rocks and pillow basalts. The Barlo orebody is composed of massive pyrite-chalcopyrite-sphalerite-bornite-tetrahedrite ores containing an average of 8–9% Cu, 6% Zn, 60 gm/MT Ag and traces of gold.

Similar deposits of this type are found in Bicobian (Isabela), Mayantoc (Tarlac), Tigbao (Leyte), Malobog (Surigao del Sur) and Balabac (Palawan).

Vein-type Copper Deposits in Mafic-Ultramafic Rocks

The mafic-ultramafic complex of the Zambales ophiolite is the host to some copper-bearing quartz veins. Deposits of this type are examplified by the Mindanao Mother Lode Mine and the Botolan Mine in Botolan, Zambales (Figs. 6 and 12).

The Botolan Mine is disposed in an area underlain mainly by serpentine and gabbro. Fissure-filling quartz veins, controlled by two strong faults, are developed in massive, unaltered gabrro. The ore minerals, consisting mainly of massive chalcopyrite and pyrrhotite, with lesser amounts of pyrite, occur in the massive quartz veins as disseminations or as replacement of silicified breccia fragments.

Kuroko-type Copper Deposits

Kuroko-type deposits are associated with intermediate to felsic lawa flows and pyroclastics with intercalations of normal sediments of late Oligocene to late Miocene age. The orebodies occur as massive lense or fragmental breccias conformable with the enclosing bedded host rocks, and as veins/veinlets in the siliceous deeper portions. These deposits have been suggested to be associated with volcanic arcs in tensional stress settings, in contrast to porphyry copper deposits which are associated with compressional settings (NISHIWAKI and UYEDA, 1980). The presence of both types of deposits in the Philippines has not been adequatily explalneed but this may underscore the fact that different arc terranes have coalesced together into the present archipelago. This is not to discount the possibility that individual arcs may have undergone variable stress conditions during its history.

The Bagacay Mine in eastern Samar is an example of this type of deposit The Bagacay Mine in eastern Samar is an example of this type of deposit (Figs. 7 and 12). The area is underlain by dacitic-andesitic volcanic flows and pyroclastics, carbonaceous sediments and reef limestone, capped by red mudstone. The main orebody, the Guild-Guila, has an irregular bottom underlain by garillized volcanic rocks and overlain unconformably by the red mudstone. Mineralogical zoning is observed, from top to bottom, as follows; a) chalcopyrite-sphalerite-chalcocite; b) pyrite-chalcopyrite-sphalerite; and c) massive pyrite (BRYNER, 1969). Accompanying gangue minerals are barite, gypsum and calcite.

Similar deposits are those of the Isabela Mineral (Isabela), Dupax (Nueva Vizcaya), Labo (Camarines Norte), Sulat (Eastern Samar), Canibongan (Zamboanga del Norte) and Labuan (Zamboanga del Sur).

Porphyry Copper Deposits

The porphyry copper deposits generally occur close to the axis of geanticlines, within or adjacent to dioritic plutons (Figs. 10 and 11). Localization of the deposits are structurally controlled by prominent fault/shear zones, in the intensely fractured apophyses of dioritic stocks and the intruded metavolcanics and metasediments. The orebodies are generally elongate tabular or funnel-shaped, tapering downwards. The ore minerals, occurring mainly as stockworks or disseminations, are chalcopyrite, pyrite and bornite with varying amounts of sphalerite, galena, covellite, chalcocite, magnetite and molybdenite.; minor amounts of gold and silver are also present. Average ore grades range from 0.30 to 0.70% Cu and trace amounts to 1.2 g/MT Au. The ores of the Sipalay Mine contain considerably higher molybdenum content (average of 0.10% Mo) and higher silver to gold ratio (35–40:1 compared to the 1–10:1 in the other porphyry copper deposits).

Based on the presumed ages of the associated dioritic intrusives, three main periods of porphyry copper mineralization have been identified: 1) Cretaceous; 2) Oligocene; and 3) Miocene. The first one includes the Biga-Barot, Lutopan and Carmen Mindanao orebodies of the Atlas mine in Cebu, and the Jetafe copper prospects in northern Bohol (Fig. 10). The Oligocene deposits are those of the Sipalay, Hinobaan, Vulcan, Basay and Aya-aya mines in southern Negros. Miocene, probably extending up to Pliocene, mineralization formed the deposits of Western Minolco, Sto. Niño, Philex and Kennon mines in northern Luzon; the Taysan deposit in Batangas; Consolidated and Marcopper mines in Marinduque Island; and the North Davao, Nadecor, Sabena and Apex mines in southeastern Mindanao (Fig. 11).

Dizon in Zambales, is the youngest known porphyry copper deposit, associated as it is with Late Miocene-Pliocene volcanism related to subduction from the Manila Trench (Fig. 13).

Contact-Metasomatic Copper Deposits

Deposits of this type are found in skarn, hornfels and/or limestone disposed along the peripheries of intrusive dioritic stocks. The orebodies occur as massive lenses, pods and veinlets localized along the contact zone of the intruded rocks and the intrusive plutons. Contact-metamorphic minerals such as garnet, clinozoisite, amphibole, apatite and cordierite are developed in the skarn-hornfels zone, but conspicuously absent in the intruded limestone bodies. The ores are massive and are composed mainly of sphalerite, pyrite and chalcopyrite with variable amounts of galena, magnetite, hematite and pyrrhotite; small amounds of gold and silver tellurides are also present. Ores of the Thanksgiving mine in the Baguio district (Figs. 6 and 11) contain an average of 0.38% Cu, 3.78% Zn 3.9 g/Mt Au, 34 g/MT Ag, and trace amounts of cadmium.

Other deposits of this type are found in Camarines Norte and in central Cebu.

Hydrothermal Vein-type Deposits

Based on the major mineralogical assemblage, two sub-types have been distinguished: 1) polymetallic base metal sulfide veins of Oligocene to Miocene in age, and 2) copper sulfosalt veins of Pliocene-Pleistocene in age.

The polymetallic base metal sulfide-quartz veins (Fig. 11) are genetically associated with the intrusion of diorite-andesite prophyry stocks and dikes of Oligocene to Miocene in age. The deposits of the Baleno mine in Masbate (Oligocene), the Pilar prospect in northeastern Panay (Oligocene), the Wildcat orebody in northern Luzon (Miocene) and the Samar mine in southeastern Mindanao (Miocene).

The sulfide-quartz veins are developed in the outer peripheries of dioritic-andesitic intrusives and in the intruded rocks within several meters from the contact. The viens are localized along fracture and shear zones developed by regional faulting or as a result of the igneous intrusions. Major ore mineral components are massive to granular chalcopyrite, pyrite, hematite, sphalerite and galena.

Although the copper sulfosalt-bearing quartz veins are proximal to dioritic instrusive bodies, their mineralization is genetically attributed to Plio-Pleistocene volcanism that produced basaltic to andesttic-dacitic volcanic lava flows and pyroclastics. The veins are localized along fault and shear zones as massive fissures and breccia fillings. The ores occur as massive bands and lenses and as replacement in silicified host rock fragments. The major ore minerals are engargite and luzonite with variable amounts of chalcopyrite, pyrite, sphalerite, chalcocite; minor tetrahedrite-tennantite, famatinite and gold-silver telurides are also present.

The deposits of the Makayan mine in northern Luzon and of the Lobo mine in central Luzon belong to this sub-type of vein deposits (Fig. 13).

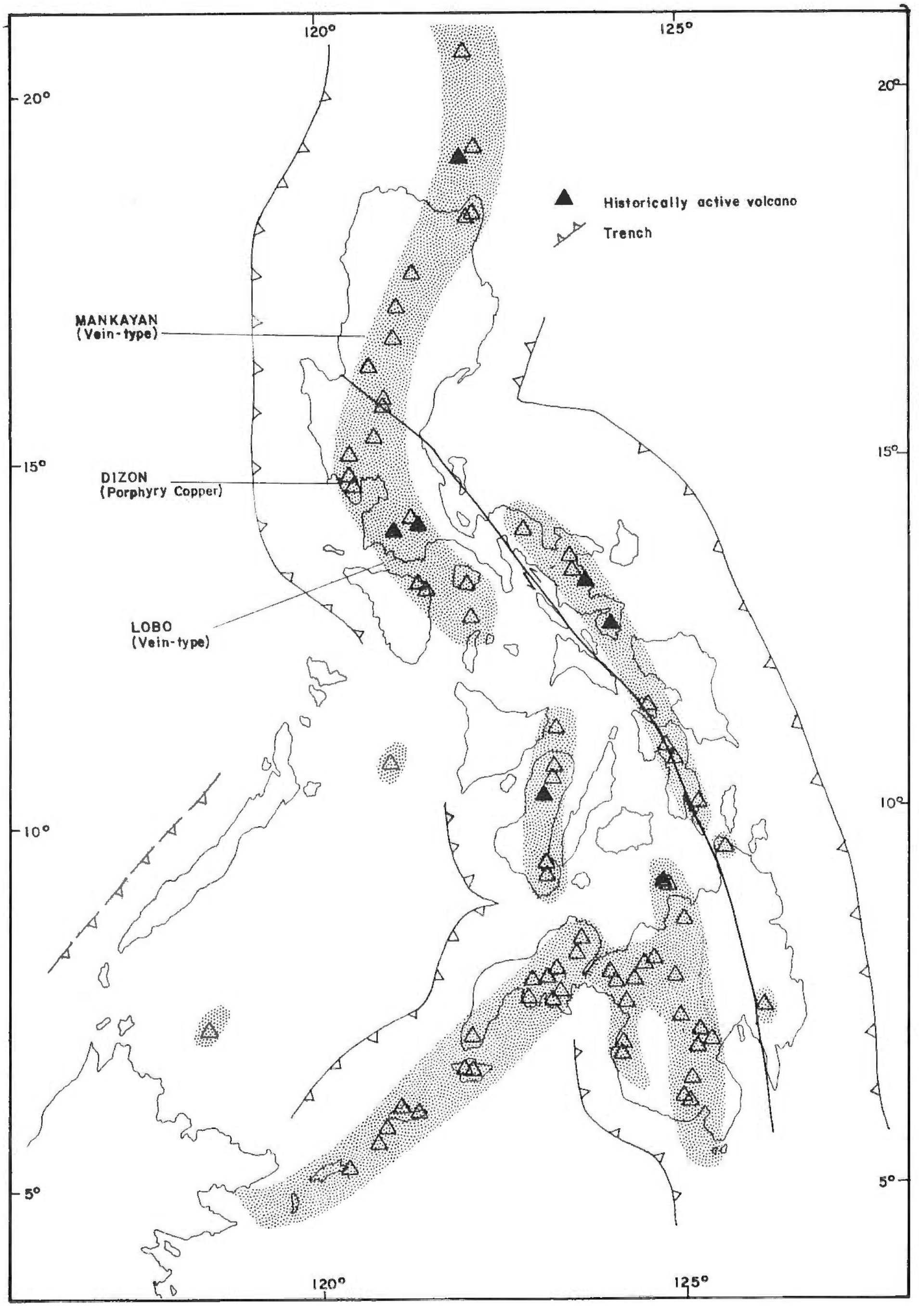

Fig. 13. Pliocene-Recent volcanic centers and associated copper deposits.

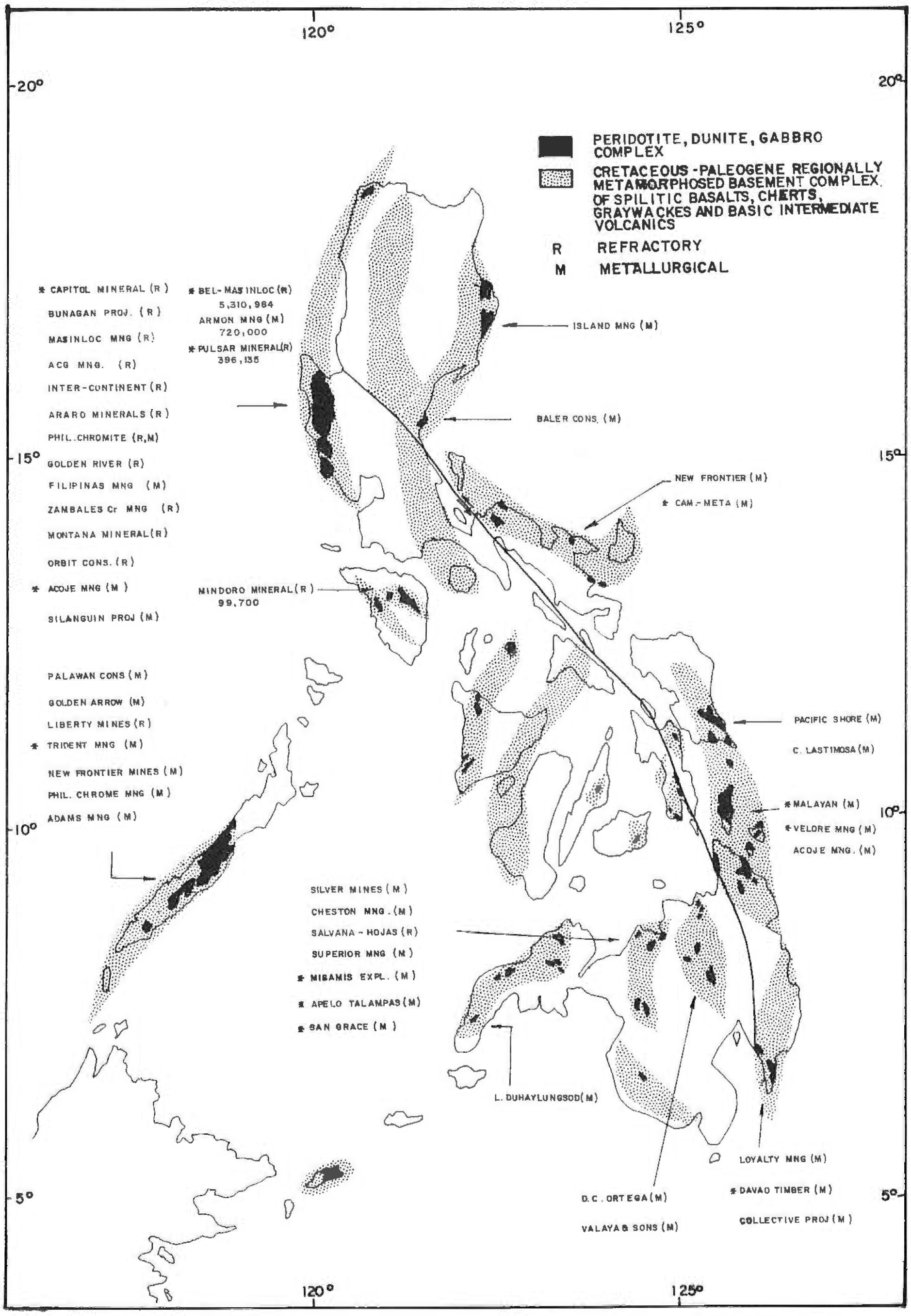

Fig. 14. Ophiolitic terranes and associated chromite deposits.

Besshi-type Copper Deposits

Deposits of this type have been observed in Mindoro Island, Caramoan Peninsula and Rapu Island in Albay (Fig. 9). The deposits occur in basic and pelitic crystalline quartzose schists that have been strongly folded and faulted. The orebodies occur as massive lenses, bands and streaks conformable to the schistosity of the enclosing host rocks. These are generally partly or entirely surrounded by a pyrite halo, especially in the hanging wall side.

The Hixbar mine in Rapu Rapu Island is underlain predominantly by chlorite-epidote schist and quartz-sericite schist. The sulfide orebodies are massive lenses that generally follow the lineation of the host rocks. Relict schistose structures parallel to the schistosity of the wall rocks are observed in some of the ores (KINKEL and SAMANIEGO, 1956) and have been interpreted as possible replacement features. Secondary enrichment zones are sometimes observed in some portions of the deposits. Ores are composed of massive pyrite and chalcopyrite with subordinate to minor amounts of sphalerite, bornite, chalcocite and covellite; minor gold and silver are also detected.

Chromite Deposits

Chromite deposits in the Philippines are exclusively associated with Alpine-type periodotite-dunite-gabbro complexes in ophiolite terranes. These are commonly associated with spilitic basalts, diabases, red cherts and basic metasediments of the ophiolite sequence although the complete sequence is rarely found.

Ultramafic complexes occur in almost all major islands of the archipelago, with an aggregate area occupying about 3.8% of the total land area. The major exposures are generally well-exposed in the western part of the archipelago (Zambales, Mindoro, southern Palawan, Antique and Zamboanga) as well as in the eastern part (Baler, Camarines Norte, Samar, Dinagat, Surigao and Pujada Peninsula). This has led some workers (HESS, 1948; SELIGMAN, 1977) to suggest that the eastern and western belts are differentiated genetically. However, there is at present no sufficient constratint on the ages as well as the dates of emplacement of most of the ophiolite bodies to warrant such a generalization. For example, the Zambales ophiolite is now well recognized to be at least of late Eocene in age (VILLONES, 1980; BACHMAN *et al.*, 1982) while the Palawan Ophiolite may be inferred to be at least Early Cretaceous based on the age of ferromagnesian shales and cherts intercalated with spilitic basalt flows (FERNANDEZ, 1962; BELANDRES, 1964) although both are found in the so-called "western belt". While it is worthwhile to try correlation between the various ophiolites, this might prove to be very difficult when applied over widely separated areas because of the suggested large-scale coalescence of different terranes in the Philippines.

The chromite deposits are typically of podiform type with shapes ranging from tabular, lensoid, pencil-shaped, wedge-shaped to irregular localized mainly within the dunite-harzburgite portion below the gabbro-peridotite transition. Texturally, the ores range from massive, nodular ('leopard type'), brecciated to disseminated. They consist primarily of chromite with varying amounts of magnetite and ilmenite, and trace amounts of nickel sulfides, platinum and palladium. Secondary minerals such as kammererite and uvarovite are developed along slip planes of shears in the host rock.

The largest and the best studied chromite deposits in the Philippines are those in the Zambales area. The Zambales ultramafic complex is divided into two major gabbro-peridotite associations: the Acoje block in the west and the Coto block in the east. The contact between the two units is presently defined by the Lawis Fault, but the age, genetic and structural relations between the two are not clear. The Acoje Block is characterized by the occurrence of metallurgical grade chromite, pyroxenite dikes and association with predominantly noritic gabbro. The Coto block is characterized by the occurrence of refractory grade chromite, mafic dikes and association with olivine gabbros and troctolites. It is the host to the Coto orebody, one of the largest "sackform" deposits in the world, which, by the time it was exhausted, would have produced over 10 million tons of high alumina or refractory ore.

Based on compositional and structural differences, EVANS and HAWKINS (1982) suggests that the Acoje block is a more depleted ophiolite that may represent primitive island arc crust and upper mantle, while the Coto block, which is less depleted, may represent back arc basin crust adjacent to the aforementioned arc.

In the Acoje mine area, a correlation appears to exist between the size, frequency of occurrence and structure, of the chromite orebodies, and their position in the ophiolite stratigraphy (Fig. 16). All of the 32 deposits occur in a zone within 1.4 km below the gabbro-cummulate peridotite boundary (Zone A). The deposits in the upper level, located within the cummulate peridotite horizon, occur in association with a dunitic layer that parallels closely the boundary with gabbro. The deposits in this zone are typically tabular to lensoid bodies, with both layered as well as massive textures and are thinly to thickly disseminated. They display a generally concordant to subconcordant relationship with the structure of the surrounding host rock.

The orebodies in the lower portion of this sections are located within metamorphic peridotite.

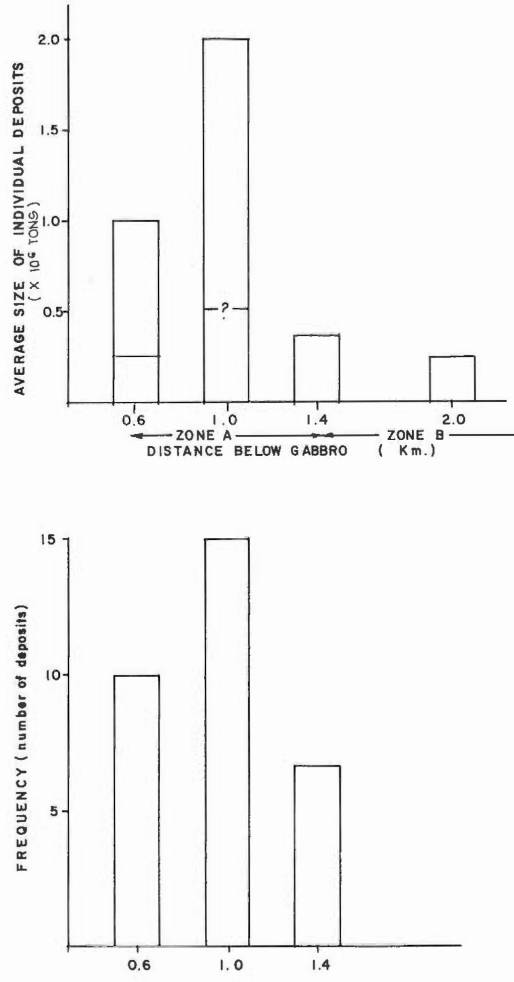

Fig. 15. Frequency and size distribution of chromite orebodies in the Acoje deposits relative to ophiolite stratigraphy.

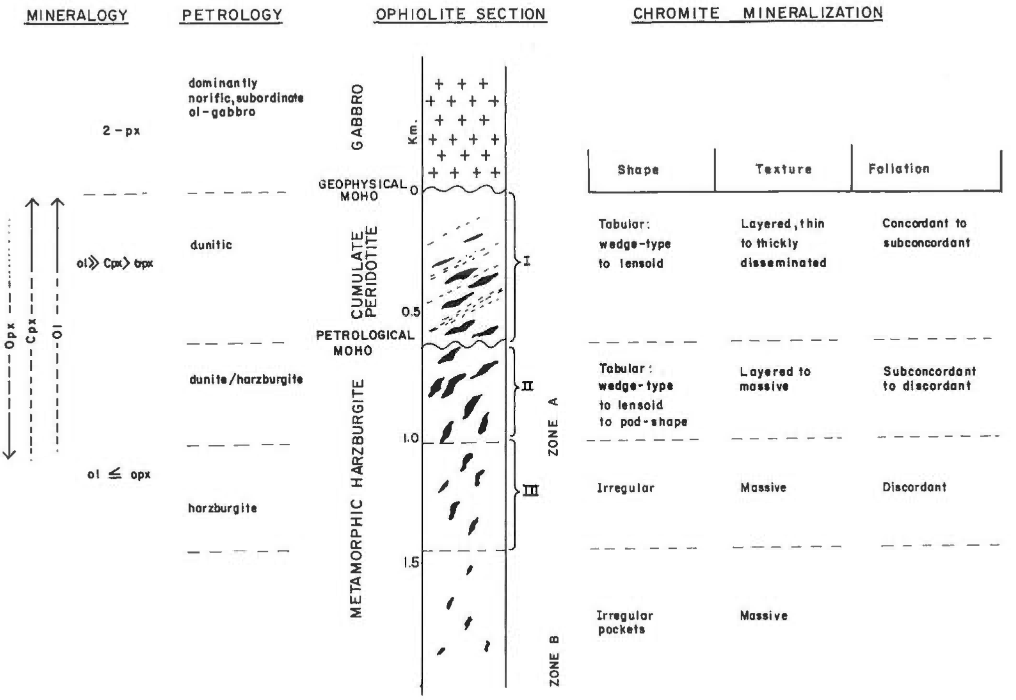

Fig. 16. Stratigraphy and chromite mineralization of the Acoje deposits.

However, these are always found to be enveloped in an aureole of dunite. The chromite bodies tend to be more irregular in shape, are texturally massive, and generally discordant to layering structures in the surrounding peridotite. Rough statistical analysis of the distribution of the orebodies show that the most productive horizon (in terms of both number and size of orebodies) gravitate around the 1.0 km level (Fig. 15). This coincides with the region close below the cummulate dunite-metamorphic harzburgite transition. Incidentally, this transition zone is considerably irregular and undulating with higher amplitudes compared to the gabbro-cummulate dunite boundary, which is less sinuous and essentially flat.

Chromite deposit are also overved to occur in deeper levels of the metamorphic harzburgite (Zone B). These are typically small lenses and pockets that are irregular in shape and massive in texture.

In Coto, chromite zone A appears to be thinner (less 1 km) and most of the chromite deposits are observed to be concordant to subconcordant to structures in the country rock.

SUMMARY AND CONCLUSION

The Philippines has undergone a complex tectonic history characterized by general convergence of various crustal elements, rapid shifting in subduction regimes and directions, back-arc spreading, collisions, rifting and accretion. The geology and structure of the islands reflect this tectonic complexity, with common overprinting and/or obliteration of the various older lithologic and structural units. From what could be deciphered from present observable features, the Philippine archipelago may be subdivided into various tectonic terranes: metamorphic terranes, ophiolitic terranes, areas of dioritic intrusion, and areas of recent or active volcanism.

Analysis of the distribution of the various copper and chromite deposits show direct genetic association between types of deposit and certain tectonic terranes and processes. Chromite deposits, Cyprus-type massive sulfides and pyrrhotite-chalcopyrite vein-type deposits are found to occur within ophiolitic terrances. The intrusive belts of the magmatic arcs are host to Kuroko deposits, porphyry copper deposits, contact metasomatic deposits and polymetallic base metal sulphide vein-type deposits. The copper-sulfosalt veins are related to active or youthful intermediate to felsic volcanism. And the metamorphic equivalents of these deposits, the Besshi-type, are found in older metamorphic terranes.

Based on their genetic association with certain tectonic terranes and processes, the deposits are classified into those of oceanic and island arc origins. The Cyprus-type copper deposits and the pyrrhotite-chalcopyrite veins are classified as oceanic; the porphyry copper, Kuroko, contact-metasomatic and vein-type deposits as island arc. The metamorphic equivalents, the Besshi-type, are classified separately because of the epigenetic deformation they have undergone.

The above is proposed as a framework for understanding the relationship between spatial distribution of the specific deposit types and tectonic regimes of emplacements. However, the insufficiency of data on the ages of mineraliztion of various deposits and the periods of tectonic activity associated with the evolution of the different tectonic terranes preclude the establishment of strict time frames for the formation of certain types of deposits.

The definition of the distribution of the deposits with regards to specific geo-tectonic environments and periods would, undoubtedly, serve as very useful guides in mineral exploration.

Acknowledgements

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The Geology and Economic Significance of Tin Deposits in West Malaysia

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ABSTRACT

West Malaysia can be divided into three different metallogenic belts which are intruded by granitoids. The granitoids in the three belts are identified as the Main Range Batholith, the Central Region and the East Coast Region. The granitic rocks of the Main Range Batholith and the East Coast Region contain economic tin deposits. Small amounts of cassiterite occur in the Central Region but is insufficient for economic exploitation.

Rb:Sr whole rock studies of the granitoids indicate intrusions in the Late Devonian (360 Ma), Late Carboniferous (280 Ma), Late Permian/Early Triassic (250 Ma), Middle to Late Triassic (200 Ma), Late Cretaceous (85 Ma). K:Ar datings suggest epirogenic movements in the Upper Jurassic/Cretaceous boundary, and also in the Late Cretaceous. WNW wrench faulting is believed to have occurred 33 Ma.

$^{87}Sr/^{86}Sr$ studies suggested that the acid intrusives were not derived from the mantle but originated from the sial, or they were products of assimilation of sialic materials with basic magmas.

Rb:Sr ratio indicated that the Main Range intrusives were more differentiated compared to the East Coast Granitoids.

Tin mineralization is thought to be genetically related to the tin-bearing granite massifs but within the same massif, there are also large tracts of granitic rocks which do not contain tin.

The tin deposits can be classified as pegmatitic; pipe; fracture fillings and pyrometasomatic replacements; lode tin; tin-iron; hydrothermal veins and stock-works; alluvial and eluvial; and aplitic deposits.

Tin mineralization is not confined to any specific geochronological event nor is hornblende granite tin-barren as was formerly believed. The different metallization in the three metallogenic belts and the paucity of tin deposits in tin-bearing granites are explained.

Malaysian granitoids are believed to be multiphased intrusives having undergone intra-intrusive processes. Sn is derived either from the intrusive itself or introduced later.

Tin had been the pillar of Malaysian economy, but its contribution to the G.D.P. is slowly dwindling. Reserves are gradually and surely being depleted. The threat to tin by substitutes is a constant battle. Recent world recession and the huge stockpile held by the US has depressed the price of tin which if not arrested will be a severe blow to the tin industry in Malaysia.

BRIEF OUTLINE OF THE GEOLOGY OF WEST MALAYSIA

West Malaysia is tectonically connected with the fold mountain system of eastern Burma which continues southward through Thailand, West Malaysia, Banka and Billiton Islands of Indonesia. Except for some local variations, the regional trend of the fold axis in West Malaysia is approximately north-south to north-northwest and the country lies essentially in the stable Sunda Shelf.

Associated with the folding are large granitic bodies aligned to the regional fold axis, the largest granite mass being the Main Range located on the western part of the country which

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extends for nearly 500 km from north to south, 60–80 km at its widest and rising to more than 2,000 m above sea-level in some places. It is estimated that almost half the total surface area of the country consists of granite and the other consists of sediments and volcanics.

The stratigraphic systems in West Malaysia range from Cambrian to Recent with regional sedimentary breaks in the Devonian, Early Traissic, Late Triassic, Jurassic, the Cretaceous, and the early Tertiary. There are, however, many local gaps in sedimentation, and to-date, there is no geographical province where a complete succession is present.

In the light of geological data collected to-date, it would appear that there were more than one basin of sedimentation and that these basins were migratory. During the Cambrian period, shelf and shallow water deposits dominantly of orthoquartzite-carbonate facies were laid down to the northwest of West Malaysia. During the Silurian the basin of sedimentaiton slowly spread southwards into west central Malaya. There was a mild period of orogeny in the Lower Devonian but post orogentic sedimentation of limestone, shale, mudstone, and conglomerate continued into the Devonian and Carboniferous. During the Late Carboniferous time there occurred a period of mild orogeny with scattered depositional breaks and granite intrusion in many parts of West Malaysia. Late Carboniferous granite are the oldest granites recorded, but granite pebbles have be found in Carboniferous strata indicating the probable existence of an earlier granite. Isotopic age determination also lend support to the probable existence of an older granite body.

Following the Late Carboniferous orogeny, sedimentation again reverted to shallow water conditions. Intensive volcanic activities were responsible for extrusion of intermediate lavas accompanied by eruption of pyroclastics confined to the basin east of the Main Range Granite batholith. Thick beds of carbonates like the Cua Musang, the Chuping, and the Rat Buri Formations were formed. Upper Permian rocks are not so widespread and is thought to signify the onset of an orogeny which reached its acme in the Early Triassic. Large scale granite intrusions are also accompanied with this orogeny. The Taku Schist in Kelantan and the recorded unconformity in the Jengka Pass may be the results of a Late Triassic earth movement.

Widespread volcanic activity is evidenced by the extrusion of andesite and other intermediate to acid lavas from numerous centres. Vast quantities of tuffs and ignimbrites were also erupted which are interbedded with normal clastics. Volcanics are conspicuously absent in the sediments of the miogeosyncline west of the Main Range. Middle and Late Triassic sedimentation came to a close with the onset of the Late Triassic orogeny which was again accompaned by granite intrusions. This orogeny brought geosynclinal conditions to a close and converted the belt to a stable tract. It appears that West Malaysia was a land mass above sea-level during most of the Jurassic. Although earth movements did occur during the Jurassic as is evidenced by K/Ar datings, there was no evidence of granite intrusion during this period.

Towards the Late Jurassic-Early Cretaceous boundary, shallow water fluviatile sediments of the Tembeling and Gagau type were deposited and they rest unconformably on pre-Jurassic sediments. They are typically arenaceous flatly dipping sediments and there is evidence of minor volcanic activity during this period. There was an episode of granite intrusion in the form of stocks and bosses in the Early Cretaceous.

The Tertiary beds which form isolated basins are non-marine and typically carbonaceous. The older Quaternary sediments consist of semi-consolidated fluviatiles and is distinguishable from the loosely consolidated younger fluviatile deposits.

Recently raised beaches are common features along the eastern coastline. Borings in several places along the coasts of Kedah, Perak, and Selangor have shown that the coastal alluvium on the west coast exceeds a depth of more than three hundred feet below the present sea-level.

The granitic rocks vary from alkaline, monzonitic to granodiorite and may differ in chemical and modal composition within the same granite mass. The extensive and voluminous occurrence of the acid pyroclastics and ignimbrites and the comparative lack of basic magma rule out the possible derivation of acid melts from a primary magma. There seem to be a close spatial relationship between the granites and the acid tuffs including ignimbrites because the granites are usually overlain by acid tuffs. Their relationship may suggest that emplacement of epizone granites reaching near surface conditions resulted in the eruption of acid tuffs and ignimbrites.

The extrusives mostly of intermediate composition are typically calc-alkaline and high in alumina. Basic lavas are rare. The Tertiary basalts of Kuantan and the basalts in Segamat signify an episode of minor volcanic activity during the Pleistocene. Recent rhyolitic ash beds have been found in many parts of West Malaysia and are deposited ash from volcanic eruption from unlocated centres.

Metamorphism both regional and thermal is widespread varying from thermal metamorphism to the grades represented by the greenschist to amphibolite facies.

Faulting on a regional scale is common. Apparently three prominent sets of fault systems are expressed; the oldest set being north-south trending normal faults, a younger set of northwest trending wrench faults, and an even younger set of north-northeast trending faults. It is significant to note that the large NW–SE Kenoboi fault appears to have shifted the regional tectonic trend of Malaya from north-south direction to a north-northwest direction. The fact that this fault movement was responsible for the anticlockwise shift of the southern portion of the peninsular indicates that the fault movements were of tectonic dimensions. The Late Jurassic-Lower Cretaceous Cagau type sediments have been also affected by these NW wrench faults and thus the age of movement would be Tertiary or Late Cretaceous.

The youngest set of faults have a NNE–SSW direction and in many instances cut and displace the north-south and north-west faults. In northern Malaya these same faults assume regional dimensions of which the postulated Kledang Range fault and the Phuket faults are the representatives. Rock fractures in the Kinta Valley are commonly mineralized particularly in the numerous shears and faults at the contact zones between granites and sediments. The same is true in other parts of West Malaysia. Thus the tin-bearing granites of West Malaysia appear to have sympathetic relationships between granite/sedimentary contacts and mineralization tends to occur where faulting or shearing have taken place.

THE GRANITOIDS OF PENINSULAR MALAYSIA

The South East Asia tin belt is believed to stretch from north Burma into Thailand and continue through Malaysia to the Tin Islands of Indonesia (Karimun, Singkap, Banka, Billiton). Its extent could be as long as 3,000 km. A fair amount of literatures have been written on the tin deposits of Malaysia.

The tin industries of Malaysia, Burma, Thailand, China and Indonesia are blessed by the numerous tin granite batholiths occurring in clear defined metallogenic zones throughout the region. The termination of the tin granites south of Banka in Indonesia still need further geological studies.

Within the so-called tin belt itself there are belts where cassiterite and other tin-bearing minerals are scarce to absent. The related granitoids commonly accepted as the source rock for the granitophile elements such as Sn, W, Mo, Ta, Nb, etc. display chemical and petrological differences.

Distinct metallogenic provinces are evident in the Geological Map and the Mineral Distribution Map (Figs. 1, 2 and 5) of the Peninsular Malaysia as follows; a tin-rich western region, a base metal-rich central region, and another lesser tin province in the eastern region. We also note that geologically the country can be divided intol three distinct regions of granitoid intrusives which are closely related to the type of mineralization in these belts (Fig. 2). The granitoids of the Main Range Batholiths and those in the East Coast regions continue north into southern Thailand and southward to the tin islands of Indonesia.

The following is a generalised account of the characteristics of the three main granetic intrusives in Peninsula of Malaysia.

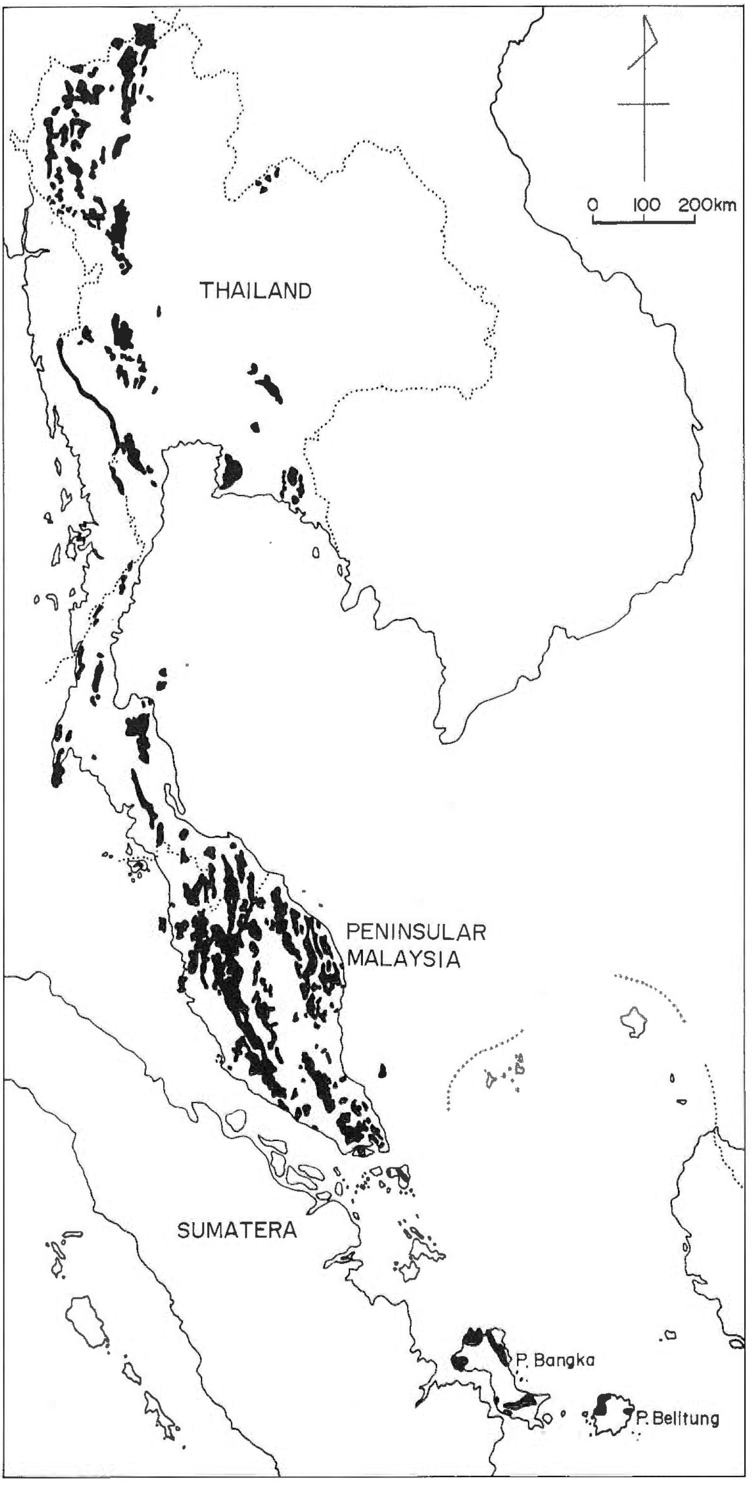

Fig. 1. Granitic rocks of the tin belt of South East Asia.

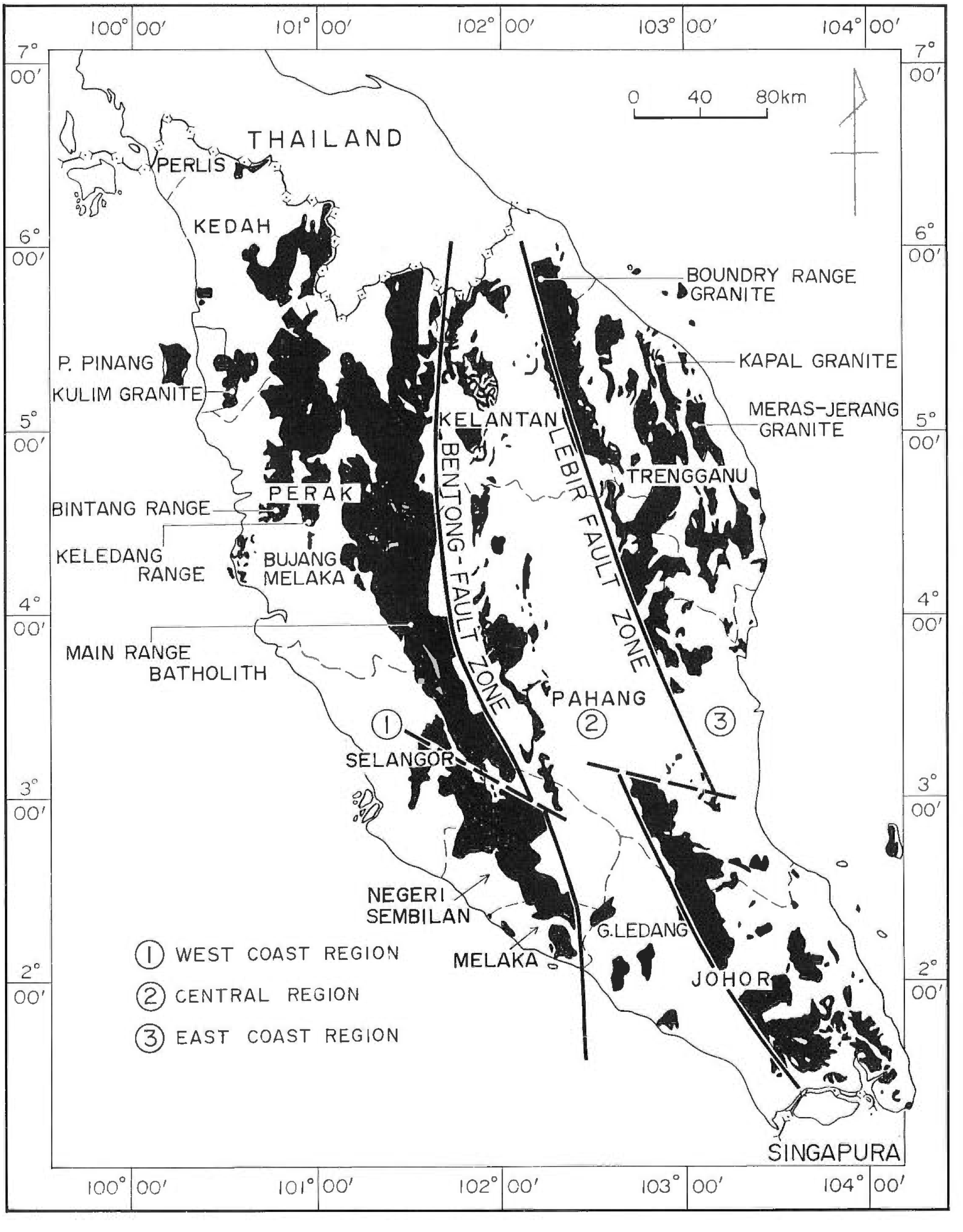

Fig. 2. Division of the granitoids of the West Coast region, the Central region and the East Coast region in Peninsular Malaysia.

Main Range Batholith

This huge batholith stretching the length of the west central part of Peninsular Malaysia continues northwards into South Thailand. Hutchinson (1977) said that the Main Range Batholith is a mesozone granite and the texture of these granitoids range from fine, medium to even grained. Some porphyritic variety has very large porphyritic crystals. BURTON (1969) mentioned the existence of two different granites in the Main Range. One is porphyritic which he named the Damar granite. The differentiation index of the former granite is 88.70 and the latter is 83.55. The Kuala Kabu granite has a higher K_2O:Na_2O ratio. Volcanic tuffs are not common except for isolated recent volcanic ash beds and the Baling tuffs found in Grik.

COBBING and MALLICK (1982) mapped parts of the Main Range granites covering the Bintang, Frasers Hill and the Malacca Sector. They recognized that many areas within the Main Range Batholith are made up of many plutons. In the Bintang Range area alone there are five recognizable plutons, and in the Malacca and Frasers Hill sector there is evidence of at least six plutons. Field evidence accumulated to-date confirms that the Main Range Batholith represents series of multiple plutons which are separated spatially and temporally. The mapping of the plutons by Cobbing, Mallick and Malaysian geologists was based on the variance in petrological, mineralogical and textural differences of the granitoids.

Granitoids of the Central Belt

These granitoids represent a series of plutons stretching from the Benom Range in Central Pahang northwards to Machang in Kelantan. They are composed of stocks of monzonite, norite, diorite, hornblende granite, gneissiose granites, and metamorphic migmatites and schists. These rocks are clearly products of tectonism, metamorphism, assimilation, and contamination by magmas ranging from basic to acidic composition. The largest of these intrusive is the Benom Massiff which is made up of horblende-bearing and biotite-bearing granites. The popular belief of former geologists that tin is absent in hornblende granites had been discredited by findings of cassierite present in the hornblende granite of Banom Massit.

The Eastern Cranitic Province

These intrusives were separately studied by BIGNELL and SHELLING (1977) who divided them into three groups, namely the Boundary Range granites, the Kapal granites, and the Maras Jerong granites. To the north of the Kapal granites and the Boundary Range granites, the rocks are characterised by a wide range of igneous bodies ranging from microdiorite, granodiorite, adamellite, monzonite, hornblende granites, tonalites, to leuco-granite. Non-porphyritic and porphyritic varieties are present. Generally the common granitic rocks are difficult to distinguish from those of the Main Range Batholith. Rhyolites and ignimbrites are common and are spatially related to the granites occurring in direct contact with, or as drapes over, the granite intrusives. COBBING and MALLICK (1982) also confirmed the multiple intrusion of the granitic massifs by distinguishing four different intrusive bodies in the northern part of the Kapal granites which range from hornblende granites to monzo-granite. The northern end of the Maras-Jerong granites consists of three separate suites of intrusives ranging from equigranular granite to tonalite. The Boundary Range granitoids consist of rocks ranging from biotite/horblende granites, granodiorites and tonalites. The occurrence of diorite, dolerite and lamprophyric dike swarms are common in the northern part of the Kapal granites.

Generally speaking, the lithologies of the East Coast granitoids are more varied and contain more basic members than the Main Range granitic bodies.

Many anthors have tried to differentiate the granites in the western and eastern province by generalizing their mineralogy, the textural and petrological differences, but generalization of granitic batholiths of such large dimensions, particularly when batholiths are multiphase intrusives of different ages, is in many cases ambiguous. Both the East Coast and Main Range granites show various textures such as prophyritic, non-porphyritic, fine-grained and medium-grained and contain the common minerals pertaining to granites. It is rarely possible to identify these granites as belonging to either the East Coast or the Main Range from petrographic features.

Geochronology of the Granitoids

The study of BIGNELL and SPELLING (1977) has given us a more complete picture of the ages of the intrusives and the tectonic events in west Malaysia. Rb/Sr datings have indicated at least four major periods of granite emplacement in the Peninsular. The earliest emplacement occurred in the Late Carboniferous (280 Ma) but an older Late Devonian granite of about 360 Ma was suspected, necessiating further datings for confirmation. Other intrusive episodes occurred in the Late Permian/Early Triassic (250 Ma) and in the Middle to Late Triassic (230–200 Ma). The latest granite intrusion occurred in the Late Cretaceous (85 Ma). None of the K/Ar datings recorded the 280 Ma intrusive episode. It appeared that 280 Ma episode was completely resetted to the 180–200 Ma ages by orogeny. The East Coast granites however had apparently remained rather stable and had not undergone any appreciable argon losses. The K/Ar datings of 222 ± 5 Ma and 250 ± 4 Ma on the micas of the Eastern Province are concordant with those obtained from whole rock Rb:Sr determinations.

The Ages of the Eastern Granitic Rocks

The granitoid bodies were intruded in two distinct ages. The Boundary Range granites and the Kapal granites were emplaced in the Late Carboniferous (280 Ma) whilst the Maras Jerong granites to the east of these two bodies was emplaced in the Late Permian/Early Triassic (250 Ma).

The Ages of the Main Range Granitic Rocks

The main intrusive episodes in the Main Range granite are in the Late Carboniferous (280 Ma) followed by another event at the Late Triassic (200 Ma). A Late Devonian granite is suspected with samples dating at 360 Ma. Late Cretaceous granite (85 Ma) was recorded in Gunong Ledang, Cunong Pulai, Johore and in Pulau Tioman Island.

The Ages of the Central Region Granitic Rocks

The Gunong Benom body was dated to have been emplaced in the 200 m.y. episode i.e. Late Triassic. The Taku Schist and Gunong Stong granite gneisses could be of Early Paleozoic in age.

Conclusions

In summary, the main intrusive events of the Malaysian granitoids occurred in the Late Devonian (suspected) (360 Ma), Late Carboniferous (280 Ma), Permian/Early Triassic (250 Ma), Middle to Late Triassic (200–230 Ma) and Late Cretaceous (85 Ma).

The discovery of granite boulders in Late Carboniferous sediments indicating the probable existence of an older granite body is supported by the datings of 360 Ma for some granite rock in the Main Range Batholith.

Results from K:Ar studies by Bignell and Snelling were the basis for the following conclusions:

(i) Late Carboniferous granites emplaced in the 280 Ma episode but the event was subsequently reset by the 200 Ma granitic intrusive.

(ii) Late Triassic granitoid intrusions occurred 200 Ma.

(iii) A peak in the 135 Ma period in the upper Jurassic/Cretaceous boundary signified uplift; followed by the deposition of the Tembeling formation and the Gagau formation.

(iv) Post Tembeling deformation uplift and granite emplacement took place in the Late Cretaceous (85 Ma).

(v) In the southern part of the Main Range, wrench faulting orientated in the WNW–ESE direction gave a K:Ar date of 33 Ma.

(vi) No substantial argon loss was experienced in the East Coast province where the Late Triassic intrusives of the Boundary Range and the Kapal Granitoids had not affected the older Late Permian/Early Triassic Maras Jerong granite mass.

Geochemistry of the Granitoids

The Malaysian granitic rocks generally have $^{87}Sr/^{86}Sr$ ratios ranging from 0.707 to 0.717 i.e., higher than the mantle-derived rocks characterized by a lower ratio ranging from 0.702 to 0.706. If we accept the findings of FAURE and POWELL (1972), the Malaysian granitic rocks would not have been derived from the upper mantle (Fig. 3). The following are the average $^{87}Sr/^{86}Sr$ ratios of the three regions.

The Main Range Batholith

(a) Late Carboniferous	Average $^{87}Sr/^{86}Sr$ ratio = 0.711 + 0.0008
(b) Late Triassic	Average $^{87}Sr/^{86}Sr$ ratio = 0.709 + 0.0005

East Coast Granitic Rocks

(a) Late Permian/Early Triassic	Average $^{87}Sr/^{86}Sr$ ratio = 0.7102 + 0.0004
(b) Late Triassic	Average $^{87}Sr/^{86}Sr$ ratio = 0.707 + 0.0003
	Average $^{87}Sr/^{86}Sr$ ratio = 0.708 + 0.0009

Central Belt Granitoids

The highest ratio was given by the Kulim granites (0.7165) and the Bujang Melaka granite

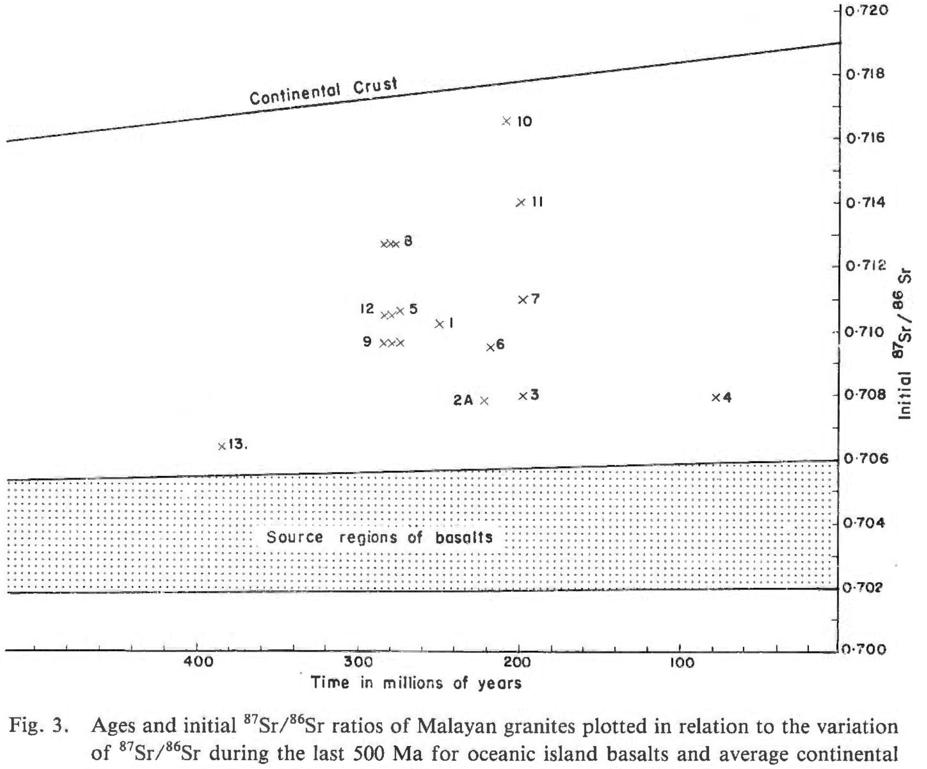

Fig. 3. Ages and initial $^{87}Sr/^{86}Sr$ ratios of Malayan granites plotted in relation to the variation of $^{87}Sr/^{86}Sr$ during the last 500 Ma for oceanic island basalts and average continental crust (after BIGNELL and SNELLING, 1977).

(0.7140) which indicates that the Main Range granite could owe its origin to the palingenesis of crustal material.

BIGNELL and SNELLING (1977) suggested that the Main Range granites with a $^{87}Sr/^{86}Sr$ weighted mean of 0.710 were generated in an ensialic geosyncline. The Triassic granitoids of the eastern and central provinces have a $^{87}Sr/^{86}Sr$ weighted mean of 0.708 which suggests that their evolution may be the result of assimilation of lesser quantities of sialic materials by a basic magma. The Late Permian Maras Jerong granitoids of the East Coast province have similar $^{87}Sr/^{86}Sr$ ratios to those of the Main Range rocks and thus are also thought to be generated in an ensialic eugeosyncline environment.

It was suggested that lower $^{87}Sr/^{86}Sr$ ratios of the Boundary Range and the Kapal granites are dur to a more rapid ascent of anatectic granitic magma giving less time for the rising granitic melt to be contaminated by Rb-rich sialic rocks.

Rb:Sr Ratios

The geochemistry of the granites in Malaysia also points to the fact that the Main Range granites are more highly differentiated. Using the Rb:Sr ratio as an indicator of the degree of differentiation of an igneous rock (NOCKOLDS and ALLEN 1952), BIGNELL and SNELLING (1977) said most of the East Coast granites have Rb:Sr ratio <4, with only a few samples having extreme ratios. The Late Palaeozoic granites of the Main Range have Rb:Sr ratios ranging from 2 to 9 whilst some of the Late Triassic intrusives have extreme ratios of 50 and 175. The suggestion seems to be that the granites of the Main Range have undergone a higher degree of differentiation compared to the East Coast granites. Some of the Late Triassic granites show extreme differentiation compared to the Late Carboniterous granites in the Main Range Batholith indicating the Late Triassic granites are more differentiated than the Late Carboniferous granites.

Brief Summary of the Properties of Malaysian Tin Bearing Granitic Rocks

(1) They are large, being of batholithic dimensions and forming part of the tin belt roughly 500 miles long continuing northwards into Thailand, Burma and southwards into the tin islands of Indonesia.

(2) In Malaysia the granitoids can be divided into the Main Range Batholith, the Central Region granitoids and the East Coast Region granitoids. Only the Main Range Batholith and the East Coast granitoids contain economic tin deposits.

(3) They are composite batholiths with a long history of multiple intrusions.

(4) They were intruded in a wide range of geological time from the Late Devonian (suspected) to the Cretaceous.

(5) While rock Rb:Sr data confirmed five separate intrusive activities:

(i)	Late Devonian (Suspected)	360 Ma
(ii)	Late Carboniferous	280 Ma
(iii)	Late Permian/Early Traissic	250 Ma
(iv)	Middle to Late Triassic	200–230 Ma
(v)	Late Cretaceous	85 Ma

(6) $^{87}Sr/^{86}Sr$ data indicate that they are not primary granites generated from the basalt source region but may be products of anactectic magmas.

(7) Rb:Sr data indicate that some of the intrusive plutons are highly differentiated magmatic bodies. The Main Range granitic rocks are more highly differentiated than the Eastern granitic rocks.

(8) They are thought to be genetically related to tin mineralization.

(9) Not all the tin-bearing granites in the same batholith contain economic concentrations of tin. There are areas rich in tin and areas devoid of tin.

(10) Metallization in the tin-bearing granites are usually of simple granitophile elements

such as W–Sn–Ta–Nb–Mo and the non-metals like F, B.

DESCRIPTION OF SOME TIN DEPOSITS IN WEST MALAYSIA

Pegmatites

These deposits occur principally in two areas, one in the Gunong Jerai area in Kedah and the other in the Bakri tin field. In the Gunong Jerai area, there occur intrusions of granite and porphyry which are subsequently intruded by pegmatites (carrying Sn, Nb, Ta and some Fe). The tin content of the granite and porphyry is low being in the order of 0.002% especially in the hornblende granite. The pegmatites contain muscovite, tourmaline, feldspar and minor garnet. Most of the cassiterite have originated from the pegmatite intrusives. In Southern Peninsular Malaysia, in the Bakri area of Johore cassiterite is observed to have originated also from pegmatitic intrusives. The common mineralogy observed in the Bakri and Gunong Jerai areas is the association of Ta–Nb minerals with cassiterite. Such association is also noticeable in the pegmatitic tin field of the Phuket area in South Thailand. There are also Ta–Nb cassiterite lodes in Cunong Bakau where mineralization is associated with pegmatites, quartz-topaz veins and aplite intrusions.

Pipe, Fracture Fillings and Pyrometasomatic Replacement Deposits

Tin pipes are encountered in the Kinta Valley in limestones like the Lahat pipes, the Beatrice Mine, and the Sin Nam Mine. They are either open space fillings or replacement of rocks of high reactivity. Intersection of faults, fracture and joints are the major controls on the formation of pipes. The Beatrice pipe is a pyrometasomatic replacement type of tin deposit, and the ore minerals are largely cassiterite and arsenopyrite, with minor amounts of stannite, chalcopyrite, barite and fluorite.

Deep Seated Lode Tin Deposits

The most famous lode tin mine in Malaysia which HOSKING (1969) described as similar to the Cornish tin lodes is in Sungei Lembing, Pahang which is essentially associated with faulting in close proximity with the granites. The tin lodes contain cassiterite, pyrite, chalcopyrite, arsenopyrite, galena, sphalerite, cobalite and manganese minerals. Gangue minerals such as chlorite, calcite, tourmaline and quartz are present.

The Tin-Iron Skarn Deposits

Tin-iron deposits are confined to the East Coast granites. Recent studies in Pelepah Kanan showed that the deposits is of a hydrothermal skarn type. The tin occurs as a fine mix with the iron ore. There had been varied views on the genesis of the tin-iron association in Buket Besi, Pelepah Kanan and Machang Setahun. Theories put forward were the secondary enrichment of the amphibole-magnetite rock, or the injection of mobile mixtures of Sn–F–B–Si, or that the iron ore was pyrometasomatic (skarn) with hydrothermal injection of cassiterite. Recent mining in Pelepah Kanan had revealed a feeder zone of the cassiterite/iron ore body which indicated that minerlizers from the granite intrusive first replaced the skarn rocks with magnetite and later supplied fine-grained cassiterite between the coarse magnetite ores.

Hydrothermal Tin Deposits, Veins, and Stockworks

Deposits of this type occur as simple cassiterite veins in granite or as vein swarms in sediments or they may occur as fracture filling or as replacement veins such as those occurring in the Kinta Valley or as lodes in the Sungei Besi Mines. These veins are mineralogically simple, commonly being associated with arsenopyrite and pyrite. Accessory minerals may be tourmaline, epidote, hematite, magnetite and apatite.

Frequently veins occur in an en-echelon fashion as the Kledang range. They are usually

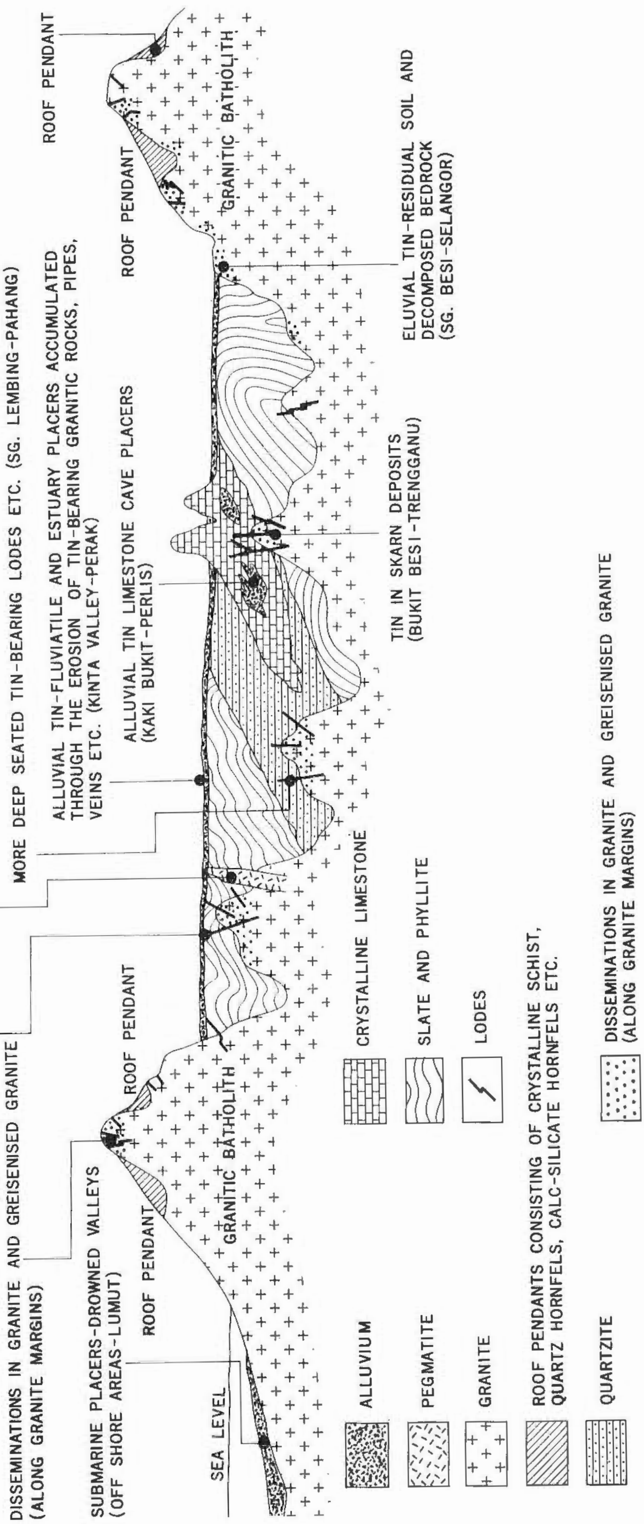

Fig. 4. Types of tin-ore deposits in West Malaysia.

associated with shear zones as thin veins carrying cassiterite, biotite, tourmaline, pyrite, muscovitem and magnetite.

In the Klian Intan area, the mineralization model is a series of closely spaced vein swarms cross-cutting one another producing stockwork type of deposit. The veins pinch and swell and are of limited extent.

Alluvial and Eluvial Deposits

By far the most economically productive mines are the widespread alluvial and eluvial tin mines particularly those situated west of the Main Range Batholith. The genesis of these ores need not be elaborated as it is common knowledge that alluvial deposits are the products of weathering, erosion of tin bearing host rocks, deposition and burial by denudation agencies. The offshore placer deposits in the nearshore areas of the Malacca Straits well formed by the same processes for the onshore deposits when sea level was lower and much of the Straits of Malacca was dry land.

Cave Deposite (Alluvial)

An interesting type of alluvial deposit in Malaysia occurs in limestone caves in northwestrn Peninsular Malaysia. These are essentially fluvial deposition of tin ore into the caves which acted as a trap for tin minerals.

Aplites

Numerous aplite dykes cutting into granites and the contact sedimentary rocks also carry tin. Their mineralogy is again very simple containing cassiterite, pyrite, some arsenopyrite, fluorite and tourmaline.

General Characteristics of the Tin Deposits

Although the alluvial tin supplies the bulk of the tin exported, it should be realized that without the presence of primary tin, there will be no possibility for exogenetic factors such as weathering, transport, and burial to concentrate the tin in the alluviums to enable the profitable mining of such deposits.

We see that mineralogically, the tin-bearing granitoids in Malaysia are rather simple when compared to those in the polymetallic ore provinces elsewhere. The chief factor that control the ore deposition and the complexity of the distribution of tin in time and space is obviously the source from which the metal was derived. The character of the igneous rocks emplaced in an orogen changes with the phases of geosyncline development and with it goes the ore which are deposited to form the tin and tungstan deposits in Malaysia. It is obvious that such ores are closely connected with the acid igneous rocks with which they are genetically related.

Tin Rich and Tin Poor Granitoids in West Malaysia

There had been many attempts by previous workers to explain the rare occurrence of tin deposits on the east side of the Main Range Batholith, the Central Region granitoids and in the Late Cretaceous plutons.

ISHIHARA *et al.* (1979) pointed out that the granitoids of the Central Region and the Late Cretaceous intrusives belong to the magnetite series which accounted for the absence of tin deposits.

HOSKING (1973) said: "The marked concentration of tin deposits on the west side of the Main Range granite particularly in the Kinta Valley and Selangor fields and the comparable paucity of tin deposits on the east side of the Range (Fig. 5) might be because deposition of much of the tin was associated with Late Cretaceous igneous activity which was largely concentrated to the west of the Main Range".

HUTCHISON (1977) on the other hand contradicted HOSKING by saying that no tin mineraliza-

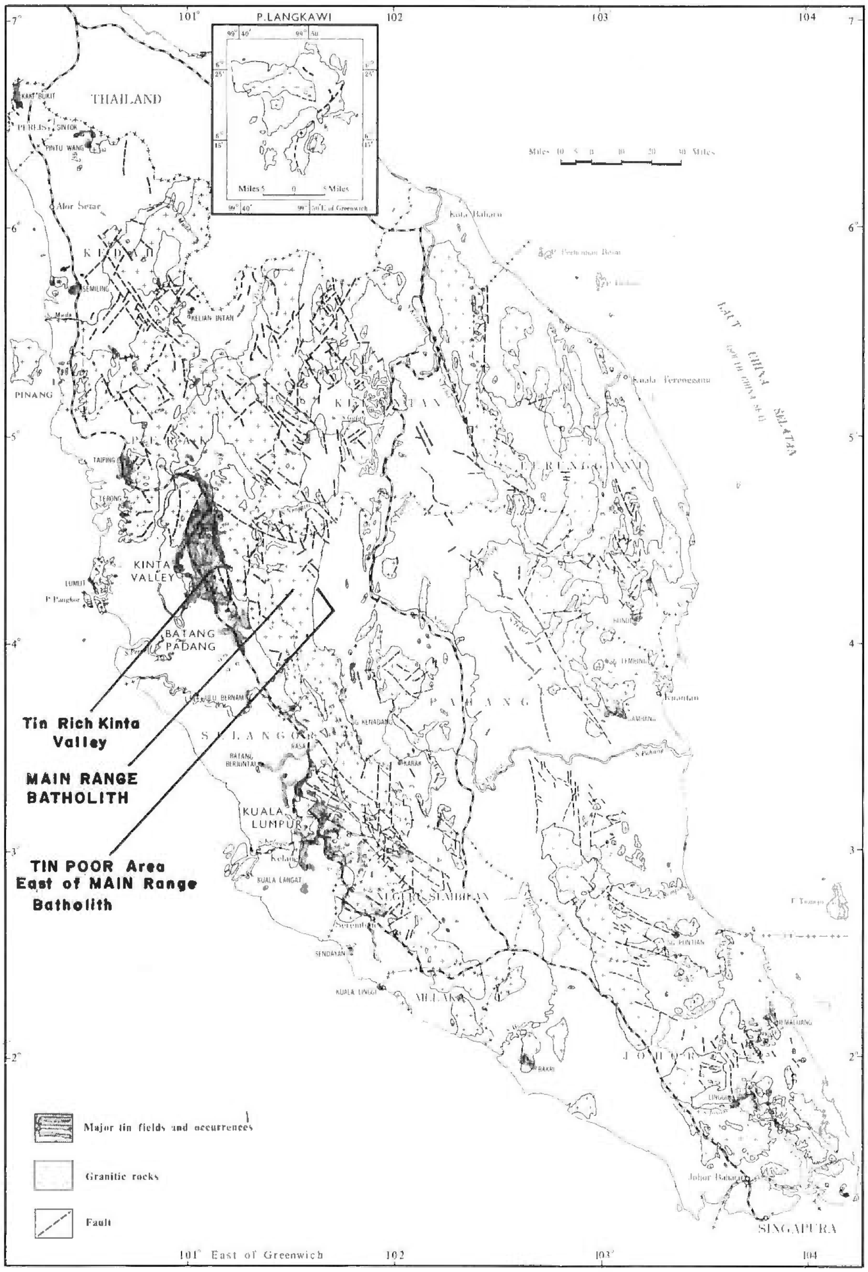

Fig. 5. Major tin fields and tin occurrences in Peninsular Malaysia.

tion is present in Late Cretaceous plutons. BIGNELL and SNELLING (1977) did not find any Late Cretaceous rocks in the Kinta Valley or in the Selangor fields refuting HOSKING's ideas of Late Cretaceous mineralization. In fact, the rocks in these areas are mostly Late Carboniferous or Late Triassic, the latter period is considered to be the period of intensive tin mineralization in the country.

The Gunong Leadang pluton is Late Cretaceous in age and contain tin, which refuted HUT-

CHISON's statement. Furthermore, the Ranong Phuket granites, which may not be part of the Main Range Batholith but they are tin-rich and are responsible for one of the richest onshore and offshore tin fields in Peninsular Thailand, and other granites in these areas were dated as Late Cretaceous in age.

BURTON (1969) said that tin mineralization in West Malaysia occurred in the Late Carboniferous, Early Triassic and Late Jurassic. BURTON at that time had no back-up evidence from geochronological data except for a very scanty incorrect determination of isotopic ages available.

My observation is that tin mineralization or the absence of it in Malaysia is not confined to a specific geological period. Tin mineralization seemed to occur in all magmatic cycles ranging from the Late Carborniferous to the Late Cretaceous. The relation of tin mineralization to any specific geological time for the tin belt of West Malaysia should not be taken seriously.

The previous postulation of the absence of tin in hornblende granites is now proved baseless as hornblende granites have been found to contain tin even in the central regions of the Peninsular Malaysia.

Reasons for Paucity of Tin in Certain Areas within the Tin-Bearing Granitoids

(1) Palingenesis in geosynclines of sediments containing different ore minerals at different centres.

(2) Fusion at different levels and differnt centres in an orogen will contribute different metals and different rock types in the resulting melt. If the source region is barren the granitoids will not contain any ore minerals.

(3) There is the possibility that the granitic magmas which were generated from different sources in the deep sialic layer become mixed with those from the upper mantle. The result will be to generate very complex ore bodies during emplacement of the mixed magma.

(4) Magmas from different sources may undergo little, moderate or extreme differentiation to give rise to differnt ore types.

Genesis of Tin-Bearing Granitic Rocks

The popular concept in the generation of granitic rocks are as follows:

(i) By differential selective melting of geosyncline sediments and metamorphics.

(ii) By melting of crustal granites (ultrametamorphic).

(iii) By differentiation of palingenetic magma.

(iv) By differentiation of a basic magma (mantle source).

It is believd that granitic melts resulting from above processes can be mobilized and emplaced from as deep as the lower crust of 20–30 km deep to about 1 km below the surface.

The close association of granitoids of batholithic dimensions with tin in West Malaysia has led many workers to state that tin concentration is the result of polycyclic generation of granitic rocks from sialic sources with gradual enrichment of tin in the magma. Some authors also postulated the scavenging of tin-rich sediments in the subscrustal wedge from volatiles emanating from a subductive plate. However, there are many instances where granitic rocks which are the products of subductive plates are found to be tin-barren.

There is a recent concept that it is possible for tin to originate from the mantle as tin is found in ultrabasics such as lherzolite (3.8 ppm), harzburgite (2.0 ppm,), dunite (0.6 ppm) and eclogites (1.4 ppm). Tin has also been recorded in basalts and diabases. Although it is possible for tin to come from a mantle source, it is not sufficiently concentrated to form ore deposits. The fact that mafic and ultramafic rocks are universally not associated with tin deposits confirms that the tin from mafic and ultramafics has not undergone the process of concentration.

The popular concentrating mechanism favoured by most workers is the concentration of tin in the magmatic phase where the magma is originated from anatexis, or partial fusion of tin-rich crustal material, or the subsequent assimilation of tin-rich rocks into a granitic magma, or the process of scavenging tin-rich sediments by volatiles to produce tin-bearing magmas. Such magmas will undergo further differentiation where the tin is progressively enriched in the late stage differentiates. It is believed that immiscible tin-rich phases can be transported by volatiles or pneumatolysis in which the chief agents are H_2O, CO_2, F and B or as sulphides or sulpho-arsenides. These mobilizers are abundant in the granitic host as is evidenced by the presence of tourmaline which is known to contain boron, tapaz and fluorite containing fluorine and water which is plentiful in geosyncline sediments (estimated to average 3 to 4% water). The polycylic generation of rocks with progressive concentration of rare tin minerals are thought to be the main concentrating mechanisms.

RATTIGAN (1960) said that Sn has a decreasing affinity for Ca, Mg, Na and K. The tin in a melt with a high K content will separate out and thus be available for distribution by hydrothermal and pneumatolytic mobilizers to be deposited in the apical portion of granite cusps or in contact zones of tin-bearing plutions.

From evidence collected to date, the Malaysian granitic rocks are thought to be multiphased intrusives and had undergone intra-intrusive processes during uprising and subsequent emplacements. The mineralizing solutions could either be derived from the intrusives itself or introduced by later mineralized fluids from deeper down the sialic crust.

We are uncertain of the mechanism operating in the concentration of tin and in the selective generation of specialized Sn–W bearing granitic rocks. We are not too sure of the post magmatic interplay of mineralizers between the country rock and the host rock in which the tin is contained. Evidence points to the fact that tin can come from acidic, intermediate, or even from mafic and ultramafic rocks, but the processes of concentrating the elements Sn–W will need further research.

HISTORY OF TIN MINING IN PENINSULAR MALAYSIA

Tin has been mined in Malaysia for many years now and according to the Dutch records, 6,000 tonnes of tin was exported from the port of Malacca in 1649. The earliest tin fields were centred in Larut, upper Perak and in Kuala Lumpur, and the tin was sold to Chinese and Indian traders. By the end of the 18th century, Malaya was producing 3,250 tonnes of tin per year.

The discoveries of large tin fields in the Kuala Lumpur Klang Valley, together with the advent of the tin industry attracted the attention of European colonialist who saw the benefit that should accrue to its industries and the British Empire. Large tracks of rich tin land were alienated to European companies with the capital and mechanical know-how to extract the tin. By the beginning of the 19th century, Malaya was producng 52,600 tonnes of tin. Labourers came from China to work in the tin fields and many died from tropical diseases especially from malaria. The first bucket dredge was introduced in 1912 and by 1929 there were 105 dredges operating in the country. Just before World War II, there were 123 dredges operating. To-day over 85% of the tin production in Malaysia is derived from gravel pump mining and dredging. Gravel pump is more labour intensive, but more effective in recovering tin. Cost of production is higher for gravel pump compared to dredges. Most of the gravel pump mines are owned by small companies or family owned. Recent advance in dredging technology has enabled the bucket dredge to treat 850,000 cubic yards (650,000 cubic meter) per month and can excavate up to 170 ft (52 m) compared to the first dredge which could only excavate 57,000 cubic yards (approx. 43,580 cubic meter) to a depth of 15 metres. By lowering the water level of the paddock it is possible to dredge up to a depth of 86 metres. There are now about 50 dredges operating in the country. About 1/3 of the dredges will soon have to shut down due to tin export control by restricting tin production. Contribution by different mining methods to the production of the tin is approximately as follows: gravel pump–55%, open cast–3%, dredging–33%, among (heavy mineral) treatment (scavenging)–2%, underground mining–3%, dulang (panning)–4%.

BENEFITS OF TIN

Tin mining industry's contribution to the Gross Domestic Product (G.D.P.) was in 1970 the third single largest contributor next to the wholesale and retail trade and rubber industries. Tin mining and quarrying accounts for 6.4% of the G.D.P. and had since declined to 5% during the period 1971–80. Its contribution to the balance of payment has fallen from 20.8% of the value exported to 9.6% during the period 1970–80. Tin mining is providing employment to roughly 40,000 people in the country. But due to recession 1/3 retrenchment of the labour force is expected. Besides earning foreign exchange and providing employment, the tin mining industry had been responsible for the development of skills which is a pre-requisite qualification in the application of the complex technology involved in the mining industry. The effect of tin mining on other industries is also significant as it acts both as a consumer of materials to sustain the tin industry and as the supplier of tin to the manufacturing sector.

One of the most fundamental contribution made by the tin industry to the welfare of Malasia is the contribution to infrastructure such as transport, communication, housing, community facilities such as water supply, health, and education. The existing roads and towns like Ipoh, Kuala Lumpur and a host of smaller towns came into existence solely because of the discovery of tin. The mining industry has attracted foreign and local capital expenditure into the country. Recent investiment in developing deep-seated tin ore (270 m depth) is about US$85 million. Each dredge of modern design will cost roughly US$15 million.

RESERVES

Although Malaysia is reported to be the largest tin producer in the world, averaging about 40% of total world production, its reserves through intensive, extensive and long period of exploitation had dwindled to the status of being the fifth in world ranking. Other countries such as Burma, Thailand, Indonesia, Nigeria, Bolivia, USSR and China are also major producers. The reserves estimate for tin in Malaysia has always been haphazard and one cannot really rely on published figures. Estimates of available reserves are subject to many assumed factors, depending on the rate of technological development, type of deposit, production cost, real price of metals, existing and future costs trends in exploration and production. However, one cannot escape the fact that tin mining is a non-renewable process and every kilogram of tin extracted from the ground is lost forever. Whatever reserves that are left in the ground will be of lower grade, more difficult to mine and more costly to extract. There is no possibility to arrest the downward trend in tin reserves unless new sources of tin fields are located. Judging from the current tin mining scenario in Malaysia, there is no compensating balance of tin mines coming into production as opposed to tin export. The cost of working in lower grade ground requires a greater volume of ore-bearing ground to be mined in order to obtain the required tonnage for economic turnover in mining expenditure. Unit cost in production has also increased both for the dredges and open cast method mainly due to price rise and inflation of mine supplies. Dredges is less costly to operate compared to open cast mining.

CONSUMPTION, PRODUCTION, PRICE AND CONTROL OF TIN

Due to world economic downturn, the tin price as is common with other commodities have fallen sharply and the situation is aggravated by the release of tin stockpile by the U.S. into an already depressed market. What then is the prospect for tin when the world economic recession recovers? Simple reasoning points to the fact that tin price depends on the supply and demand situation. Where the demand is high, the price will rise and vice versa when the demand lessens. Recent evidence had shown that the situation is of some concern to producers. The International Tin Research Institute had revealed that the biggest consumer of tin which is in the tin plate industry has continued to decline worldwide. The U.S. tin plate industry has lowered tin consumption by 30% in the last 20 yars i.e., from 36,000 in 1960 accounting for 64.5% of world total demand to 13,200 tons in 1981, a drop of 34% of world total demand. The recent price fall although can be directly attributed to lower consumption of tin due to the recession, the other direct threat to the tin industry in the long term, is the use of tin substitutes and secondary recycling of tin through conservatin efforts. The increasing use of aluminium by the introduction of the seamless aluminium-can has helped the aluminium industries to capture a sizeable volume of the tin-can market for beverages. The use of tin-free steel, plactics, glass, paper, and aseptic packaging, are also strong challengers to tin in the food preservation business.

The scenatrio seemed rather pessimistic for the future for tin as an industry which had hitherto been one of the strongest dollar earning commodity and which had been the pillar of Malaysia's economy. One of the most important task of government agencies will be, to arrest the trend of depleting tin reserves by increasing its effort in the search for tin in order to bring into production of higher grade new reserves to counter-balance the rate of depletion, and to lower the cost of production. The challenge by tin substitutes has to be accepted and resolved by filling ways and means to overcome this challenge. The increase use of tin through Research and Development must be seriously looked into, in order to revitalise the demand sector. The cost of beneficiation and improved mining technology through efficient mining methods could bring into economic production a sizeable portion of those tin ores still buried in the deeper alluvium and also those low grade reserves which constitute a sizeable potential reserve in the country.

A lot depends also on the effectiveness of the International Tin Council when world economy recovers. The cooperation of both consumer and producer countries in maintaining the price of tin relative to the production cost is of vital importance to the tin industry. There is a surplus of tin in the world market of about 80,000 tons excludng the buffer stock holding of 39,000 tons due to economic recession. Production is exceeding consumption by 25,000 tons/year. It is estimated that producers will have to cut back production by 36% before the surplus tin in the world can be eroded. Analysts have predicted that it won't be by 1985 that tin export control by the International Tin Council will be lifted. World tin production for next year 1983 is estimated at 156,000 tons and Malaysia's total contribution will be 38,064 tons i.e., 24.4% of world production. Total Malaysian exports of tin decreased by 23.9% to 50,600 tons compared to 66,460 tons in 1981.

The cost of tin price fell from M$29.71 per kilogram which is far below the average production cost of M$33.84 per kilogram for open cast mines and M$26 per kilogram for dredges. Unless there is a reversal of the price slide, many mines in Malaysia will have to close particularly the high cost mines and marginal grade open cast mines. The unemployment and lost of export earnings will be a blow to the tin mining industry of the country.

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Tungsten and Molybdenum Ore Deposits in South Korea

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ABSTRACT

South Korea has been one of the largest tungsten producting countries in the Western World. Her tungsten supply to the Western World is as much as 10%.

South Korea has more than 500 tungsten and molybdenum claims within the country with the main concentration at the north east provinces of South Korea. Among these, 34 mines have been developed for tungten and/or molybdenum.

The generally accepted South Korean metallogenic epochs are four fold: Precambrain, Paleozoic, Jurassic to Early Cretaceous, and Late Cretaceous to early Tertiary. The tungsten and molybdenum were mineralized during the last two metallogenic epochs with close relationship to the Daebo granite and Bulkuksa granite magmatism.

The Korean tungsten and molybdenum deposits are classified into three main genetic groups: pegmatite deposits, contact metasomatic deposits and hydrothermal deposits.

The hydrothermal deposit is further subdivided into three subtypes: vein type, breccia pipe type and disseminated and stockwork type. The characteristics of these genetic groups are generallized by comparing the ore mineral paragenesis and the subtype is further described by selecting one representative mine from each type: Ssangjeon mine for pegmatite type deposits, Sangdone scheelite mine for contact metasomatic deposits, Cheongyang mine for hydrothermal vein type deposits, Ilkwang mine for hydrothermal breccia pipe type deposits, and Sobo molybdenite mine for hydrothermal disseminated and stockwork deposits.

The homogenization temperatures of the tungsten and molybdenum ore vein materials range from 200°C to 500°C although its mineralization temperature is not conclusive.

Some of the mineralization ages measured from the vein materials of the tungsten and molybdenum ore bodies indicate Late Cretaceous to early Tertiary which is similar to the Bulkuksa granite ages. Some other tungsten and molybdenum mineralizations are correlated to the Daebo granite from the field geologic evidence.

INTRODUCTION

Tungsten and molybdenum, usually occur together mostly in quartz veins in Korea. Therefore, the deposit is called tungsten deposit if the tungsten is the major ore element, and otherwise molybdenum deposit. This is the reason why they are described together in this paper. Tungsten and molybdeum also occur as minor elements in some lead and zinc deposits, copper deposits, and magnetite deposits and have been recovered as by-products.

South Korea has been one of the largest tungsten producers in the Western World. South Korea's total productions of tungsten and molybdenum ore are 123,492.7 (WO_3 70%) and 5,541.5 (MoS_2 90%) metric tons respectively from 1946 to 1980. South Korea has been supplying about 10% of recent Western World Tungsten consumption.

DISTRIBUTION

Over 500 tungsten and molybdenum mine claims are registered in Korea (Gallagher, 1963; Kim, W.J. *et al.*, 1982). Of the 500 mine claims, more than 80% are concentrated near the provincial boundary of Kangwondo, Kyongsangbukdo and Chungchung-bukdo which is located at the northeast central part of South Korea. The rest is scattered around the country except in the Chullanamdo and Chullabukdo which is in the southwestern part of South Korea. Some of the major mines are shown in Fig. 1 and Table 1.

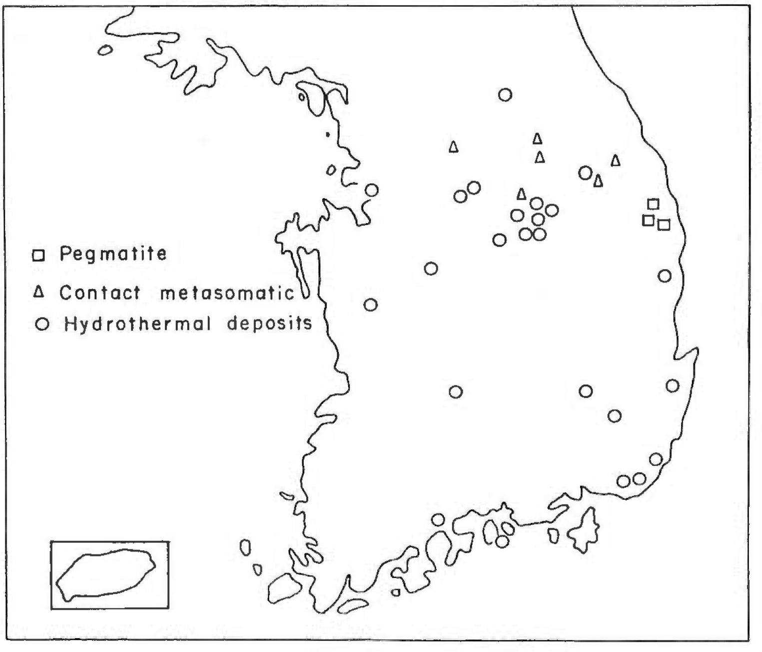


Fig. 1. Tungsten and molybdenum deposits in S. Korea.

Table 1. The major tungsten and molybdenum mines

Serial No.	Name of mine	Main ore minerals	Serial No.	Name of mine	Main ore minerals
1	Garisan	Wf<Sch, Mo	18	Yongha	Wf<Sch, Mo
2	Chilbo	Sch, Bi (Mo, Wf)	19	Samduk	Wf<Sch, Mo
3	Namyang	Wf<Sch, Mo	20	Ssangjeon	Sch (Wf)
4	Sindae	Sch, Bi (Mo, Wf)	21	Okbang	Sch (Wf)
5	Guirae	Sch, Bi (Mo, Wf)	22	Hyundong	Wf<Sch, Mo
6	Dongnam	Mo,Wf	23	Cheongpung	Wf<Sch, Mo
7	Sinyemi	Mo, Wf	24	Sobo	Mo
8	Sangdong	Sch, Bi (Mo, Wf)	25	Chungyang	Wf<Sch, Mo
9	Donsan	Wf<Sch, Mo	26	Duckdong	Mo
10	Daewha	Wf<Sch, Mo	27	Dalseong	Wf, Cp (Sch)
11	Cuemseong	Mo	28	Sannae	Wf<Sch, Mo
12	Boksu	Sch, Cp	29	Jangsu	Mo
13	Guemnueng	Wf<Sch, Mo	30	Ilkwang	Wf, Cp (Sch)
14	Danjae	Wf<Sch, Mo	31	Dongbo	Wf<Sch, Mo
15	Susan	Wf<Sch, Mo	32	Backyang	Wf<Sch, Mo
16	Suri	Wf<Sch, Mo	33	Oksan	Mo
17	Wolak	Wf<Sch, Mo	34	Samdong	Mo

*Wf: Wolframite, Cp: Chalcopyrite, Sch: Scheelite, Bi: Bismuthinite, Mo: Molybdenite

General Characteristics

The Korean tungsten and molybdenum ore deposits can be classified into three genetic groups: pegmatite, contact metasomatic and hydrothermal deposits. The hydrothermal deposits can be subdivided into three sub-types: vein, breccia pipe, and disseminated-stockwork types. A short summary of geology of these deposits is given in Table 2.

A lithological control is apparent on the types of ore deposits and the major mineral association. The host rocks of most contact metasomatic deposits are limestones and those of hydrothermal deposits are granites and granitic gneisses. Majority of the tungsten and molybdenum deposits in South Korea are distributed in association with the granitic stocks and batholiths of Daebo granites (Jurassic) and Bulkuksa granites (Late Cretaceous) (KIM, O.J., 1971; PARK, 1975) (Fig. 2).

Four major disturbances have been identified in South Korea, that is, pre-Triassic disturbance, Triassic Songlim disturbance, Jurassic Daebo disturbance, and Late Cretaceous to early Tertiary Bulkuksa disturbance (KIM, W.J. *et al.*, 1982). Among these, the latter two disturbances were accompanied by large scale granitic intrusions, and associated mineralization.

The major tungsten and molybdenum ore minerals are wolframite, scheelite, and molybdenite.

Table 2. Genetic classification and summary of the geology of Korean tungsten and molybdenum deposits

Types of ore deposits		Major ore minerals	Host rocks	Location	Type mine
Pegmatite deposit		Sch, (Wf)	Amp.	(1)	Okbang
		Sch, (Wf)	Amp. gn.	(1)	Ssangjeon
		Mo	gn.	(4)	Jangsu
Contact metasomatic deposits		Sch, Bi (Mo, Wf)	Ls	(1)	Sangdong, Sindae, Guirae, Chilbo
		Sch, Mt.	Ls	(1)(3)	Woolsan
		Mo, Sp.	Ls	(1)	Sinyaemi
		Mo, Mt	Ls	(1)	Dongnam
		Mo	Do, Ls.	(1)	Guemsung
Hydrothermal deposits	Vein	Wf, (Sch), Mo	gr. gn. Hf	(1)	Wolak, Susan, Suri, Daehwa, Donsan
			Sl.		Hyundong, Yongha, Daejei, Samduk, Kuemnueng
		Mo	gr.	(2)	Namyang, Garisan
		Mo	gr. Ad.	(3)	Sannae, Dongbo, Backyang
		Mo	gr. gn	(4)	Chungyang, Chungpung
		Sch, Cp	Sl	(1)	Boksu
	Breccia pipe	Wf, Cp (Sch)	gr. Ad	(3)	Dalseong, Ilkwang
	Disseminated and stockwork	Mo	gr.	(1)	Sobo
				(3)	Samdong, Oksan, Kyongju (Duckdong)

Sch: Scheelite, Wf: Wolframite, Mo: Molybdenite, Mt: Magneite, Sp: Sphalerite, Cp: Chalcopyrite, Bi: Bithmuthinite, ( ) shows minor minerals. Amp: Amphibolite, gn: Gneiss, Ls: Limestone, Do: Dolomite, gr: Granite, Ad: Andesite, Sl: Slate, Hf: Hornfelse

(1) Kangwon-Kyongbuk-Chungbuk Province

(2) Kyonggi-Kangwon Central Province

(3) Kyongbuk South-Kyongnam Province

(4) Other Provinces

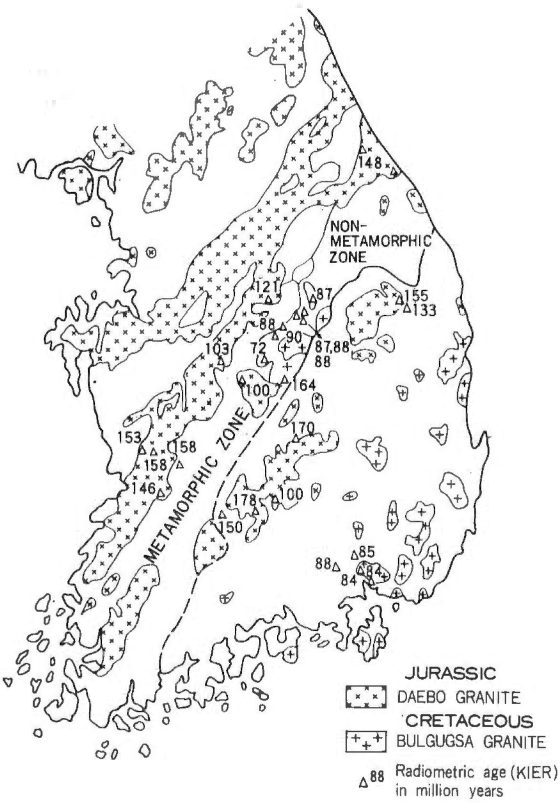


Fig. 2. Two major granites in S. Korea.

Wolframite is the most important ore mineral in the pegmatite deposits although scheelite also constitutes a major mineral in some of the highly enriched pegmatite deposits. Scheelite is the main ore mineral in the hydrothermal deposits, but in some deposits wolframite predominates as a main ore mineral. Molybdenite is recovered as by-product in most tungsten mines, but some mines produce molybdenite as the main ore mineral. Other associated ore minerals are chalcopyrite, magnetite, sphalerite, galena, bismuthinite, pyrite, pyrrhotite and flurite. Chalcopyrite (Dalsung, Ilkwang) and bismuthinite (Sangdong) are recovered as by-products. Some magnetite deposits contain scheelite (Woolsan) and molybdenite (Dongnam), and some lead-zinc deposits molybdenite (Sinyemi). At present these minor minerals are recovered as by-products.

Tugsten and molybdenum ores are closely associated with some characteristic gangue minerals depending on the genetic types. The gangue minerals of the pegmatite deposits in the amphibolite host (Okbang scheelite deposit) are quartz, plagioclase and biotite, whereas those in gneissic host (Jangsu molybdenite deposit) are quartz, K-feldspar, muscovite and biotite. The gangue minerals of hydrothermal deposits are mainly quartz with very little amounts of sericite and carbonates.

The gangue minerals of contact metasomatic deposits in limestone host are skarns consisting of garnet, hedenbergite and diopside, and minor wollastonite, but epidote predominates when the hosts are impure limestone or intermediate volcanic rocks.

A zonal arrangement is well developed in some of the vein deposits. In most hydrothermal vein deposits, tungsten minerals tends to decrease downward but molybdenite tends to increase. At the Wolak mine, scheelite, chalcopyrite, native bismuth, and bismuthinite are concentrated at the top zone and they gradually give way downward to wolframite, and finally to molybdenite, where the ore body encountered the granitic rocks. At the Samduk mine, the major mineral assemblage changes from chalcopyrite-wolframite until 30 m below outcrop, through chalcopyrite-wolframite-molybdenite between 30 m and 60 m, and to molybdenite below 60 m. The Samdong molybdenite deposit shows rather well defined ore zones such as quartz-molybdenite zone, hornblende-molybdenite zone, pyrite-magnetite zone, quartz-pyrite zone, feldspar-sericite-kaolinite zone with molybdenum enriched in the first three zones. The mineral zones of the Sangdong scheelite deposits are arranged in the order of quartz-mica zone, quartz-hornblende zone, garnet-diopside zone, and wollastonite-garnet zone from the ore-bearing central zone outwards to the host rock.

A wall-rock alteration also varies depending on the host rocks and deposit types. At the Okbang pegmatite deposit, hornblende of the host amphibolite has altered to biotite and at Ssangjeon, the gneiss has changed to greisen. The granitic and gneissic wall rocks of the hydrothermal deposits have suffered silicification, sericitization, pyritization and greisenization, and propylitization is characteristic in andesitic rocks (Dalseong). Several alteration zonations are reported in disseminated-stockwork type deposits and contact metasomatic deposits. The Duckdong mine shows quartz-sericite zone, quartz-pyrite zone, and chlorite zone outwords from the ore vein. Woolsan mine shows salite, garnet-salite and garnet zone in the limestone, and epidote zone, garnet-epidoe zone and garnet zone in the volcanic debris.

The fluid inclusion studies have been done recently on the tungsten and molybdenum deposits. These results are given in the Tables 3, 4, and 5.

Table 3. Homogenization temperatures (°C) of fluid inclusions form some of the tungsten and molybdenum deposits in Korea

Mineral / Mine	quartz	scheelite	barite	fluorite	calcite	other minerals
Okbang	220—357			208—280		
Sangdong	120—410	190—367		237—167	289	apatite 287—345 biotite 381 hornblende 293 garnet 387—480 hedenbergite 383—573
Daehwa	205—314	245—300	287—353	170—295	170—240	
Wolak	239—360		288—360	159—202		
Susan	235—335			225—305		
Chungyang	200—350		280—348	164—253		rhodochrocite 283—295
Dalseong	154—335					
Woolsuk	310—355				160—280	
Woolsan	230—360					

after Kim, K.H. (1977), Moon (1979)

Table 4. Salinity of the inclusion fluids in the minerals from some of the tungsten and molybdenum deposits in Korea (wt.% NaCl equivalent)

Minerals / Mine	quartz	scheelite	barite	fluorite	apatite
Sangdong	1.4-13.8	1.9-4.4			5.1
Wolak	3.9- 9.6		5.3-7.7	1.5-2.9	
Susan	4.0- 9.7			5-7.7	

Table 5. CO_2 concentrations of the inclusion fluids in the minerals from some of the tungsten and molybdenum deposits in Korea (wt.%)

Mines	Sangdong	Daehwa	Susan
CO_2 concentrations	0.148—1.184	10–20	7—30

Tabel 6. K-Ar ages of tungsten and molybdenum mineralization and related granites (in m.y.)

Mines \ Ages and samples	vein materials	biotites of the related granites
Sangdong	muscovite: 81.2±2.4	
	biotite: 83.6±2.6	
	hornblende: 83.9±2.9	
Sannae	sericite: 65.0±2.4	
Ilkwang	sericite: 0.69±2.6	
	biotite: 66.0±2.4	81.1±3.5[1)]
Hwanggangri area		87.7±8.6
Woolsan		58

1) Horblende in quartz monzonite

The mineralization ages have been studied directly with the vein materials of the tungsten and molybdenum deposits in several localities. These ages are shown in Table 6. They are very close to the age of Bulguksa granite of Late Cretaceous to early Tertiary. It is also believed that many other tungsten and molybdenum deposits in Kyonggido and northern Kangwondo were formed during the Daebo granite intrusion (KIM, O.J., 1971; KIM, J.H., 1977).

Description of Individual Ore Deposits

Five tungsten and molybdenum deposits are selected to typify each genetic type: the Ssangjeon deposit for pegmatite type deposits, the Sangdong scheelite deposit for contact metasomatic deposits, the Chungyang deposit for hydrothermal vein deposits, the Ilkwang deposit for hydrothermal breccia pipe deposits, and the Sobo molybdenite deposit for hydrothermal disseminated and stockwork deposits.

Ssangjeon Mine

The mine is located at Ssangjeonri, Seomyon, Wooljingun, Kyongsangbukdo, South Korea; Lat. 36°58′20″ N, Long. 129°20′00″ E.

The geology of the area is composed of Precambrian Wonnam Formation and Buncheon granitic gneiss (Fig. 3). The Buncheon granitic gneiss intrudes the Wonnam Formation. The Wonnam Formation is composed of biotite gneiss, banded gneiss, injection gneiss, mica schist, and quartz-sericite schist. It also contains amphibolite lenses of calcareous sediment origin.

The tungsten-bearing pegmatitic quartz veins are developed typically at the contact between amphibolite at the hanging wall and Buncheon granitic gneiss at the footwall (KIM, S.E. *et al.*, 1979). The strike and dip of the ore vein which is parallel to the regional foliation are EW-N 80° and 40°-50° NW, respectively. The ore-bearing pegmatitic quartz vein extends 1,200 m in length but the zone of tungsten enrichment is 800 m long and 10–40 m thick (YUN, 1966). Greisenization is observed only at the footwall contact but the hanging wall contact is sharp and no alteration is observed. The tungsten is enriched close to the hanging wall contact (Fig. 4).

The ore minerals are wolframite and scheelite associated with molybdenite, chalcopyrite,

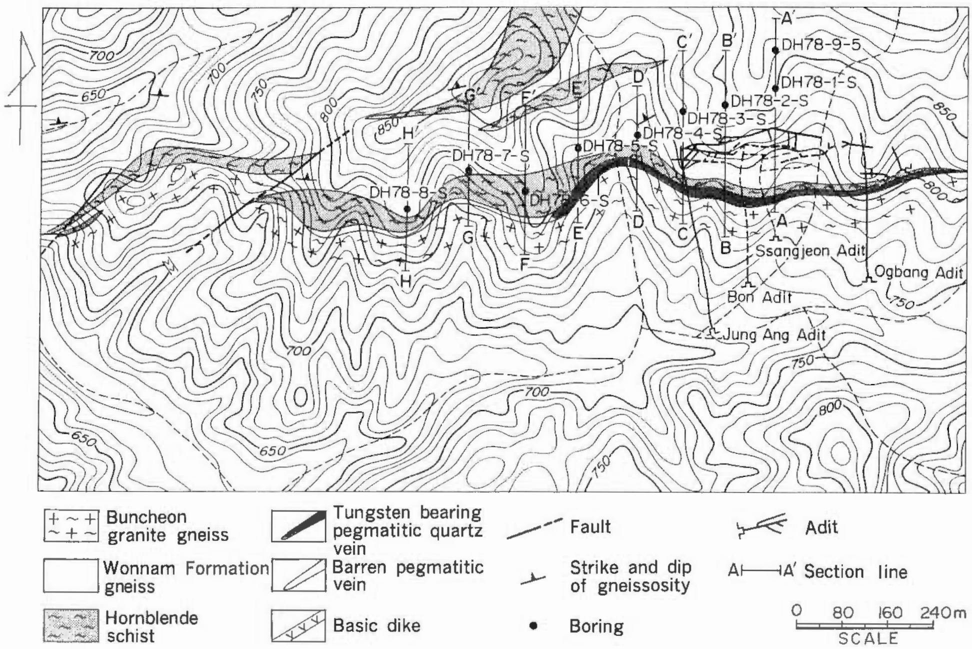


Fig. 3. Geologic map of Ssang Jeon area.

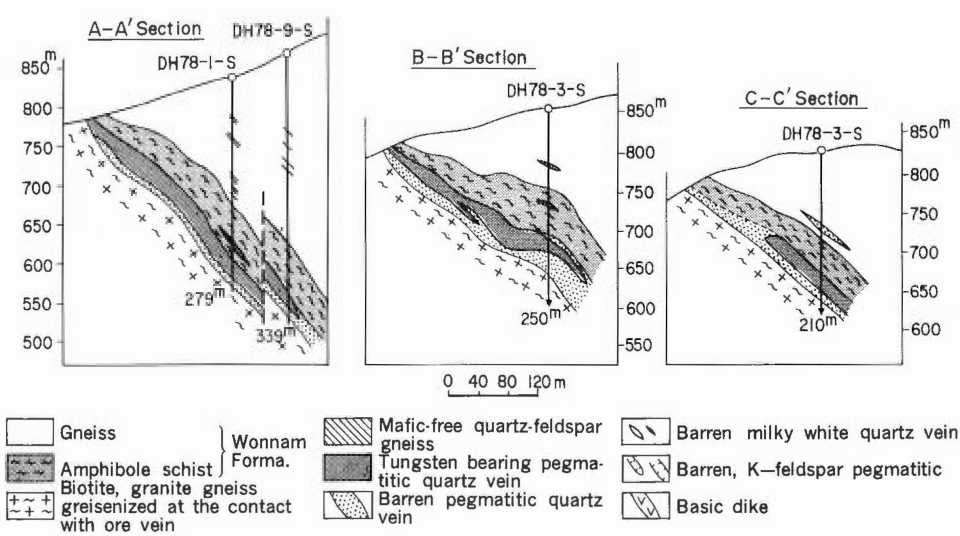


Fig. 4. Section map of Ssang Jeon ore body.

pyrite, arsenopyrite, tourmaline, and fluorite (So, 1972). Wolframite tends to be rich to the east side of the ore-bearing pegmatite vein whereas scheelite to the west. Arsenopyrite content increases with the wolframite enrichment. The average grade of the ore vein is 0.14% WO_3, 0.1–0.3% As, 0.04% Cu, 0.03% Mo and 0.01% Bi.

The KIER exploration team has been working on this ore deposit since 1978 and calculated more than 3 million metric tons of proven ore reserves. The mine is now under construction of mining and milling facilities with a capacity of 500 metric ton per day. Besides tungsten, the mill is designed to recover high grade silica from the pegmatite as a by-product. The grade of quartz concentration is >99.8% SiO_2, <0.16% Al_2O_3, and <0.02% Fe_2O_3.

Sangdong Scheelite Mine

The mine is located at Sangdongeup, Yongwolgun, Kangwondo, Korea; Lat. 37°08′41″ N, Long. 128°50′17″ E.

The deposits are located at the southern limb of Hamback syncline. The geology of the area is composed of Cambrian Jangsan quartzite, Myobong slate, Pungchon limestone, and Hwajeol Formation (CHUNG, 1966; HONG *et al.*, 1970; JOHN, 1963, 1964; KIM and PARK, 1970) (Fig. 5). They are conformably overlain by the Ordovician formations to the north and unconformably overlies the Precambrian Taebaeksan series to the south. These sedimentary beds trend N 70°–80° W and dip 20°–35° NE near the ore deposit. Igneous rocks are not observed at the mine area, but granodiorite porphyry (105 Ma) crops out at Eopyong, 4 km to the southeast, and two mica granite and numerous pegmatites at Kakhi (Kakhi granites, 1760 Ma), 4 km to the south and basic dikes to the east.

The Sangdong scheelite deposits are embedded mainly in the Myobong slates, but minor scheelite and chalcopyrite mineralizations are also found in the Pungchon limestone and Hwajeol Formation. It has been proved by drilling that wolframite and molybdenite mineralizations occur in the Jangsan quartzite and in the Precambrian basement. The Sangdong scheelite deposit comprises six parallel veins along the bedding plane of the Myobong Formation. The main vein in the Myobong Formation extends 1,500–2,000 m laterally with a thickness of 3–5 m. The maximum dip-side extension is confirmed by diamond drilling to be 1,500 m. The rich ore zone extends more than 600 m. The other veins appear at the footwall side

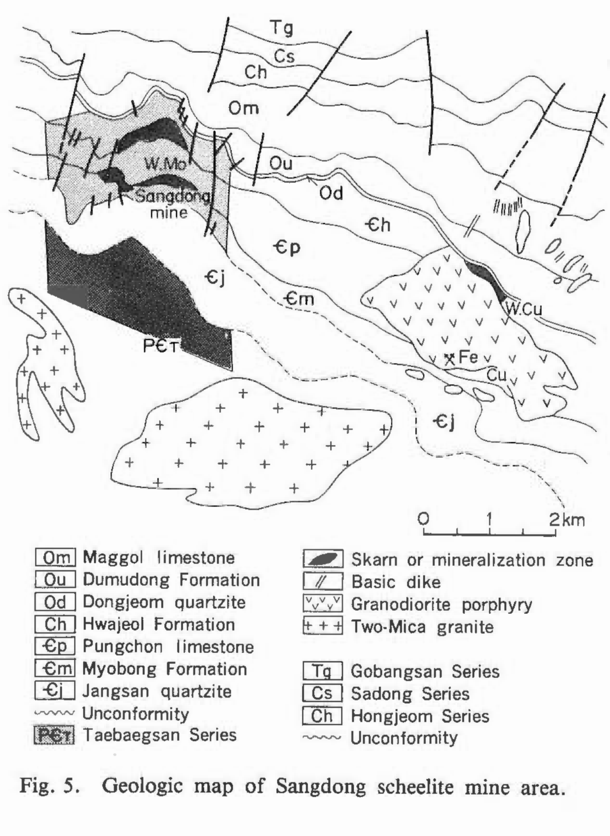


Fig. 5. Geologic map of Sangdong scheelite mine area.

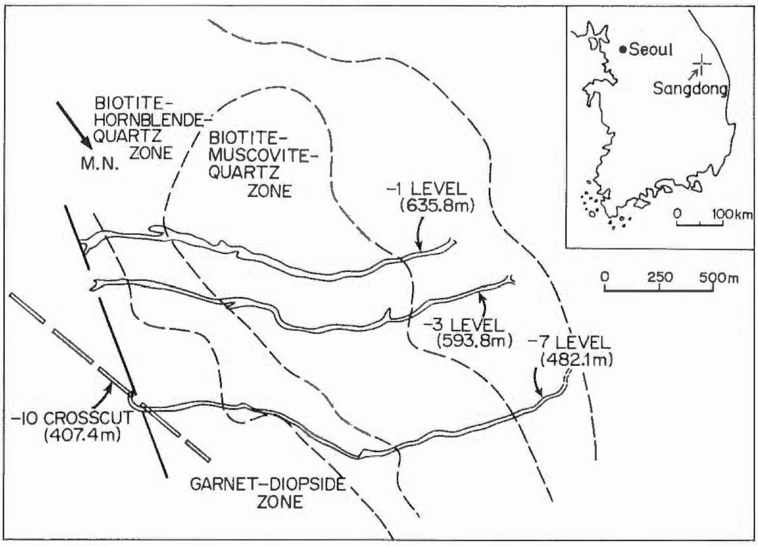


Fig. 6. Alteration zones of skarn minerals in Sangdong scheelite deposit (plan) (after O.J. KIM, 1976).

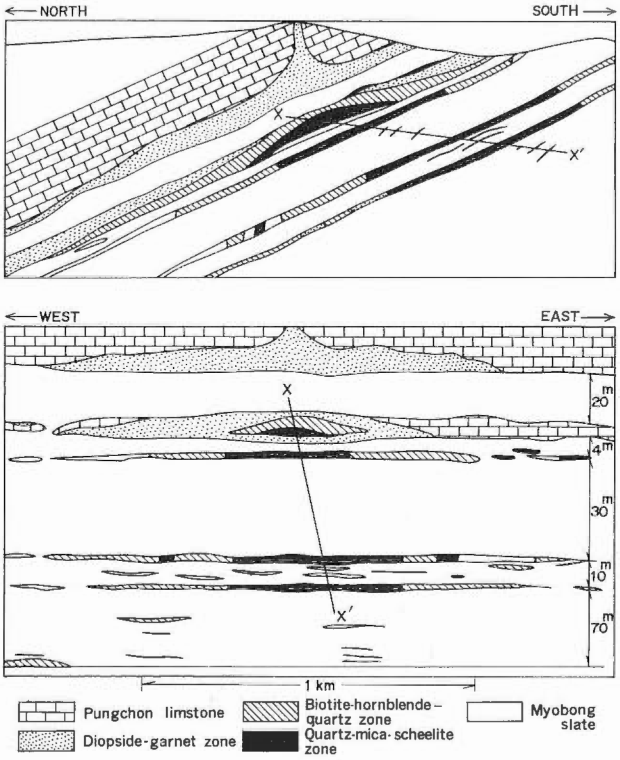


Fig. 7. Alteration zones of skarn minerals in Sangdong scheelite deposit (section).

of the main vein and are relatively discontinuous.

No clear boundary exists between the vein and the host rock in most cases, but host rocks are intensively silicified and sericitized near the ore veins. The intensity of silicification is higher at the footwall side than the hanging wall side. This fact is consistent with the stronger tungsten mineralization to the footwall side.

The deposit usually shows zonal arrangement from the centre to both ends of the vein comprising three subzones; richest scheelite-quartz-mica zone, moderately enriched biotite-hornblende-quartz zone, and diopside-garnet border zone (CHUNG, 1964) (Figs. 6 and 7). These subzone boundaries, however, are not clear and only recognizable by the major index mineral content in the corresponding zone. The main ore minerals are scheelite and powellite but wolframite, molybdenite and bismuthinite are also accompanied (LEE and KIM, S.W., 1982; MOON, 1972, 1974; MOON and KIM, T.S., 1972; MOON and LU, 1980; PARK *et al.*, 1980).

Ore grade is 1.5–2.5% WO_3 in the central zone decreasing gradually in the biotite-hornblende-quartz zone and finally to less than 0.5% in the garnet diopside zone at the margin. The grade of ore, in general, is proportional to quartz content of the ore vein.

The homogenization temperatures of the fluid inclusions in quartz, fluorite, and calcite in the vein are 120°–410°C, 134°–267°C, and 289°C, respectively (MOON, 1979).

The K-Ar ages of mineralization are 81.2±2.4 Ma (muscovite) to 83.9±2.9 Ma (hornblende) (FARRAR *et al.*, 1978). These ages correspond to those of the Bulkuksa granite.

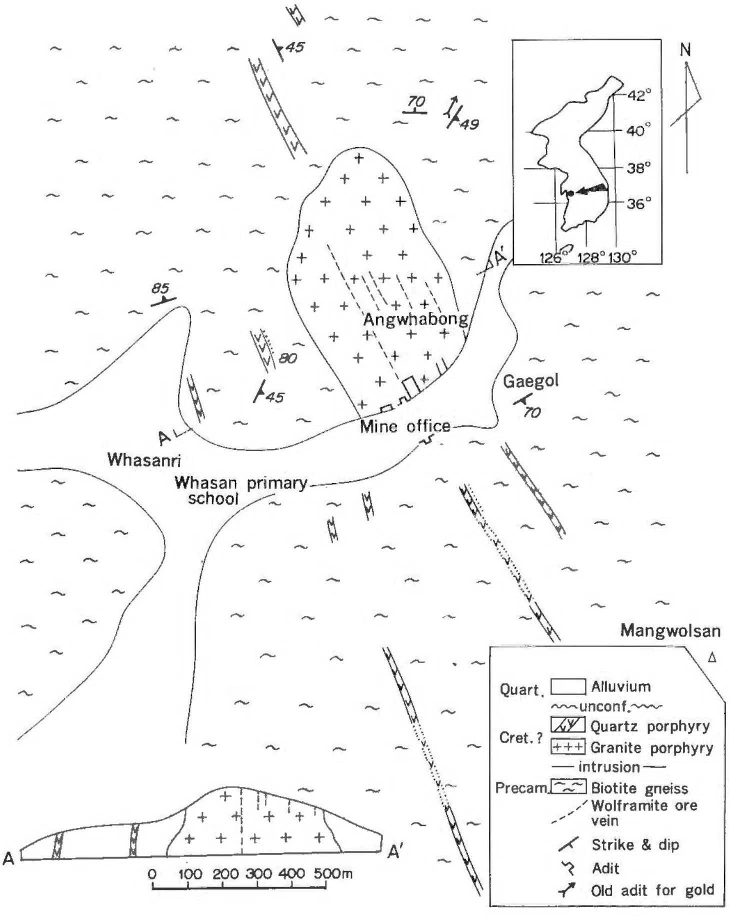


Fig. 8. Geologic map of Chungyand tungsten mine.

A great attention is paid on the molybdenite occurrence in the Jangsan quartzite at this mine. Molybdenite-bearing fissures have been previously known from the old adit but recent deep drilling shows that the molybdenite-bearing fissure system in the quartzite is so large and widely distributed that it might be minable as a large molybdenum deposit in the near future inspite of the fact that its grade is very low.

Chungyan Tungsten Mine

The mine is located at Hwasanri, Jeokgokmyon, Chungyanggnu, Chungcheonnamdo, Korea: Lat. 36°21′20″ N and Long. 126°51′44″ E.

The geology of the area is mostly composed of Precambrian biotite gneiss intruded by granite porphyry stocks and quartz porphyry dikes (Fig. 8).

The ore deposits occur in the granite porphyry stock intruded in the biotite gneiss. The ore deposit comprises 7 quartz veins. The largest of them extends 2 km with the thickness of 0.3–1 m. The ore grade ranges from 1 to 2.5% WO_3. Mining has continued since its discovery in 1913 and is underway at 600 m level at present.

The ore minerals are wolframite, scheelite, molybdenite, bismuthinite, native bismuth, with small amounts of gold and silver; pyrite, chalcopyrite, pyrrhotite, galena, sphalerite, barite and fluorite are the associated minerals. Vertical zonation of the ore minerals is such that scheelite and wolframite mainly in association with pyrite occur at shallow depths, and bismuthinite and molybdenite tend to increase at depth. The wall rocks near ore veins are silicified in case of granite, or chloritized and sericitized in case of biotite gneiss (Fig. 9).

Fluid inclusion study of the ore body indicates that the mineralization temperature was around 200–355°C. The MnO/FeO ratio of the wolframite is 0.78–0.94 indicating relatively high mineralization temperatures. The age of the mineralization is estimated to be Late Cretaceous to early Tertiary by geologic inferences although no direct measurement was made on the ore vein.

Ilkwang Mine

The mine is located at Jwacheonri, Ilkwang myon, Dongraegun, Kyongsangnamdo, 25 km northeast of Pusan, Korea: Lat. 35°18′ N, Long. 129°14′ E.

The mine was originally one of the largest copper mines in Korea until it was closed down in 1945 (Jim, 1977), but the mine was reopened for tungsten minerals since Geological Survey of Korea, the former name of KIER, had discovered these minerals at the depth.

The geology of the area is composed of shale and sandstone of Cretaceous age which are intruded by a granodiorite stock (Imai and Lee, 1978) (Fig. 10). The granodiorite stock has an elliptical form with a long axis 1.5 km and a short axis of 0.7–0.8 km. The granodiorite stock has quartz-monzonitic core which is brecciated to form breccia pipe and

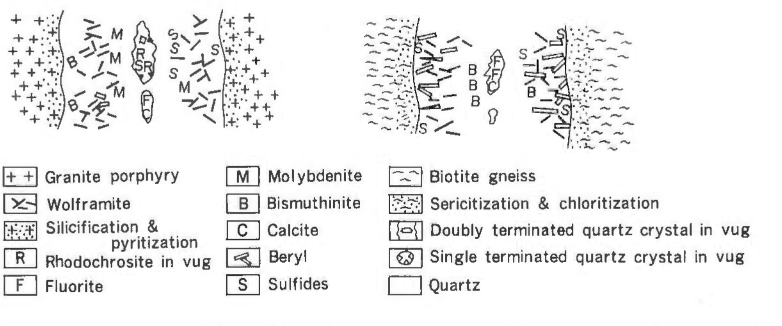


Fig. 9. Comparative sketch of the wolframite-bearing grartz vein in granite porphyry and biotite gneiss of Cheonhyan tungsten mine.

is hydrothermally altered.

The tungsten mineralization occurs in the breccia pipe within the quartz monzonite (JOHN, 1971; KANG *et al.*, 1976). The breaccia pipe appears to be two vertical pipes at the surface but they merge into one pipe below 40 m from the surface (Fig. 11). The hydrothermal mineralization is restricted to the margin of the pipe near surface but the intensity of mineralization increases downwards. In the deeper parts the breccia form is completely obscured by strong hydrothermal alteration. The horizontal section of the breccia pipe is of 80 m×50 m. The ore minerals are chalcopyrite, wolframite, and scheelite associated with pyrrhotite, pyrite, arsenopyrite, sphalerite, galena, and native bismuth.

The gangue minerals are quartz, tourmaline and calcite. The mineralization took place in two stages; one is pneumatolytic stage when the tourmaline, wolframite and scheelite were

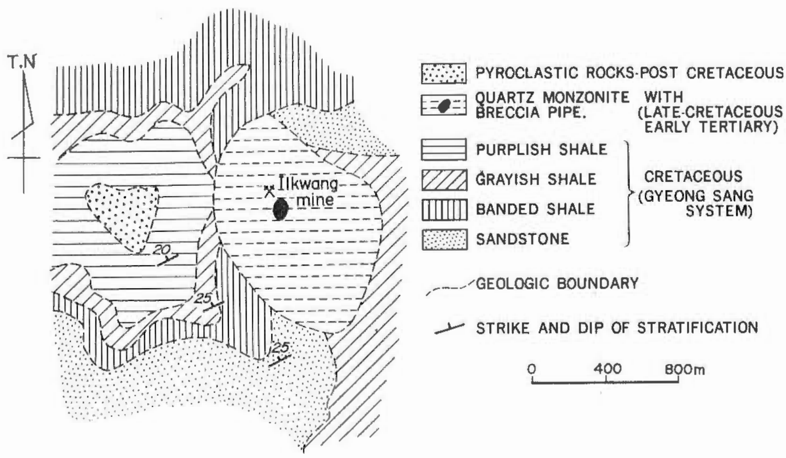
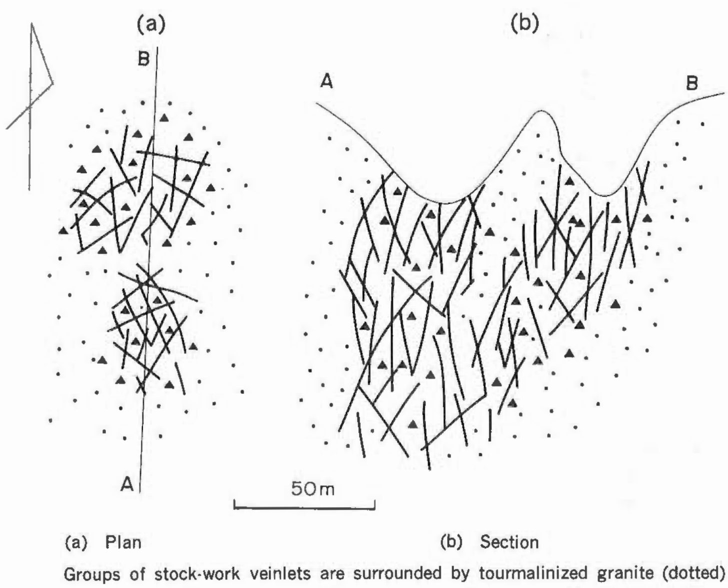


Fig. 10. Geologic map of Ilkwangd mine.



(a) Plan (b) Section

Groups of stock-work veinlets are surrounded by tourmalinized granite (dotted) and sericitized, chloritized, or silicified granite (triangular).

Fig. 11. Diagrammatic geologic map of breccia pipe of Ilkawang mine.

formed and the other is hydrothermal stage when the most sulfide minerals were formed.

Alteration zones are developed both within the breccia pipe and in the quartz monzonite around the pipe (Fig. 12). The majority of the quartz monzonite stock lie within the propylitic zone, which has been divided into two subzones: an outer tourmaline subzone characterized by the development of tourmaline rosettes, and an inner garnet subzone which lies within 10 m of the pipe margins. The garnets within this subzone are essentially spessartine-almandine and are either disseminated throughout the rock or contained within tourmaline-filled fractures. Within the pipe the majority of the fragments have suffered alteration of the sericitic zone except for the larger ones in the deeper parts of the mine which have cores of the garnet subzone (FLETCHER, 1977).

The age of the alteration is measured to be 69±3 Ma by K–Ar method with sericite from

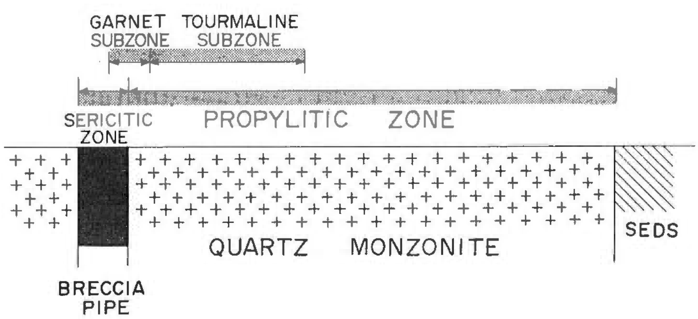


Fig. 12. Alteration zones and subzones relative to the position of the Ilkwang breccia pipe.

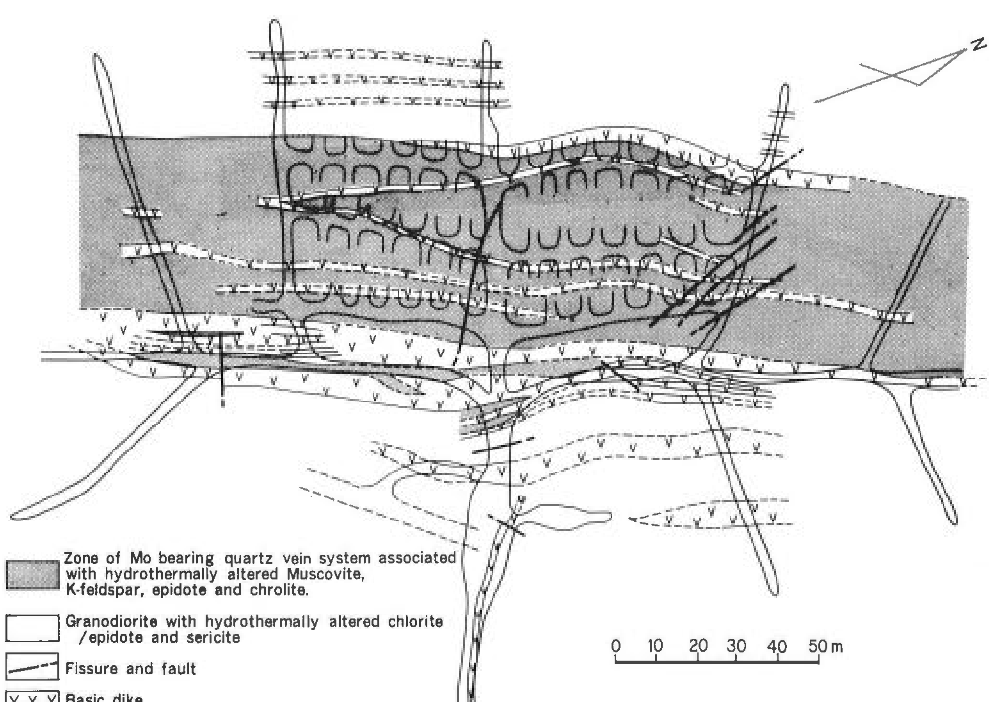


Fig. 13. Underground geologic map of -1 level Sobo molybdenite mine.

the breccia (FLETCHER and RUNDLE, 1977). The mechanism of the brecciation is rendered to the pneumatolytic force of the hydrothermal solution form the magma (JOHN, 1971), thus the age of the brecciation should be about at the same time with the alteration.

Sobo Molybdenum Mine

The mine is located at Samyulri, Pyonghaemyon, Wooljingun, Kyongsangbukdo, Korea: Lat. 36°40′46″ N, Long. 129°25′54″ E.

The geology of the area is mainly composed of Jurassic Onjeongri granite intruded by N–S trending basic dikes (Fig. 13) (KIM, S.Y. *et al.*, 1981). The Onjeongri granite include diorite, granodiorite and quartz monzonite, and the lime-alkali index of the granite is 58% indicating calc-alkaline series.

The ore deposit occurs in the granodiorite of the Onjeongri granite as stockworks (Fig. 14). Molybdenum is enriched only in the N 15° E trending fissures and not in the E–W trending fractures within the shear zone, which extends 500 m with 80 m width. The individual ore bearing fissures are quartz veinlets only 0.1 cm to 5 cm wide and a few meters long, but new ore bearing veinlets may develop both laterally and vertically as soon as one veinlet pinches out.

The granodiorite is hydrothermally enriched in K_2O, SiO_2 and H_2O near the ore body. The alteration zones are divided into propyllitic, sericitic, and k-feldspar-quartz-molybdenite zones (KIM, S.Y., 1981).

The mineralized veinlets are parallel with and developed in close spatial association with basic dikes but the basic dikes appear not to be related directly to the ore genesis. The main

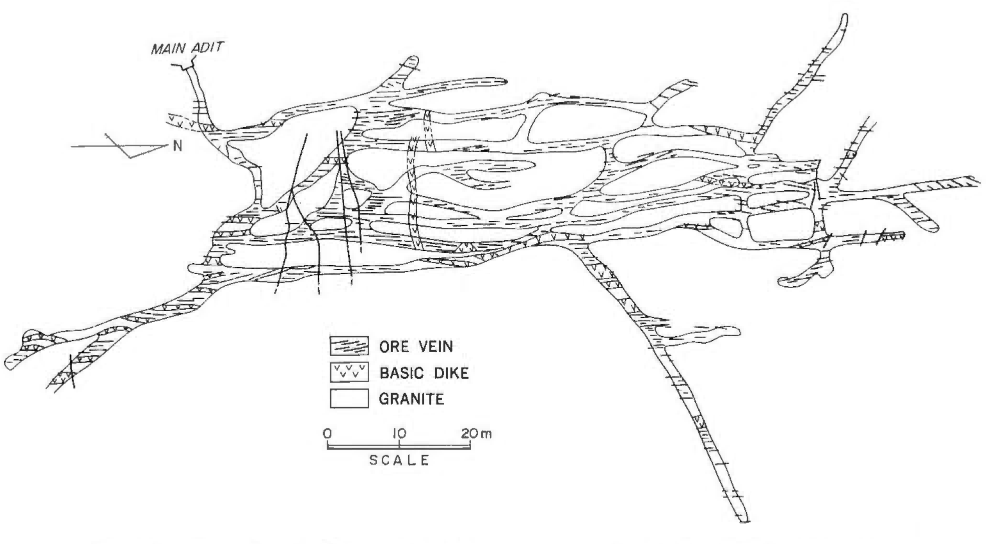


Fig. 14. Ore veins in NS trending fissure systems of main level, Sobo Mo mine.

ore mineral is molybdenite with minor pyrite and chalcopyrite. The E–W trending fractures often contain galena and sphalerite.

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Carbonatites and Associated Mineral Deposits in Brazil

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ABSTRACT

Alkaline complexes are distributed in many parts of Brazil and their ages are Precambrian, Mesozoic and Cenozoic.

The oldest ones appear in Bahia, Goiás, Pará, Amazonas and Mato Grosso States. The Cenozoic complexes occur mainly in Ceará State and in the Fernando de Noronha and Trindade Islands.

Of these the Mesozoic complexes are by far the most important in terms of rock varieties and asociated mineral deposits. They occur mainly in the southern portion of the country and can be classified into two classes: those with carbonatites and those apparently without carbonatites. Although dunite, peridotite, pyroxenite, serpentinite, gabbro and/or syenite are the main constituent rocks of both classes, presence of carbonatite is economically important because carbonatites are associated with rich deposits of phosphate, niobium, titanium, rare-earths, and vermiculite.

Among the fifteen carbonatite-bearing complexes so far recorded in Brazil. economic deposits have been discovered in the following complexes: phosphate (Anitápolis and Lages in Santa Catarina State; Morro do Serrote and Jacupiranga in São Paulo State; Tapira, Serra Negra and Salitre in Minas Gerais State; Catalão in Goiás State), niobium and rare-earths (Araxá, Salitre, and Catalão), titanium (Tapira, Araxá and Catalão) and vermiculite (Catalão). Uranium-thorium mineralizations are also found in Minas Gerais. The Arazá Complex contains the most important niobium orebody in the world, with reserves of about 463 million tons of ore averaging 2.5% Nb_2O_5. In Catalão, reserves of rare earths ore are estimated 15 million tons with 4% $Ce_2O + La_2O_3$.

INTRODUCTION

Alkaline complexss in Brazil are distributed in Santa Catarina, Minas Gerais, Goiás, Bahia, Pará, Mato Grosso and Amazonas States (Fig. 1). Normally they are intruded into Precambrian rocks and their ages of intrusion are Precambrian, Mesozoic and Cenozoic. The Precambian ones appear in the eastern, centeral and northern portions of Brazil, while the Mesozoic and Cenozoic complexes are distributed in southern and northeastern parts, some complexes of Mesozoic and Cenozoic ages have also been recorded in the Amazonic Region.

Based on the petrographic studies of individual complexes, ULBRICH and GOMES (1981) proposed a tentative classification of the Brazilian alkalic intrusives into eight groups or types: 1) A saturated to undersaturated syenitic association with alkalic syenite, pulaskite and nepheline syenite, frequently associated with trachyte and phonolite; 2) A subsaturated, peralkaline syenitic association with nepheline syenite, phonolite and tinguaite; 3) A mafic to ultramafic, alkali-saturated to peralkaline association with glimmerite, dunite, peridotite, pyroxenite, alkali syenite, malignite, shonkinite, as well as stronyly undersaturated and peralkaline species, with or without carbonatite; 4) A mafic-ultramafic alkali-gabbro association with pulaskite, nepheline syenite, essexite, theralite and, sometimes, monzonite; 5) An alkali basalt-trachyte-phonolite association mainly expressed as dykes, sills, minor stocks and chimneys; 6) An alkali granite-alkali syenite association; 7) A strongly undersaturated and peralkaline volcanic association with leucitite, ugandite, analcitites, and, sometimes, undersaturated basalt and phonolite; 8) An

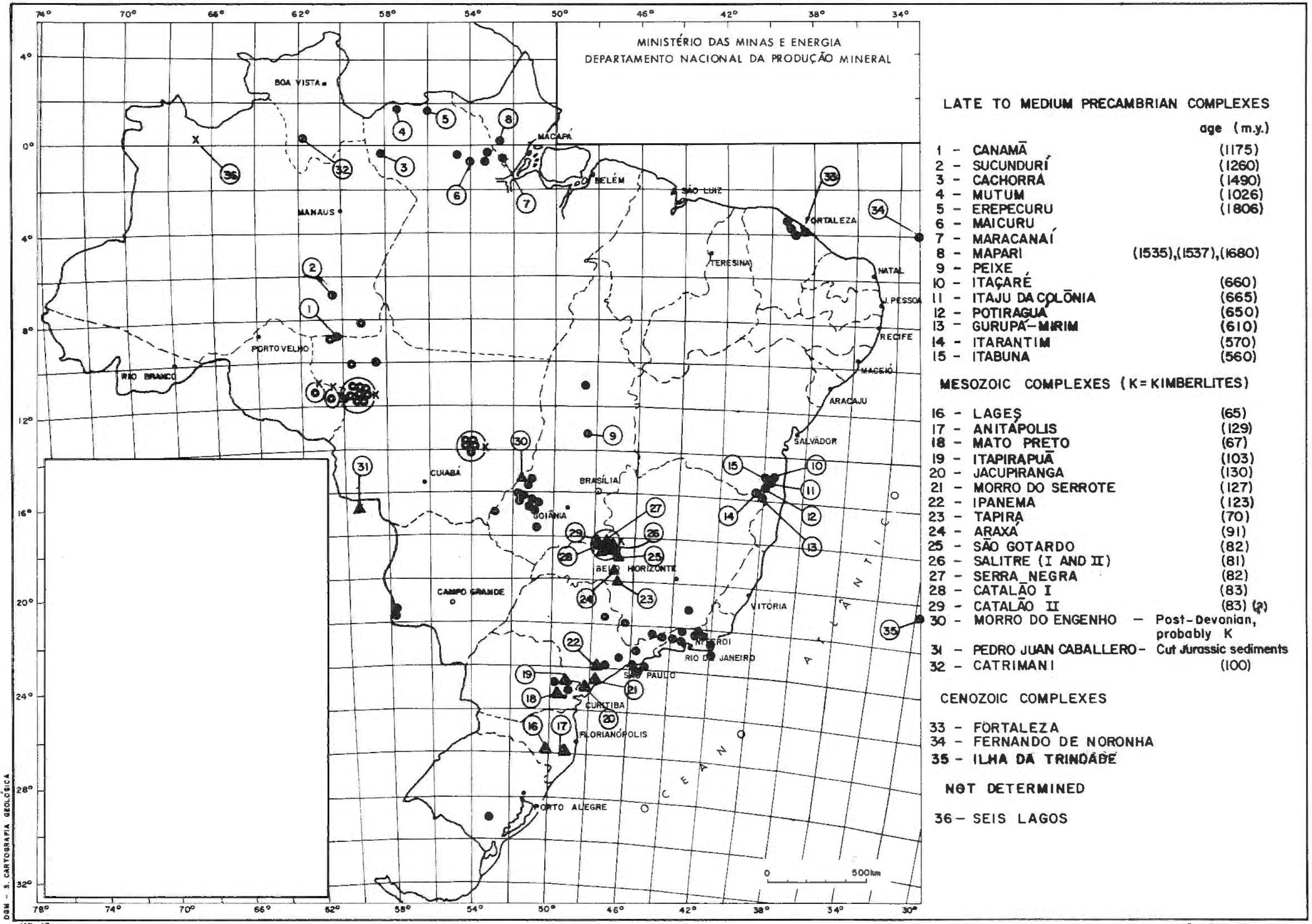


Fig. 1. Main alkaline complexes in Brazil.

undersaturated, persodic association with alkali syenite, sodalite syenite and syenite-litchfieldite as main rock types.

This classification, of course, is not definite for many comprehensive chemical and petrographic data and geological mapping are still lacking.

On the other hand, as ULBRICH and GOMES stress, in most of the Brazilian complexes there are both lateral and vertical zonings in rock types suggesting that surface manifestation may not be sufficient to ascribe the complex in one or other class or type.

Considering that the aim of this paper must be carbonatites, only general remarks will be made about carbonatite-free alkaline complexes.

ALKALINE COMPLEXES IN NORTHERN BRAZIL

The northern portion of Brazil can generally be characterized by the presence of the Amazonian Craton, subdivided into two Provinces seperated by the Amazonas Sedimentary Covers: the Rio Branco Province, to the North, and the Tapajós Province, to the South (ALMEIDA, *et al.*, 1981). These Provinces have not been subjected to geosynclinal evolution since at least 1,800 Ma and are formed by granite-greenstone, migmatites, old gneisses, granulites, basic and ultrabasic intrusives, and extensive magmatic extrusive rocks containing some Precambrian and younger sedimentary basins.

The Amazonas Sedimentary Covers are made of Paleozoic sediments covering an area of more than 1,250,000 km^2 of low relief.

Up to now the alkaline complexes detected are situated in both the Rio Branco and Tapajós Provinces and were discovered mainly during 1970's as the result of the RADAM* Project. Of 15 alkaline bodies known in this area, 7 of them have been determined for their ages. One of them, the Catrimani Complex is 100 Ma and consists of sodalite-nepheline syenite, litchfieldite and phonolite dykes (SALAS and SANTOS, 1974; ISSLER *et al.*, 1975; ULBRICH and GOMES, 1981). The other six have ages of 1,026 to 1,480 Ma (Mutum and Cachorro in Pará State; Sucunduri in Amazonas; Canamã in Mato Grosso State; Mapari in Amapã Territory) and 1,806 Ma (Erepecure, Pará State). Due to the deep weathering and extensive lateritization, fresh rocks are not exposed on the surface in most of the complexes of this region; they were recognized as alkalic complexes by their oval or round shapes and mainly by geochemical anomalies. In those with age determinations the main rock type is nepheline syenite. Their exposed areas vary from hundreds of squere meters to more than 16 km^2.

In the northwestern portion of Amazonas State, the Seis Lagos Complex is unique because of the possibility of carbonatite presence. It was discoverd by Projeto RADAM's geologists in 1975 and consists of three circular structures (diameters of 5.5, 0.75 and 0.50 km) in a north-south trend; it is intruded in basement gneisses and migmatites, and has altitudes from 300 to 400 meters. They crop out as thick lateritic radioactive hills (3,000 to 15,000 cps, and U/Th ratios between 1:2 and 1:4). Chemical analysis of samples of these laterites showed 1.3 to 3.4% Nb_2O_5 and 1.0 to 2.1% Ce. The complex is deeply weathered (more than 230 m depth) and covered by a capping with iron and manganese ores, limonitic ochres and pisolitic laterites. A drilling program still continues in the area by Companhia de Pesquisa de Recursos Minerais-CPRM, with the objective of evaluating the mineral potential of the complex, mainly for manganese, niobium and rare earths. Although no fresh rock has been found yet, chemical analyses and X-ray difraction studies have permitted to recognize the following main minerals in the ferruginous carbonatitic breccia collected in core samples; siderite, goethite, pyrite, phosphate, rutile. One interesting aspect of the complex is the presence of thermal spring with water temperature of 41°C and an out-flow of 1,657 liters/hour (ISSLER, 1981).

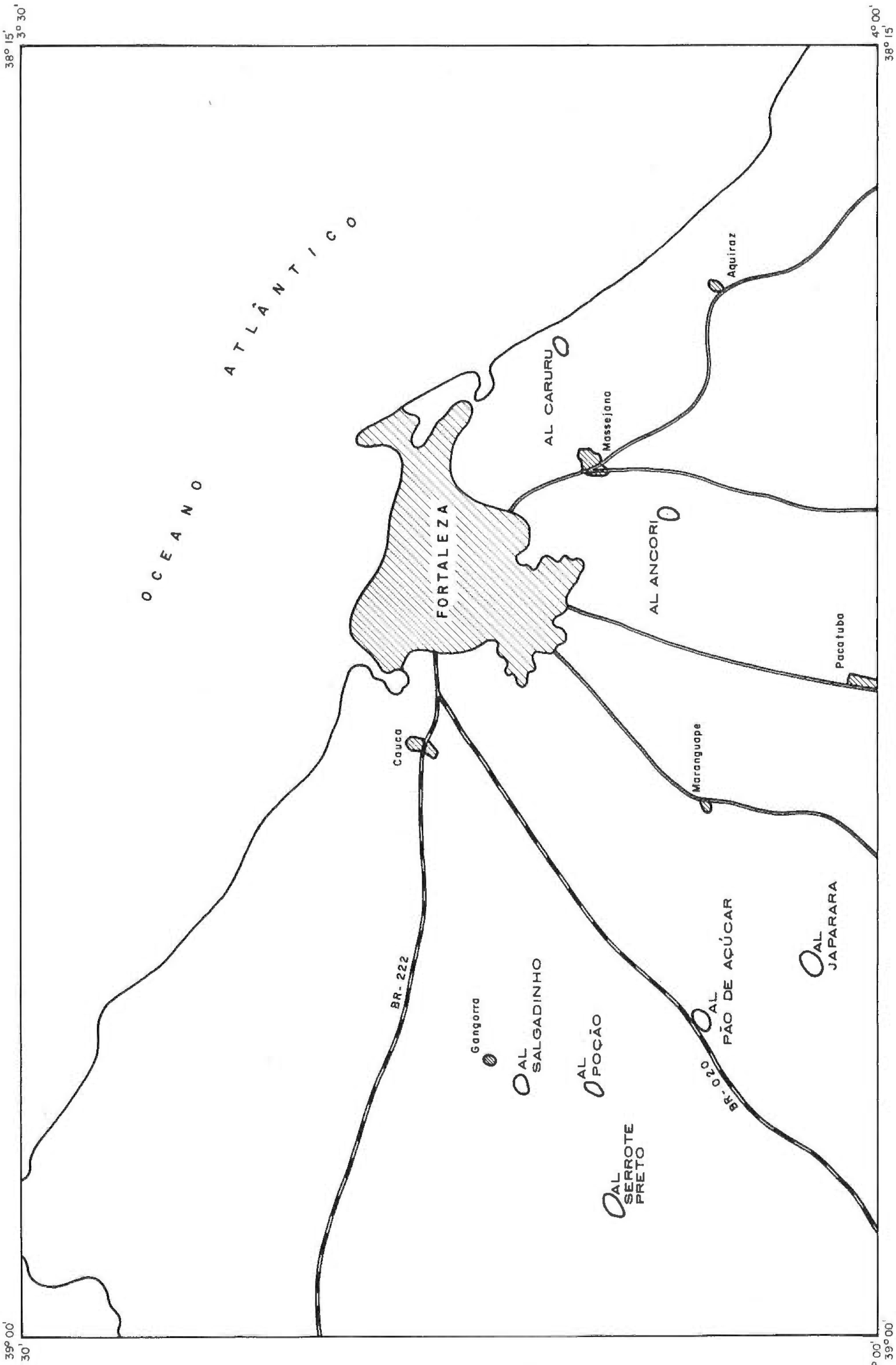


Fig. 2. Cenozoic alkaline complexes in Ceará state.

ALKALINE COMPLEXES IN SOUTHERN BAHIA AND CENTRAL GOIÁS STATES

At least 7 alkaline complexes were studied in the southern portion of Bahia State, with ages between 560 and 670 Ma, forming a second Precambrian group of alkalic intrusions in basement migmatites and granulites.

The Itabuna, Itarantim, Gurupá Mirim, Itaçaré and Ilhéus complexes have nepheline syenite and alkali syenite as dominant rocks, with subordinate trachyte. With the exception of the Itarantim body, which reaches tens of km^2, the others are very small (CORDANI *et al.*, 1974). The Itaju da Colonia is a N-S elongated complex, about 1 km^2, with litchfieldite and sodalite syenite as main rocks (FUJIMORI, 1967; CORDANI *et al.*, 1974), while the Potiraguá complex is made of three separate masses disposed in a N-S trend, covering an area of about 26 km^2. Its main rocks are nepheline syenite and sodalite syenite (SOUTO, 1972; CORDANI *et al.*, 1974). The importance of these complexes is the exploration of the sodalite syenites for beautiful bluish blocks of building stones.

In the central portion of Goiás State appears a huge body of lichfieldite (30 km N-S; 5 km E-W) of Precambrian age associated with pegmatoid granite and alkali monzonite, intruded into biotite gneisses. This complex is cut by various pegmatite bodies rich in zircon, corundum, Nb-ilmenite, rutile, moscovite, microcline and rare tourmaline (SCHOBBENHAUS FILHO, 1975). The weathering of these rocks produces alluvium and colluvium concentrations of zircon and other heavy minerals (BARBOSA *et al.*, 1969; MARTINS and LEMOS, 1981).

Other small alkaline complexes, probably of Precambrian age, have been detected in the area, mainly through the combination of magnetometric and radiometric airbone surveys, but detailed studies are still lacking.

THE CENOZOIC ALKALINE COMPLEXES OF NORTHEASTERN BRAZIL

Cenozoic alkalic intrusions appear in two regions of the northeastern portion of the country the Fernando de Noronha Territory and Ceará State.

Fernando de Noronha is a small group of volcanic islands, 345 km from the Brazilian coast, with a total area of about 18.5 km^2. They represent the remains of a volcano, whose base is about 60 km diameter (NNE-SSW) and is located at least 4000 m deep.

ALMEIDA, in 1958, made an excellent study of the islands and recognized three major episodies of volcanism. The first one is characterized mainly by pyroclastics (tuffs and breccias), cut by discordant bodies of phonolite and trachyte and dykes of alkali ultrabasic rocks (different kinds of lamprophyres). The second stage of volcanism is represented by tuffs, lapilli-tuffs, breccia-tuffs and agglomerates and by nepheline basalt and dykes of nephelinite. The third stage was made by extrusions of nepheline basanite which crops out in three islands of the group. Each stage is separated from the older by surfaces of erosion and deposition of sediments.

In Ceará State, near its capital, Fortaleza, a Tertiary volcanic suite has been known since 1968 when VANDOROS and OLIVEIRA reported the first occurrence of phonolite near the city of Messejana. During the 1970's, descriptions were presented in the literature about that and other alkalic bodies in the region (CORDANI, 1970; RAO and SIAL 1972; BRAGA *et al.*, 1977; GORINI, 1977; PASSOS *et al.*, 1978). In 1982, petrographic and geochemical studies of the area were presented by GUIMARÃES *et al.*, (Fig. 2). The suite is predominantly composed of phonolite, trachyte and nepheline syenite occurring in plugs, domes, conic-structures, concentric-structures and dykes. The bodies cut the Precambrian basement and were emplaced along SW-NE trending fractures. K/Ar age determinations by VANDOROS and OLIVEIRA (1968) of whole rock indicated values of 26.6 ± 0.8 Ma for the alkaline massifs, while ISSLER *et al.*, (1977, in GUIMARÃS *et al.*, 1982) obtained values of 34.2 Ma, using the Rb/Sr method with

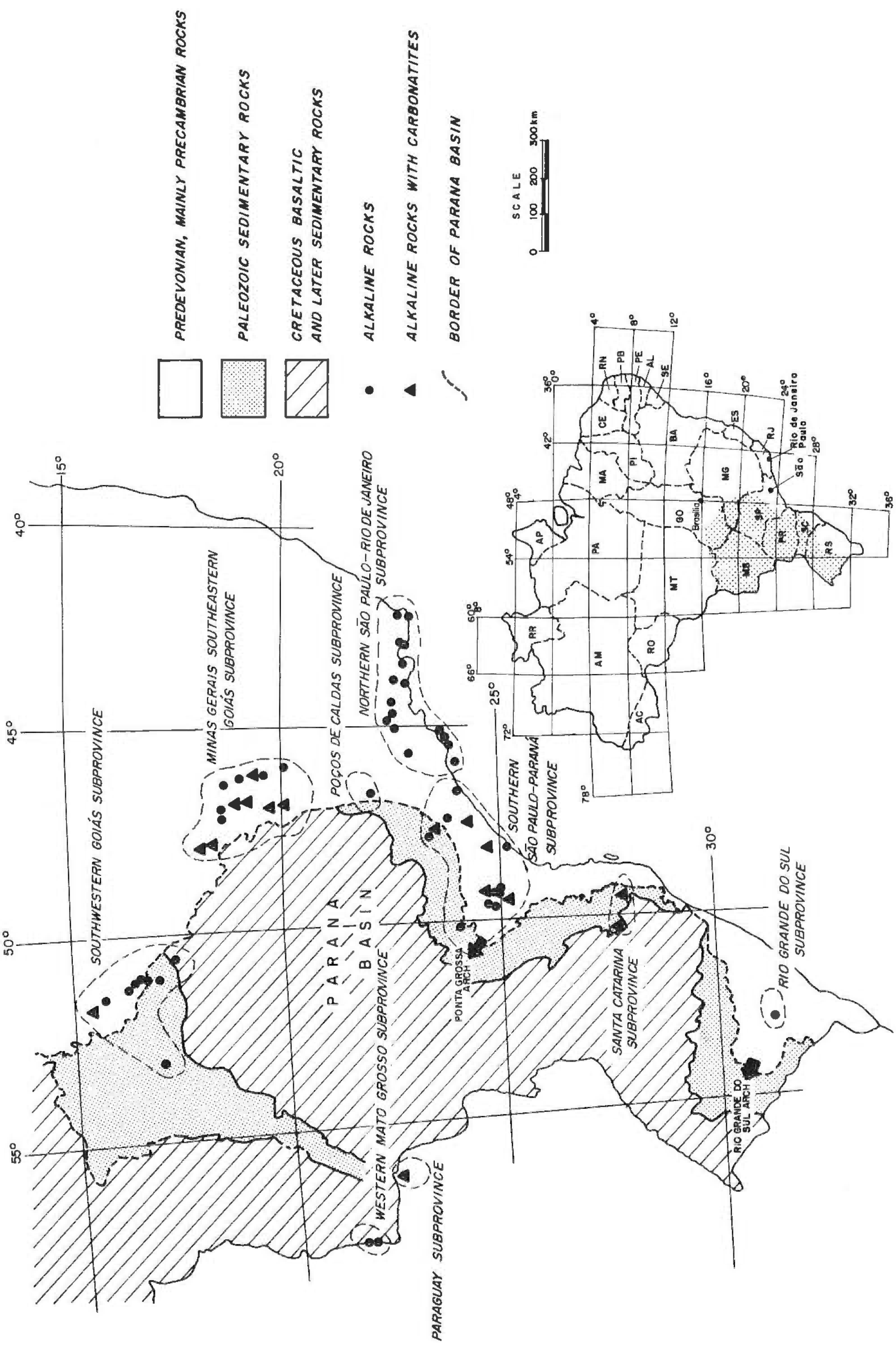


Fig. 3. Mesozoic alkaline complexes in southern Brazil.

an initial $^{87}Sr/^{86}Sr$ ratio of 0.7032 ± 0.0002.

The alkalic volcanic episodes in Fernando de Noronha and Ceará can be correlated, according to the many authors who studied the areas.

No economic deposits have been detected in these regions up to now.

THE MESOZOIC ALKALINE COMPLEXES OF SOUTHERN BRAZIL

More than 50 alkaline complexes are known in the southern portion of Brazil and Paraguay, directly or indirectly related to the extensive basaltic volcanism of Paraná Basin (Fig. 3). This basaltic volcanism first appeared as dykes and sheets followed by outpourings of lavas about 147 Ma, and this phenomenon continued till 119 Ma, reaching maximum between 120 and 130 Ma (CORDANI and VANDOROS, 1967; ULBRICH and GOMES, 1981).

The alkaline complexes of this portion of the country crop out around the Paraná Basin, and are generally located along NE-SW fractures (mainly those in the coast) or NW-SE archs (such as the so-called Paranaíba Structural High in Goiás and Minas Gerais States and possibly the Ponta Grossa and Rio Grande do Sul Archs).

More or less arbitrarily, the distributional areas of these complexes can be grouped into the following subprovinces.

1) *The Rio Grande do Sul Subprovince*, where more than 30 circular chimneys, with diamaters seldom greater than 500 m and ages around 79 Ma (in ULBRICH and GOMES, 1981), were studied by RIBEIRO (1970), in the region of Piratini, Bagé, Pinheiro Machado, Caçapava do Sul, Santana da Boa Vista and Canguçu. Trachyte, tinguaite and phonolite are their main rocks as well as dykes of olivine basalt.

2) *The Santa Catarina Subprovince*, where two major intrusions are recognized: Lages and Anitápolis. The first one is 65 Ma (AMARAL *et al.*, 1967) and forms a more than 25 km diamater domical structure, with radial and concentrical faultings with displacements up to 350 m (SCHEIBE, 1978). The alkalic rocks are more or less equidimensional in plan, some kilometers in diameter, or crop out as dykes. Sills were detected in subsurface. They are intruded into Gondwanic formations and their main rock types are nepheline syenites (phonolite, nepheline microsyenite, foyaite, tinguaite and others, according to SCHEIE, 1978). At the begginning of the 1970's. SCHEIBE discovered carbonatites related to the complex, which will be described in the following chapter.

The Anitápolis alkalic intrusion, known since the begginning of the century, has been studied since 1927 and in 1977 a private company started a program of evaluation of the phophate deposits (fluorapatite) of the intrusion. The complex is 129 Ma, with a possible intrusive span of more than 20 m.y. (in ULBRICH and GOMES, 1981), and is intruded into Precambrian granite terrain. The stock, about 6 km^2 in area has a fenitized halo and is composed of nepheline syenite, pulaskite, biotite pyroxenite, ijolite, melteigeits with the more mafic rocks localized mainly in the central portion. A small carbonatite (sövite) plug, a few square meters in area, is also situated in the central portions, but numerous lenses and veins of this rock cut the mafic and ultramafic rocks.

3) *The Southern São Paulo-Paraná Subprovince*, which comprises the following complexes: Mato Preto (67 Ma; three stocks less than 1.5 km diameter, comprising phonolite and carbonatite), Barra do Teixeira (73 Ma; a small circular phonolitic neck); Tunas (110 Ma; elongated intrusion of 22 km^2, containing alkali syenite, pulaskite, nepheline syenite, alkali gabbro, monzonite, diorite) in Paraná State; Cananéia (82 Ma; pulaskitic stock with 1 km^2 area); Itapirapuã (103 Ma 4,5 km^2 elongated intrusion, with nepheline-syenite, pulaskite, malignite, melteigeite and a carbonatitic core); Piedade (122 Ma; shonkinitic dyke cutting Precambrian rocks); Ipanema (123 Ma; intrusion with 13 km^2 area, containning pulaskite, lusitanite, aegirinite, and a glimmeritic core cut by carbonatitic veins); Morro do Serrote (127 Ma; 14 km^2 stock, with peridotite, pyroxenite, ijolite, nepheline syenite, pulaskite, alkali gabbro and the first described carbonatite

body in Brazil); Itanhaem (110 Ma; dykes cutting basement rocks possibly related to olivine sövite dykes found in the same area), and Jacupiranga (130 Ma; the biggest of the intrusions of this subprovince, with a 65 km^2 wide oval shape, comprising a northern core of peridotite and a southern core of ijolite and carbonatite, both surrounded successively by pyroxenite, nepheline syenite and fenite towards the contact with the Precambrian rocks of basement) in São Paulot State (ULBRICH and GOMES, 1981).

4) *The Northern São Paulo-Rid de Janeiro Subprovince*, with the following complexes: Ilha de São Sebastião (81 Ma; three stocks with pulaskite, nepheline syenite, theralite, essexite, tinguaite, nordmarkite and late trachytic dykes); Ilha do Monte de Trigo (80 Ma; two stocks containing nepheline syenite and theralite); Ilha dos Búzios (stock with alkali syenite flanked by nordmarkite); Ilha da Vitória (nepheline syenitic small stock); Campos do Jordão (80 Ma., cluster of tinguaite, shonkinite and monchiquite, cutting basement rocks) in São Paulo State; Cabo Frio (a 6 km^2 intrusion with pulaskite, nordmarkite, nepheline syenite and dykes of trachyte and lamprophyre); Morro de São João (73 Ma.; circular stock, 17 km^2, containning hornblende syenite, nepheline syenite, pseudoleucitite, syenite, malignite and tinguaite and a central corundum-bearing plug of trachytic breccia); Itaúna (a pulaskitic-phonolitic elongated stock, 6 km^2); Itatiaia (66 Ma.; 220 km^2 zoned body with nepheline syenite, pulaskite, quartz-alkali syenite and alkali granite); Tinguá (66 Ma.; subcircular intrusion with nepheline syenite, tinguaite and phonolite); Tanguá (67 Ma.; 50 km^2 stock, with pulaskite, nepheline syenite, nordmarkite and fluorite veins); Rio Bonito (69 Ma.; 28.5 km^2 zoned stock, similar to Tanguá); Soarinho (30 km^2 irregular stock; alkali syenite, nordmarkite, monzonite and mangerite); Canaã (20 km^2 intrusion with a core of alkali syenite surrounded by litchefieldite) and Mendanha (72 Ma.; small intrusions of nepheline syenite, pulaskite, alkali syenite and phonolite) in Rio de Janeiro State (ULBRICH and GOMES, 1981).

5) *The Poços de Caldas Subprovince*, represented by the complex of the same name. Besides its great dimension (800 km^2), it has the following characteristic aspects: ages varying from 87 Ma to 53 Ma, showing different stages of intrusion, and the uranium deposit now being exploited by Brazilian Government; zircon, thorium-rare earths and bauxite also economically important. The main rocks are ankaratrite and pyroclasts in the first stage of intrusion followed by marginal nepheline syenite and ring-dyke tinguaite, and then by phonolitic dykes as the last stage.

6) *The Minas Gerais-Southeastern Goiás Subprovince*. This is the most important subprovince in terms of economic mineral deposits in alkalic complexes among which more expressive are: Tapira (70 Ma.; a 35 km^2 stock with jacupiranguite, biotite pyroxenite, alkali syenite, phonolite and carbonatite enriched in apatite, perowskite, pyrochlore, anatase, rare earths and vermiculite); Serra Negra (82 Ma.; a 85 km^2 oval intrusion with a core of dunite and peridotite surrounded by jacupiranguite and shonkinite, and also containing carbonatite enriched in pyrochlore and Th-U minerals; Salitre (81 Ma.; two stocks about 40 km^2, with alkali syenite, biotite pyroxenite, trachyte and carbonatite, with apatite, perowskite, niobium, uranium-thorium and rare-earths mineralizations); Araxã (91 Ma; a 20 km^2 stock with pyroxenite, malignite and carbonatite with pyrochlore, apatite, titanium barite, rare earths and uranium-thorium mineralizations) in Minas Gerais State; Catalão (83 Ma.; two circular intrusions, named Catalão I and II, around 27 km^2 each, consisting of glimmerite, pyroxenite, peridotite, carbonatite and economic deposits of pyrochlore, anatase, magnetite, apatite, rare-earths, titanium and vermiculite) in Goiás State (ULBRICH and GOMES, 1981).

7) *The Southwestern Goiás Subprovince* is represented by more than 20 bodies. The main bodies in this subprovince are Morro do Engenho, Serra da Água Branca, Santa Fé, Morro dos Macacos, Salobinha, Diorama and Rio dos Bois (BERBERT, 1977). Their main rocks are: dunite; peridotite; serpentinite (which generally forms the core of the intrusions, but also occurs as external rings to syenite and gabbro); pyroxenite; gabbro (which is the predominant rocks type in some bodies); various types of fenites and, more rarely, alaskyte, nordmarkite

and missourite. In some bodies, serpentinite and peridotite constitute more than 95% of the whole complexes. Dykes of lamprophyre, basanite, diabase, trachyandesie and tinguaite are common, but extrusive rocks are rare except for two complexes. Carbonatite dykes were detected in only one complex (Morro do Engenho).

Some of these bodies are circular in shape but the majority of them are small oval stocks, reaching up to 10 km in diameter. Lateritic nickel deposits are present in some of the complexes.

8) *The Western Mato Grosso Subprovince* contains at least one major intrusion (Pão de Açúcar), 207–238 Ma, with nepheline syenite and no economic deposits (PUTZER and VAN DEN BOOM, 1962; COMTE and HASUI, 1971).

9) *The paraguay Subprovince* contains a group of intrusions close to the Brazilian border. The Pedro Juan Caballero is a circular structure 7.5 km in diameter surrounded by a ring of sandstones. Its main rocks are syenite and diabase, but its most important aspect is the presence of a carbonatitic mass in the central-northwestern portion of the intrusion (BERBERT and TRIGUIS, 1973). No economic mineralization has been discovered so far, although copper geochemical anomalies were detected.

ALKALINE COMPLEXES WITH CARBONATITE-GEOLOGY AND ECONOMIC ASPECTS

As it has been mentioned in the previous chapters, at least 15 alkaline complexes with carbonatite are recorded in Brazil up to now. Fourteen of them are in the southern portion of the country, belonging to the following subprovinces: Santa Catarina, Southern São Paulo-Paraná, Minas Gerais-Southeastern Goiás and Southwestern Goiás. Another body, the Seis Lagos Complex in Amazonas State, was already described briefly. In Paraguay, near the border of Brazil, there are references on two carbonatite bodies, one of which (the Pedro Juan Caballero Complex) was already cited (Fig. 4).

More Detailed descriptions will be made about the southern Brazil carbonatite bodies especially about those of the Minas Gerais-Southeastern Subprovince, where the main niobium, rare-earths and other mineral deposits are found.

The Santa Catarina State Subprovince

The Anitápolis Complex

This intrusion is a pear-shaped zoned stock of 6 km^2, and is intruded into Precambrian granitic terrain.

Biotite pyroxenite forms the complex core, which is partly surrounded successively by ijolite, melteigeits, nepheline syenite and fenite. Pulaskite is also present and in the central portion of the intrusive there is a small sövite plug (ULBRICH and GOMES, 1981). Carbonatitic veins, lenses and veinlets also cut the ultramafic rocks.

The complex has phosphate deposits which are related to the weathering of the rocks. Fluorapatite is the main ore mineral. It occurs as disseminations, veins, veinlets and masses. Pyroxene, micas, feldspar, amphibole, nepheline and calcite are other minerals present in the ore.

The ore is of two types: residual (60 million tons, 8.5% P_2O_5) and "rock-ore" (260 million tons, 6.0% P_2O_5 (INDÚSTRIA-LUCHSINGER MADORIN S/A, 1981).

In 1983, it will be in operation by a local industry, producing 600,000 tpy of phosphate concentrates from the complex, with a grade of 36% P_2O_5.

The Lages Complex

The Lages Complex is related to a domical structure of more than 25 km in diameter, where it is possible to observe the whole sedimentary sequence of the Paraná Basin. This dome resulted from the intrusive activities of alkaline magmas in many phases, probably around 65 Ma (AMARAL *et al*, 1967).

The alkalic rocks are more or less equidimensional in plan with some kilometers in diameter,

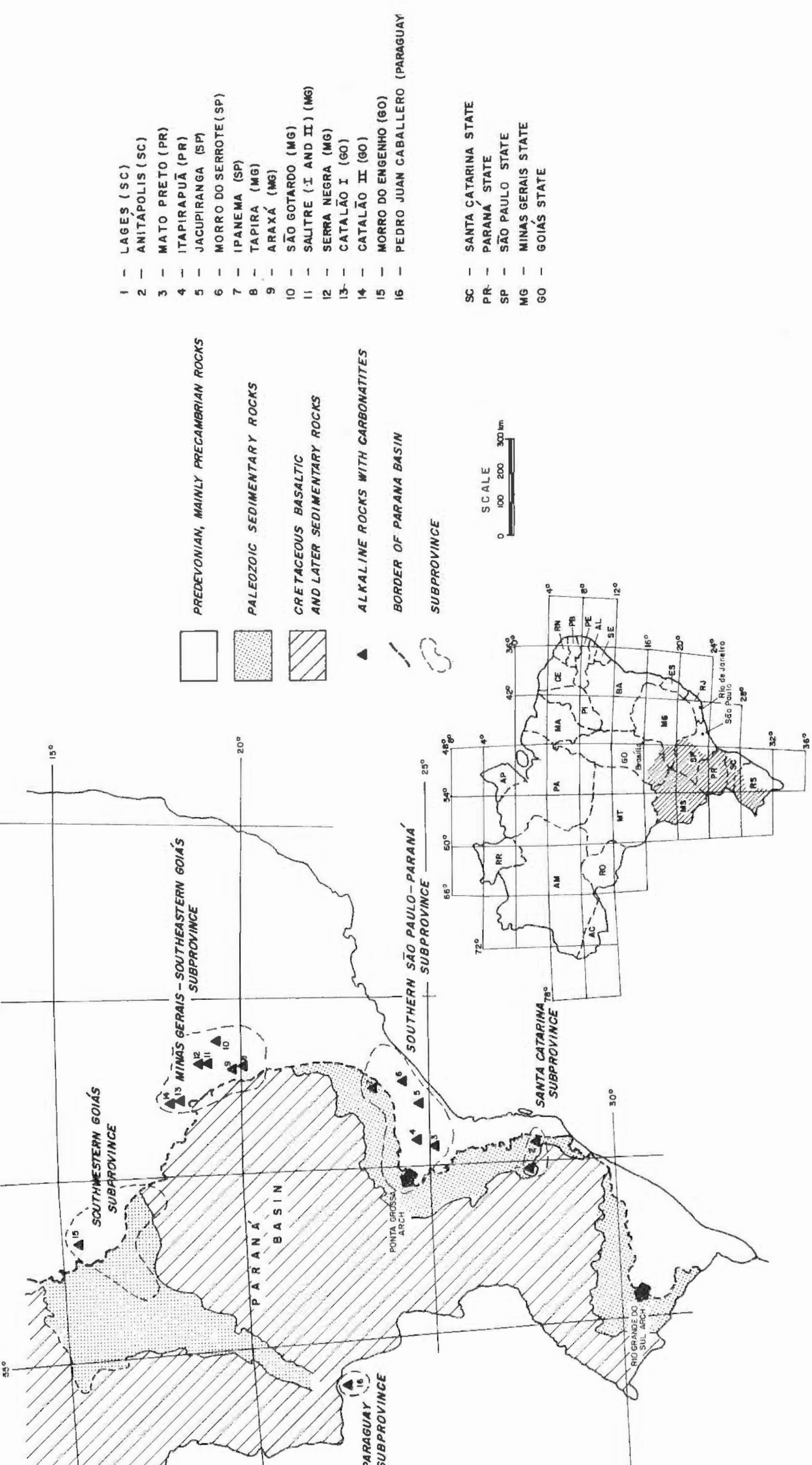


Fig. 4. Alkaline complexes with carbonatites in southern Brazil.

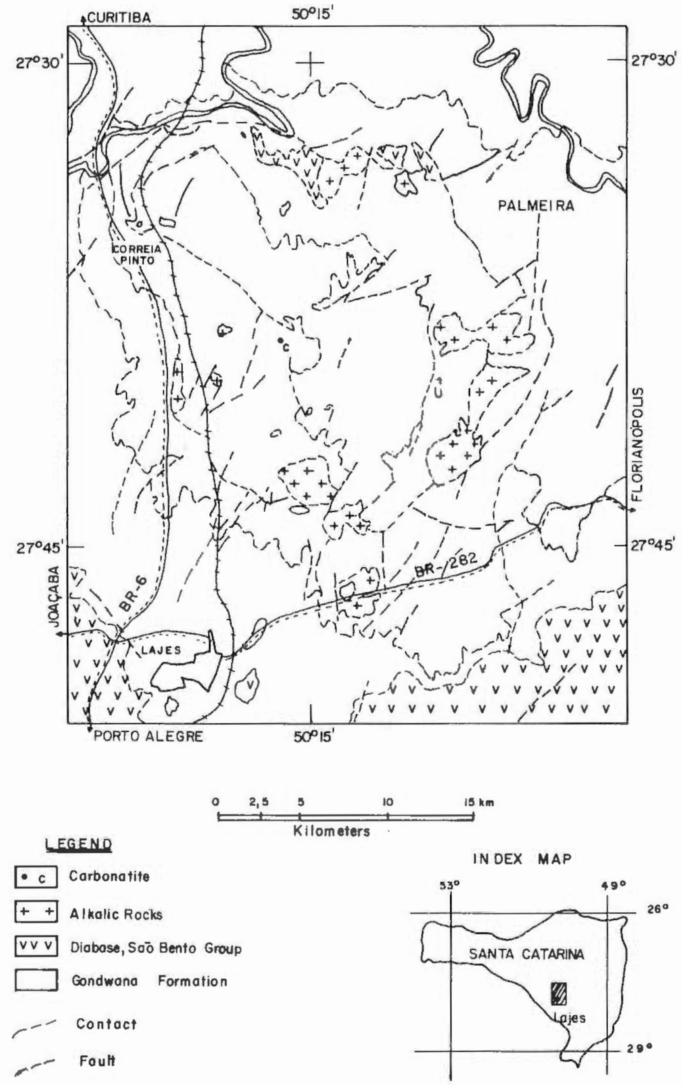


Fig. 5. Geology of the Lajes dome, SC, with location of the carbonatite occurrence (Base map: Guazelli and Feijo, PETROBRAS, 1970).

and also crop out as dykes (Fig. 5). Sills were detected in subsurface.

The alkalic rocks are in contact mainly with Permian sandstone, which is cut by veins of carbonates and enriched in potash. The fenitized halo is usually quite narrow.

According to SCHEIBE, (1978), the main rock types are nepheline syenites with textural and mineralogical variations (phonolite, nepheline microsyenite, foyaite and tinguaite), and olivine mellilite occurring as narrow dykes. The carbonatite bodies appear approximately at the central portion of the complex, at two hills in the Fazenda Varela area. One of the hills, 4,000 m in diameter, is made of carbonatized pipe breccia of basic and sedimentary rocks cemented by greenish aphanitic matrix, both cut by carbonate veinlets. The other hill, named Morro do Carbonatito, is circular in shape, about 600 m in diameter, and is made up of "feldspathic breccia". This breccia is interpreted as the product of the final stage of fenitization, and

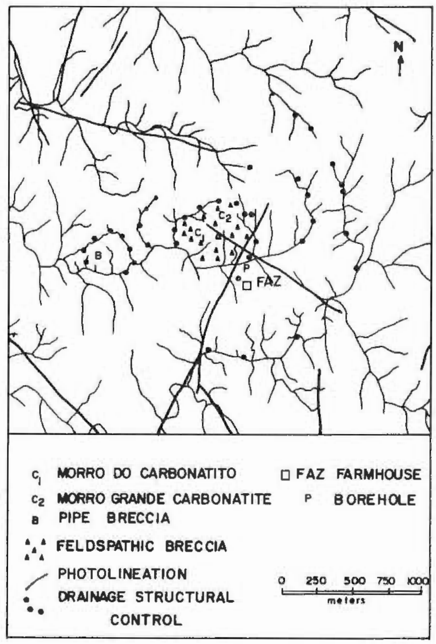


Fig. 6. Drainage and photointerpretation of Fazenda Varela region, Lajes, SC, Brazil (Reproduced from SCHEIBE, 1978).

is cut by carbonatitic dykes and veins (Fig. 6).

SCHEIBE (1978) distinguishes two main types of carbonatites in the area. One is light and beforsitic, occurring as a dyke about 15 m wide and the other is an ankeritic beforsite cropping out as thin stockwork veins and filling fractures in the feldspathic breccia.

Although no economic concentration of rare-earths elements has been discovered at the complex yet, petrographic and petrochemical studies and the high rare-earths anomalies led to the conclusion that the carbonatites of Lages belong to the RE type, similar to those in the Lake Chilwa Alkalic Province, Malawi, Africa, described by GARSON (1966).

The Southern São Paulo-Paraná Subprovince

Although carbonatite appear at the Mato Preto Complex in Paraná State (associated with phonolite) and at the Itapirapuã Complex in São Paulo State (associated with nepheline syenite, pulaskite, malignite and melteigeite), the main occurrences are at the Ipanema, Morro do Serrote and Jacupiranga bodies, all in São Paulo State.

The Ipanema Complex

This complex is 13 km^2 in area and is intruded into Precambrian schists and Permian sandstones, which were fenitized (ULBRICH and GOMES, 1981).

Its main rocks are glimmerite, pulaskite, lusitanite and aegirinite. The inner portion of the fenitic halo contains numerous veins of apatite and glimmerite. The core of the body is made up of glimmerite cut by aegirinite and carbonatite (sövite) veins and dykes. Shonkinite dykes also cut alkaline and shield rocks.

The complex is deeply weathered and on surface magnetite and silexite blocks are found in lateritic soil.

The Morro de Serrote Complex

This is the first carbonatite complex identified in Brazil and was studied mainly by FELICÍSSIMO JR. (1978a, b), who compares it to the Bukusu Complex of Eastern Uganda, described by DAVIES (1947).

The Morro do Serrote Complex is a zoned stock, 14 km^2 in area, roughly circular at the surface, and intruded into gneisses and quartzites of Precambrian age (Fig. 7).

Mafic (alkaline gabbro) and ultramafic (pyroxenite and peridotite) are its main rocks, occurring mainly at the eastern, southern and northern portions of the complex. At the central-southern portion occurs an oval shaped nepheline syenite body, and this rock also appears in a separate intrusion at the northeast of the main complex (Morro da Casa da Pedra). Ijolite and melteigeite are of restricted occurrence.

The carbonatite appears at the western portion of the complex, ocupying an area of about 2 km^2. BORN (1971) recognized two carbonatitic bodies: one (external and older) is less magnesian and is coarse-grained, with magnetite, apatite, barite, pyrochlore and mica as accessory minerals; the other one (internal) is made up of many phases of carbonates and has bedding suggesting fluidal texture; its main accessory minerals are dolomite, ankerite, magnetite, ilmenite, barite, rabdofanite, pyrochlore, ancyllite, atrontianite, pyrite and galena.

The fenitized halo is poorly developed and is expressed by the formation of K-feldspars and augite in the enclosing rocks.

Phosphate is the main economic deposit of the complex and is restricted to the south of the Serrote hill. The ore has P_2O_5 contents between 5% and 30% and the reserves are around 3,000,000 tons (FELICÍSSIMO JR., 1978b).

The Jacupiranga Complex

This is one of the best studied carbonatitic complexes in Brazil. Among the studies there are those made by MELCHER (1954, 1965, 1966) and AMARAL (1976).

It is oval shaped, 65 km^2, and intruded into Precambrian mica schists and granodiorite. To the north, there is a mass of periodotite partly serpentinized, surrounded by pyroxenite

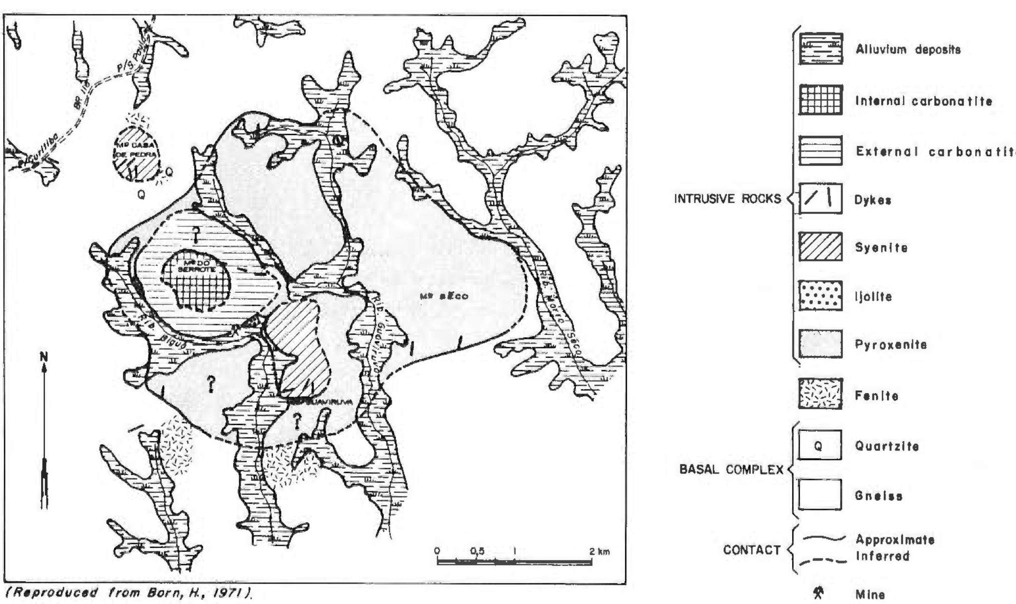
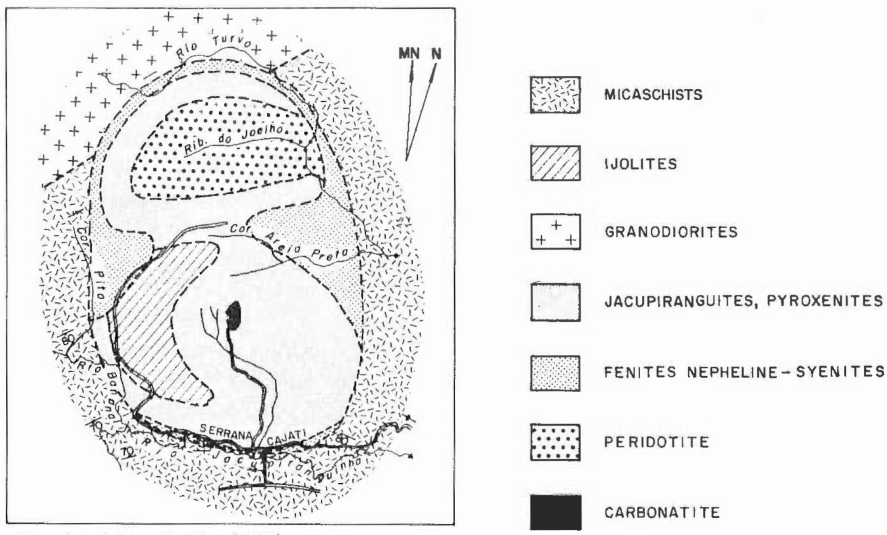


Fig. 7. Geological map from Morro do Serrote complex.



Reproduced from Melcher (1954).

Fig. 8. Geological map of the Jacupiranga alkaline comples.

(jacupiranguite), which are surrounded by a complex zone composed of nepheline syenite. Fenite, containing alkalic feldspars, plagioclase, augite, hornblende and biotite forms a halo around the complex (Fig. 8).

Carbonatite appears as an intrusive body in the jacupiranguite, more or less at the center of the complex. It is composed of dolomite, apatite, magnetite, phlogopite, pyrrohtite, forsterite, serpentine, pyrite, perowskite and other minerals.

A crescent-shaped intrusion of ijolite-melteigeite appears to the west of the carbonatite body.

Lateritic nickel deposits are related to the ultramafic rocks, mainly to the peridotite. Apatite ore is mined from residual deposits originated from carbonatites. Total reserves are around 97 million tons of phosphatic ore averaging 5.59% P_2O_5.

The Minas Gerais-Southeastern Goiás Subprovince

This subprovince includes many economically important carbonatitic occurrences such as Tapira, Serra Negra, Salitre, Araxá (Barreiro) and Catalão.

The Tapira Complex

This complex is an oval shaped zoned stock, 35 km^2 in area, located in the southwestern portion of Minas Gerais State (Fig. 9). Its intrusion caused the formation of a domic structure with 10 km in diameter involving quartzite and low grade metamorphic schists of Precambrian age.

The carbonatite-peridotite-pyroxenite association is dominant in the complex (GROSSI-SAD, 1972). Pyroxenite is mainly jacupiranguite and a biotite-rich type. Nepheline syenite and phonolite are other rocks present in the complex. There are two phases of carbonatite generation. The earlier dark-colored fragmented variety contains 40% phlogopite, 20% calcite, 10% diopside, 10% magnetite and 5% apatite, besides fayalite and perowskite. The later light-colored carbonatite consists of 60–90% calcite, 5–15% apatite, 5–20% magnetite, 15% phlogopite, and fayalite, biotite, pyrite and epidote (BARBOSA *et al.*, 1970). Titanium, phosphate, niobium, rare-earths and vermiculite are the main economic deposits of the complex.

Titanium occurs as ilmenite, perowskite, anates, titanite, leucoxene and rutile, associated with magnetite, barite, pyrochlore and other minerals. The main ore mineral is anatase, the

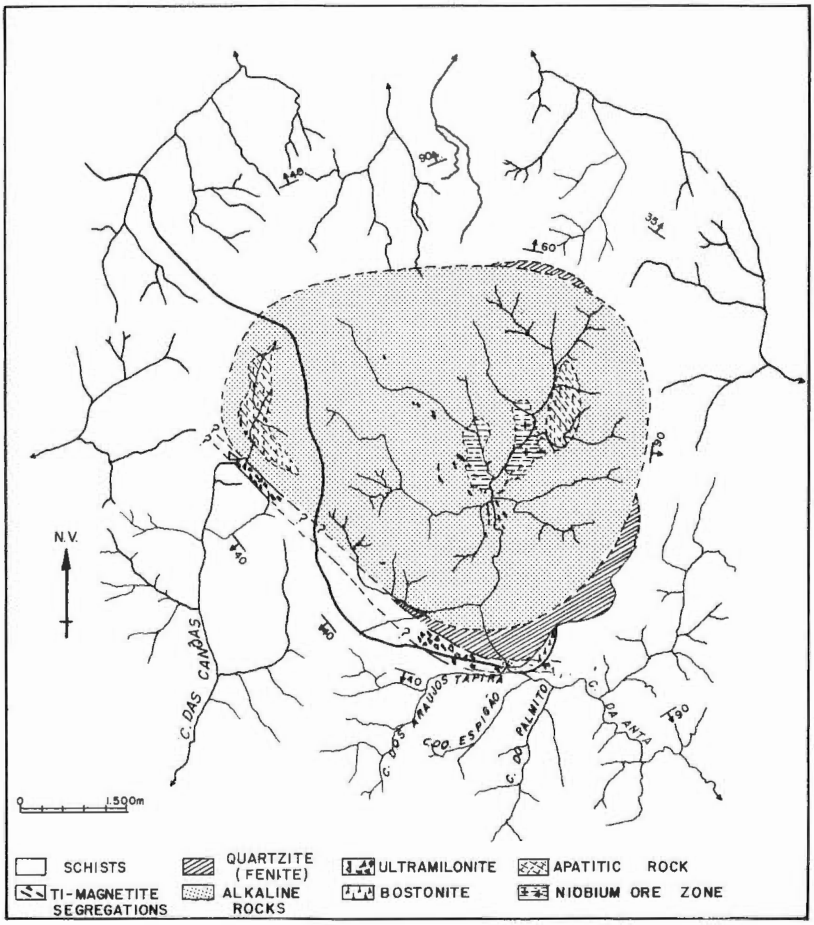


Fig. 9. Geological map of the Tapira alkaline complex (reproduced from ALVES, B.P., 1960).

reserves of which are about 325.5 million tons. The mineralized zone has a grade of 16.31% TiO_2.

Reserves of apatite deposits are around 991 million tons of ore averaging 9.04% P_2O_5. Reserves of pyrochlore reach more than 165.9 million tons containing 11.76% Nb_2O_5 (DNPM/DEM, 1980).

The Serra Negra Complex

This complex is situated to the north of Tapira Complex, forming a spectacular domical structure 20 km in diameter, inside which is the ultramafic-alkaline body with surface about 65.5 km^2. The complex is intruded into Precambrian metasediments and presents the following association: carbonatite-dunite-peridotite, with jacupiranguite and shonkinite, the latter apparently forming a thin outer envelope to olivine rocks.

Dunites, partially serpentinized, form a huge mass in the complex, with 70% of olivine in volume, serpentine, magnetite, carbonates, perowskite and ilmenite. The carbonatite doesn't crop out. A drilling program in the area detected small carbonatitic masses enriched in pyrochlore.

Anatase, perowskite and ilmenite form considerable concentration and Th-U mineralization is also recorded.

The Salitre Complex

This complex contains two stocks, about 40 km^2 in area, interconnected by trachytic dykes. They are situated southeast of Serra Negra Complex, which may be genetically related.

The smaller stock to the NW is made up of biotite pyroxenites. The other stock to the SE contains alkali and nepheline syenites, biotite pyroxenite and a small elliptical plug of apatite-rich carbonatite no bigger than 500 m^2 in area. A quartzitic ring, 600–700 m wide, surrounds the complex. Although titanium minerals are present in the rocks of the complex as anatase, ilmenite, perowskite, titanite, leucoxenite and rutile, the only economic one is anatase, which is the altered product of perowskite and concentrated as residual deposit. There is a gradual enrichment in perowskite towards the deep portions of the weathered rock.

The reserves of the district are estimated about 389 million tons of ore grading 27.5% TiO_2 (DNPM/DEM, 1980).

The Araxá (Barreiro) Complex

This is one of Brazil's most important carbonatitic complexes. It is located about 6 km south of Araxá town and is emplaced into Precambrian quartzites which form a complete ring around the complex.

It is approximately circular in plan, about 4.5 km in diameter, but the domical structural caused by its intrusion is more than 15 km diameter (Fig. 10). The outer rocks of the dome are muscovite and chlorite schists with some interbedded quartzites, followed inwards by the ring quartzites (with some interbedded schists), and weathered carbonatite cut by thin veinlets of jacupiranguite and malignite. The rocks are deeply weathered and outcrops are extremely rare. Their surfaces are covered by lateritic deposits with high P_2O_5 and Nb_2O_5 grades.

The first detailled studies of the complex were taken by Departmento Nacional da Produção Mineral (DNPM) which encharged a private Brazilian Company (GEOSOL) for a mapping and drilling program in 1965.

The main mineral deposits of the area are those of niobium, phosphate and rare-earths. Niobium is concentrated in the central portion of the complex, forming a circular zone, 1,800 m in diameter. The high concenration of niobium is the result of deep weathering and enrichment of niobium minerals in the carbonatite. The weathering reaches depths of about 200 m (PARAISO and FUCCIO JR., 1982) and in this zone the average content of niobium is higher than 2.5% Nb_2O_5, with some zones containning up to 5.0% Nb_2O_5. The ore is capped by a layer of red overburden (0.5 to 40 m thick) in which the Nb_2O_5 grades are less than 0.4%. The main minerals in the ore are limonite, goethite, barite, magnetite, pandaite (bariopyrochlore), gorceixite, monazite, ilmenite and quartz (CBMM, 1982). Niobium occurs mainly in the mineral

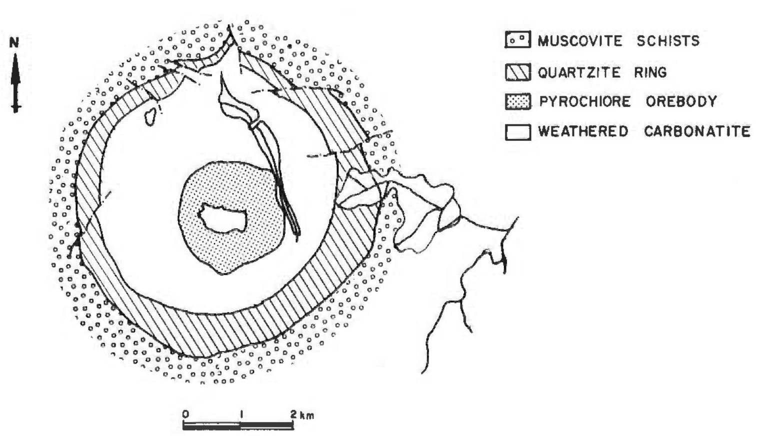


Fig. 10. Geological map of the Araxa carbonatite (after CBMM, 1981).

pandaite (63.4% Nb_2O_5). The total ore reserves in the complex are about 461.7 million tons, grading 2.50% Nb_2O_5, from which more than 173 million tons are measured reserves. This represents more than 70% of the world's economically extractable reserves.

The Companhia Brasileira de Metalurgia e Mineração (CBMM) is mine-metallurgical industrial complex which exploits the niobium. The major part of the niobium produced in Araxá is exported mainly as ferroniobium to Europe, U.S.A., Japan, URSS, Canada and other countries, but metallic niobium (99.9% Nb) has also been produced. The company produces 42,000 tpy of concentrate and 22,800 tpy of ferroniobium (CBMM, 1981).

Phosphate deposits appear in north-northeastern portion of the complex and is also derived from residual concentration. According to GROSSI-SAD and TORRES (1976), this concentration occurs in two main ways: dispersed apatite grains in the cover, associated with collophanic phosphate, giving rise to a soft lateritic material rich in iron; and concentrations of collophanic phosphate of secondary origin, giving rise to brecciated zones a few meters thick. The first kind provides apatitic ore over 39% P_2O_5 and $BaO + Fe_2O_3$ 4%. The second kind, although sometimes very rich in P_2O_5, presents problems for concentration processes, due to the close association of iron oxides and collophanic phosphate.

The lesser the barite content the better is the phosphate ore. The main minerals in the ore are goethite (30–45% in volume), apatite (20–50%), monazite (4–8%), magnetite (5–10%), quartz (2–6%), pandaite, ilmenite and goyazite. Phosphate reserves are about 161.3 million tons, 15–20% P_2O_5, or 37.5 million tons, 20–25% P_2O_5 (GROSSI-SAD and TORRES, 1976) or 560.4 million tons, 14.4% P_2O_5 (DNPM/DEM, 1980).

Rare-earths mineralization, usually associated with phosphate and uranium, occurs mainly to the north of the central area, but also at the central part of the complex and at southeast of the niobium deposit. The main ore minerals are monazite and goyazite, but quartz, goethite, rutile-leucoxene, pandaite, magnetite-ilmenite, zircon and barite are also present. CeO_2, La_2O_3 and Nd_2O_3 are the main rare-earths oxides, reaching grades about 6.28%, 3.80% and 1.58%, respectively, in the principal mineralized zone (the Mata Stream zone), but Sm_2O_3 and Pr_2O_3 are also present. The mineralized material is earthy phosphatic and has a whitish to yellowish colour. Estimated reserves are about 546,000 tons of mineralized rock with 10–11% RE.

Uranium is also present in association with pyrochlore, monazite and phosphatic rocks. In the first case, the grades are low (0.005% U_3O_8). In the second case, goyazite and monazite concentrations reach 0.09% U_3O_8 and 0.32 U_3O_8 respectively, but no commercial recovery is possible. In the phosphatic rock, autunite and uranocircite are very locally present and the ore may contain 0.11% U_3O_8.

The Catalão Complexes

In the southeastern portion of Goiás State there are two alkaline complexes named Catalão I and Catalão II. The first one is better studied. Its area is around 21 km^2 but the total dome, involving the enclosing rocks, reaches 8 km in diameter (Fig. 11). Both complexes are intrusive in mica schists and quartzites of Precambrian age.

Glimmerite is the main rock type in Catalão I, as well as pyroxenite and serpentinized peridotite, cut by carbonatite veins (sövite). Silicification processes acted intensively over those rocks, originating silexitic zones which occur in almost whole part of the complex at depths more than 100 m from the surface. It is supposed that a carbonatitic plug exists under this silexite in the central portion of the intrusion (CARVALHO, 1974). The carbonatitic veins can vary in width from few millimeters to more than 10 m, and formed in more than two stages. Calcite is the main constituent mineral, but apatite (60–95% in volume), phlogopite, serpentine, magnetite, pyrite, barite and others are usually present in the veins.

The complex has been prospected since the 1960's by two mining companies: Metais de Goiás S/A and Mineração Catalão de Goiás. The economic deposits of the area are phosphate, niobium, titanium, rare-earths and vermiculite.

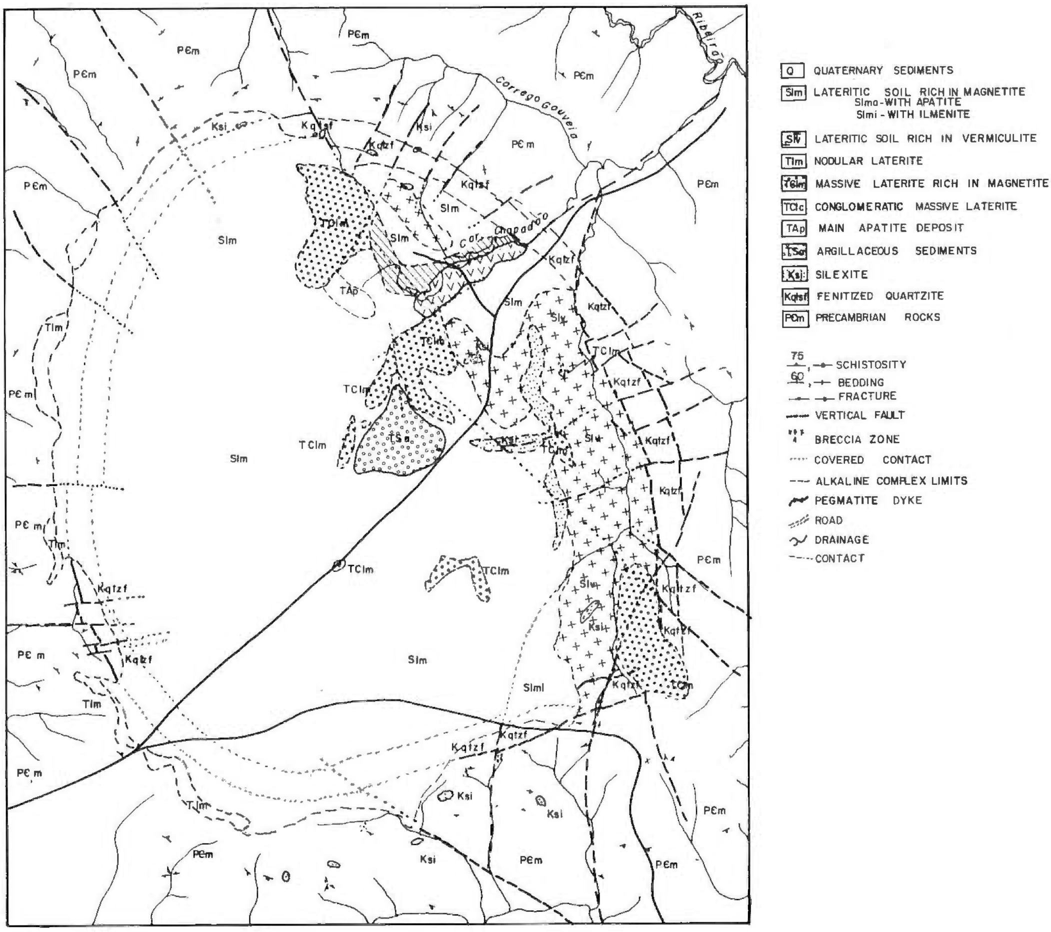


Fig. 11. Geological map of Catalão I alkaline complex (geology by Metais de Goias-METAGO).

Table 1 Mineral reserves of

Complexes	Pyrochlore		Rare-earths	
	1,000 t	Grade (% Nb_2O_5)	1,000 t	Grade (% RE)
1. Anitápolis (SC)	–	–	–	–
2. M. do Serrote (SP)	–	–	–	–
3. Jacupiranga (SP)	–	–	–	–
4. Tapira (MG)	165,940	11.76	–	–
5. Salitre (MG)	–	–	–	–
6. Araxá (MG)	461,700	2.50	546	10–11
7. Catalão (GO)	21,096	2.64	22,500	2
Total reserves	648,746	–	23,046	–

References cited in text.

Fluorapatite and dalhite are the main phosphate ore minerals but other secondary and non-economic phosphatic minerals are present. Magnetite, ilmenite, hematite, anatase, pyrochlore and barite are also usually present in the ore. As a consequence of the irregular distribution of the apatite-rich carbonatitic veins, the phosphate ore has variable grades. Total reserves are estimated about 130 million tons of ore containing over 10% P_2O_5.

Main mineralized zones of titanium occur at the eastern portion of the complex and appear as concentrations of TiO_2, concentrations of TiO_2 plus P_2O_5 and TiO_2 plus vermiculite (CARVALHO, 1972). Anatase, titanite and perowskite are the principal Ti minerals in the ore, anatase being the most important. Reserves are about 63.9 million tons of mineralized rock with 19.92% TiO_2 (DNPM/DEM, 1980).

The niobium mineralization appears mainly at the western portion of the complex, extending towards north, where it is overlapped by the phosphate zone (CARVALHO, 1972). The main ore mineral is pyrochlore, but niobium is also present in the structure of other minerals (apatite, perowskite and anatase). These minerals are also present in association with the magnetite-rich crusts of the carbonatites and in the soilds originated from it. Pyrochlore reserves are about 21 million tons in the area grading 2.6% Nb_2O_5 (DNPM/DEM, 1980).

The rare-earths mineralized zone occurs associated with the silicified carbonatite (silexites) and its grade increases with depth. The main RE elements are cerium and lanthanum. Yttrium is rare. The $CeO_2+La_2O_3$ content is 10%, but can reach up to 29%. The mineralization is similar to the one in Araxá and Mrima Hill (Kenia), but in Catalão the grades are lower and uranium was not detected. The measured reserves reach 22.5 million tons with grades more than 2% $CeO_2+La_2O_3$ (CARVALHO, 1972).

The vermiculite zone is situated at the southern, eastern and northern portions of complex. It is charcterized by low radioactivity and is related to the weathering of the glimmeritic rock of the area. Vermiculite has different granulometries and is associated with argillaceous material containing magnetite, ilmenite, anatase and apatite. Measured reserves are about 2.3 million tons of ore (around 20% vermiculite over 325 mesh).

The Southwestern Goiás State Subprovince

Among more than 15 alkaline bodies of the region, in which serpentinite, dunite, peridotite, gabbro and/or syenite are the main rock types, only one complex has carbonatite, the Morro do Engenho Complex.

This intrusion has a serpentinized dunitic-peridotitic core surrounded successively by pyroxenite, gabbro and nepheline syenite. It is roughly circular (30 km^2) in plan and its main

Brazilian carbonatite complexes.

Phosphate		Anatase		Vermiculite	
1,000 t	Grade (% P_2O_5)	1,000 t	Grade (% TiO_2)	1,000 t	Grade (%)
320,000	6.41	–	–	–	–
3,000	5–30	–	–	–	–
97,000	5.59	–	–	–	–
991,127	9.04	325,500	16.31	–	–
–	–	389,664	27.5	–	–
560,435	14.4	–	–	–	–
130,000	10	63,914	19.92	2,300	20
2,101,562	–	779,078	–	2,300	–

mineralization is lateritic nickel (over 18 million tons, 1.3% Ni). Carbonatite appears as small veins cutting the dunitic core.

CONCLUSIONS

The present review on alkaline rocks and carbonatites in Brazil is not definite of course. The classification proposed for the alkaline subprovinces is tentative and it is based more on geographic parameters visualized by the author than properly on chemical and petrological studies, which lack in most of the complexes.

Still, some words must be said about kimberlites. Although diamonds have been mined in Brazil since the first quarter of the eighteenth century, only in the last 15 years have kimberlite pipes been detected mainly through studies of heavy minerals in alluvium deposits and geophysical data. Today, inumerous occurrences of kimberlites are recorded in western Minas Gerais State, eastern and northern portions of Mato Grosso State, and eastern Rondônia in Piauí State (BERBERT, SVISERO, SIAL and MEYER, 1981; SCHOBBENHAUS FILHO, 1981). They generally vary from 50 to 500 m in diameter, but can reach 1 km, and are intrusive in Precambrian and Paleozoic rocks. Their ages seem to be Mesozoic and their intrusions keep directly or indirectly relation with the alkaline magmatism which also occurred during Mesozoic times. Intensive studies of these rocks and their xenoliths have been made by SVISERO (1977, 1981) and kimberlite prospections have been taken by a French group named SOPEMI as well as by other private companies. Perhaps because of the secret character of these prospections there are no news about diamond mineralizations in the pipes up to now, but it is interesting to note that the richest diamond alluvium deposits in Brazil are close to recently discovered kimberlitic rocks, although most of these deposits come from weathered Cretaceons Formations.

Acknowlegments

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V. Geologic Hazards

Chairman Y. KINUGASA

1. Man-Induced Land Subsidence, Sea-Level Rise and Coastal Protection.
2. The Significance of Explosive Volcanism in the Prehistory of Japan.
3. Volcanoes and Volcanic Hazards in Papua New Guinea.
4. The Importance of an International Earthquake Data Bank.
5. Excavation Survey of Active Faults for Earthquake Prediction in Japan with Special Reference to the Ukihashi Central Fault and the Atera Fault.

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Man-induced Land Subsidence, Sea-level Rise and Coastal Protection

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ABSTRACT

The subsoil of The Netherlands consists of deposits supplied mainly by the rivers Rhine and Meuse which are filling the subsiding North Sea Basin. An equilibrium exists more or less between the tectonic subsidence and the in-filling of the basin. However, interglacial sea-level rises as well as the Holocene sea-level rise has led to incursions by the sea followed by marine erosion and deposition. After man occupied and exploited the area, the natural process of tectonic subsidence was augmented by his activities. Empoldering, groundwater withdrawal and hydrocarbon exploitation form further causes of lowering the land surface, increasing the vulnerability for flooding.

Measures for the coastal protection are determined also by the course of the sea-level rise and man's interference with coastal dynamics. Recent sea-level studies confirm the view that fluctuations in intensity occur. The studies have also shown, that higher water-levels have occurred in the coastal area due to a high frequency of storm surges, high rates of discharge by the rivers and by other factors. These high water-levels could exist for periods lasting over several centuries.

Man's activities in the delta and along the coast-line requires measures, that in the short term will give sufficient protection. The present tendency in shoreline regradation together with the afore-mentioned intensities in sea-level rise or events of higher water-levels may pose more serious problems in the future.

INTRODUCTION

The Netherlands are situated on the delta of the rivers Rhine and Meuse. This delta was partially invaded by the sea during Pleistocene interglacials as well as in the Holocene. Man occupied the coastal area some 6000 years ago, living on the beach barriers and the natural levees along the rivers and tidal gullies. During later transgressive phases the settled areas were temporarily abandoned, but some 1000 years ago, at the time of the youngest transgressive phase, man's attempts to protect himself led him to start building dikes. The first dikes were only meant to prevent flooding, but later the system was extended to the reclamation of new land for the growing population. However, the empoldering of land, peat digging and increasing groundwater withdrawal as well as exploitation of hydrocarbons have contributed to a relative land subsidence with respect to the sea-level. Such movements occur at more rapid rates than those of natural processes such as tectonic subsidence and eustatic sea-level rise. As a matter of fact, the acceleration of this ongoing process must find its expression in measures for coastal protection.

A second factor, which plays a role in establishing such measures is the rise in the level of the sea. Recent studies confirm the view that this process has fluctuated in intensity. These studies have also shown, that at several periods, in the past, higher water-levels have occurred in the coastal areas than the sea-level trend curve seems to indicate.

Thirdly, man's interference with the shoreline has had a serious effect on the natural processes as well.

We may discuss the three above-mentioned aspects separately.

LAND SUBSIDENCE CAUSED BY MAN

The Construction of Polders

During an international congress on "Polders of the World" it was stated that only one-third of the total reclaimable land area had been empoldered. This implies that the construction of polders is still possible for many low-lying areas of the world. This makes it all the more important, to obtain a full understanding of the effects that empoldering may have on natural processes.

Compaction of the Upper Layers

After dike construction the first step in preparing new areas for cultivation is to make a drainage system. The subsequent aerification and influence of vegetation cause further desiccation of the upper layers leading to compaction of the land. According to DE GLOPPER (1973) 4 factors determine the amount of compaction i.e. the percentage of particles smaller than 2 μm, the organic contents, the clay-mineralogy and the climate. In The Netherlands the two latter factors are not so important, as they are in certain other parts of the world. In The Netherlands by far the dominant clay mineral is illite, whereas the climate never gave rise to tropical weathering processes. In The Netherlands a sediment layer, composed of 50 percent clay-particles may shrink as much as 50 percent in the first 100 years. This means a reduction of 0.75 m of a clay layer with a thickness of 1.5 m.

Oxidation of Peat

Peat also is undergoing compaction. However, much more important here is its oxidation. Vast areas of The Netherlands were originally covered by a layer of peat. After draining the land dry, peat becomes susceptible to a biochemical process induced by the growth of bacteria, which results in its oxidation. The peat disintegrates and decomposes with the result that the level of the land falls. When the water table is one metre below the surface, the subsidence resulting from oxidation can be as much as 0.6 cm a year. Due to this subsidence, the new land surface becomes wet again, and man reacts by, further lowering the groundwater table. This of course leads to a repetition of the above sequence of events. It is estimated that in some of the Dutch polders a peat layer with a thickness of 2.5 meters has disappeared in the course of several centuries (BORGER, 1973).

In this context it should be noted that in earlier times peat was dug for fuel. After the forests had all been cleared, peat cutting was done on a large scale due to the lack of other forms of fuel. This led to accelerated lowering of the land surface. Such activity was the cause of extensive flooding of coastal areas in medieval times.

Since plans are being considered to create new land in Indonesia by digging peat in low-lying near-shore areas, the case history of this European country should be taken into account before a decision is made to proceed.

The Polder and its Surroundings

Lowering of the water level in a new and usually deeper polder will cause inflow of water from surrounding areas. As a result the artesian pressure exerted by the feeding aquifer upon the upper layers in the surroundings will be reduced. Reduction of the water pressure leads in turn to a decrease of the pore water pressure and an increase in the grain pressure. The result of these changes is a further compaction of the sediments lying above the aquifer, the degree of compaction being determined by the nature of the sedimentary sequence.

An example of recent studies may be mentioned. After its closure in 1932, part of the former Zuiderzee (Fig. 1) was subdivided into a number of new polders. Only one of the planned polders-the Markerwaard still remains unconstructed. Since there are a number of

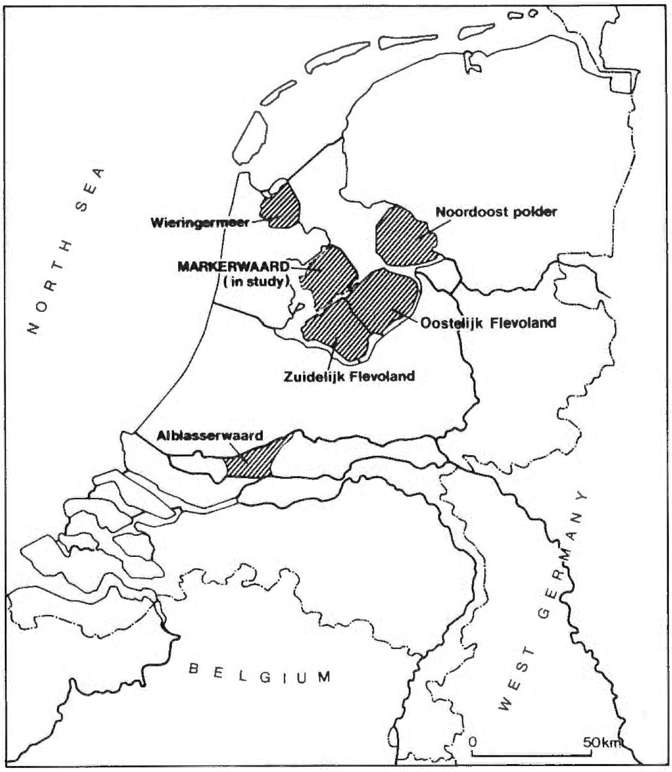

Fig. 1. Geographical position of the Markerwaard in the central parts of The Netherlands.

small towns to the west of the Markerwaard one of the studies required in connection with the effect of empoldering was the effect subsidence would have on these towns. It was decided to establish a mathemetical model and calculate the compaction in the area under consideration. Besides hydrological data, information on the sequence of sediments to be subjected to the reduction in pore-water pressure had to be taken into consideration especially the Holocene deposits for which a schematic sequence was constructed. The Holocene strata comprise mainly clayey, but also some sandy tidal flat deposits. These sediments alternate with layers of peat which were formed during regional and local regressions. Several times during the Holocene, gully-systems developed which became infilled with sediments. The result is that the Holocene succession is very variable throughout the area. A subdivision, however, of twenty units each representing a local sequence of clay-, sand- and peat layers at various levels, was introduced to the calculations. It is stressed, that such detailed information could be provided, because the Quaternary geology of the area had been thoroughly mapped.

Another approach was also used. Some four centuries ago, part of the area involved was empoldered. Later this area became compacted due to the creation of a deeper, neighbouring polder. The effect of the latter could be estimated and compared with the results of the mathematical model.

Although in the new polder, the Markerwaard, subsidence of the order of 1.5 m can be expected, subsidence in the surrounding areas is more likely to be limited to several tens of centimetres. Since this figure corresponds to the subsidence due to oxidation and compaction of peat at the surface over a period of 30 years it could be concluded that the creation of the Markerwaard would only accelerate the ongoing processes.

We may summarize the foregoing by stating, that in The Netherlands empoldering and peat digging have given rise to severe subsidence. Over the past 300 years the rate of subsidence has amounted to several metres and this exceeds by far tectonic subsidence, which is of the order of 0.3 m per 1000 years (CASTON, 1979).

Ground-water Withdrawal

Land subsidence resulting from ground-water withdrawal has been recognized in many places in the world. Reports have come for instance, from Japan, where more than 40 areas are said to be subsiding after ground-water withdrawal. Large cities like Jakarta, Bangkok and Shanghai also suffer seriously from this problem.

Subsidence due to water withdrawal is based on the reduction of pore water pressure already mentioned. Not only the layers above the aquifer but also the aquifer itself can be involved in the process of compaction. The amount of subsidence varies widely, the effect depending on the amount of water extracted, the lithology and thickness of the overlying layers and other factors. An extreme case is Mexico City, where 9 m of subsidence have been measured. For Bangkok, a subsidence of 2 to 6 cm per year has been mentioned. Although the latter case also includes tectonic subsidence, the main cause is water withdrawal, which has lowered the piezometric ground-water level from close to the surface to a depth of 47 m (NUTALAYA and RAU, 1982).

In The Netherlands ground-water withdrawal has caused land subsidence on a more limited scale. The effect has been established in certain places, but the rate of subsidence is very low indeed. In the western part of the country, water withdrawal from a depth of 10–30 m has caused subsidence of 0.25 m, due mainly to the presence of a compacted peat layer about 10 m below the surface. The peat is no longer water-saturated. However, it is only very recently that attention has been paid to the phenomenon. Most of the ground-water in the western regions is captured from the rivers or from the coastal dune area. Not far below the soil surface the water is already brackish to saline.

In some countries, for instance Japan, water withdrawal has been regulated and restricted, because of the damage suffered or the vulnerability of low-lying areas to marine or fluvial flooding. It appears that some recovery takes place, and that some restoration of the land surface can occur. However, there can be no doubt that in some compacted sediments the process is irreversible.

Gas Extraction

World's largest gas fields under exploitation occur in The Netherlands. Here, gas extraction has been taking place since the early sixties. The gas field covers an area of some 900 square kilometres, the thickness of the reservoir ranging from 70 to 240 m at a depth of about 3000 m.

Compaction of the reservoir and overlying layers would of course be expected due to the appreciable reduction in pressure. Analyses of core material provided the data for developing a mathematical model designed to calculate the subsidence. As a result it is predicted that a subsidence of 1.00 m will occur in the central area by the year 2050. Since exploitation started, measurements have however been made regularly, and the findings though confirming the expected pattern have proved that the rate of subsidence has been less than anticipated. The revised prediction for 2050 is only 0.30 m (SCHOONEBEEK, 1976).

For other deltaic areas of the world much higher figures have been reported. For instance, in Venezuela (Lake Maracaibo) subsidence due to oil extraction has surpassed 4.00 m. Consequently an area of more than 400 square kilometres has had to be protected against flooding by constructing dikes, and these required repeated heightening (NUÑEZ and ESCOJIDO, 1976).

SEA-LEVEL CHANGES

As already mentioned, rise of the sea-level intensify the effects of subsidence. Attempts have been made in various ways to establish a curve depicting the changes in sea-level during the Holocene. JELGERSMA (1961), who is responsible for the best-known Dutch curve, based her work entirely on data obtained from peat samples at the base of the Holocene succession. Other authors like Louwe KOOYMANS (1976) used other information such as archaeologic data.

Recently, consideration was given to whether these curves could be refined and a more detailed approach to sea-level changes was possible. A new study was undertaken by VAN DE PLASSCHE (1982), who carefully reviewed all previous data and their interpretation, and who also carried out supplementary investigations. With new data from the beach plain in the former Rhine estuary, conclusions could be reached on changes in Mean High Waterlevel (MHW).

Moreover, he sampled organic layers, deposited on the flanks of buried late-Pleistocene river dunes situated further inland. The data from the peat layers around the river dunes are supposed to correspond with changes in Mean Sea Level (MSL). Combining his own data with those of previous authors, he made an interpretation, which led to a new trend curve for the Holocene MSL rise especially for the period 5000 BP to 2500 BP. The second curve drawn is one reflecting the MHW changes in the coastal zone. The newly derived curves (Fig. 2) show some remarkable refinements, which deserve discussion.

Attention is drawn to the fact that both curves demonstrate fluctuations. The first fluctuation, expressed in both curves, occurs around 4500 BP and is explained by a rise of the mean sea-level (MSL) which later slowed down. The next peak, between 4200 and 3700 BP, is more pronounced in the curve for the beach plain than in that for the river dunes and the subsequent decrease also is even more pronounced in the beach area. After combining his own data and observations with those of other investigations, VAN DE PLASSCHE (1982) concluded that the ascending part of the curve represents only a relatively small sea-level rise, whereas a high discharge of the rivers and storm surges had been responsible for the higher values shown by the fluctuations in the curve for the beach plain. In the period around 3450 BP, the beach-plain curve shows a fluctuation that is not reflected by the MSL curve. Here, too, it could be established that at that time there had been a high fluvial discharge which raised the water level in the estuaries. The last fluctuation, around 2950 BP, can be attributed solely

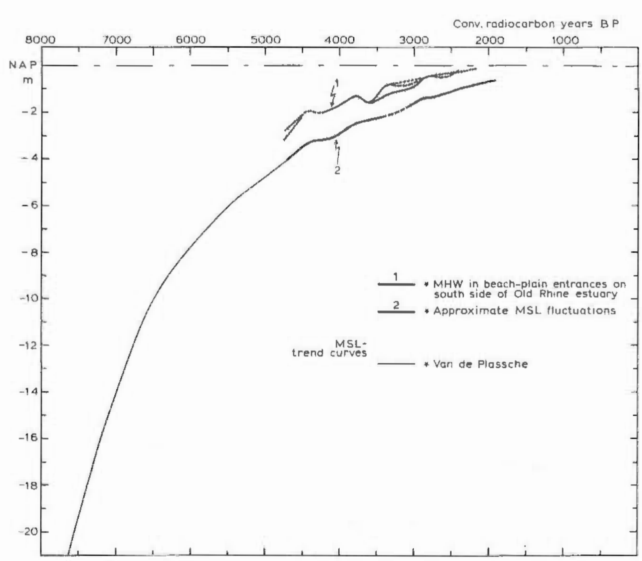

Fig. 2. Trends of relative Mean Sea Level rise for the Netherlands after and Mean High Water Level for the coastal zone after VAN DE PLASSCHE (1982).

to a rise of the sea-level, since it is recorded in both curves. The refinement of the sea-level curves constructed by other authors (e.g., JELGERSMA, 1961; Louwe KOOYMANS, 1976) has clearly demonstrated that besides transgressive phases, i.e., periods with a more rapid rising sea-level, strong river discharges and storm surges periodically caused higher water levels.

These results mean that meterological changes also play a contributary role and temporarily reinforce the general trend of the sea-level rise. From historical records it is deduced, that indeed during late Medieval times the frequency of storm surges was definitely higher along the NE coast of the North Sea. LAMB (1961) already pointed out, that during the last millenium, changes in the North European meteorologic system have taken place. They not only affected the average yearly temperature, but also may have been accompanied by a periodic increase in number of storm surges, attacking the coast line.

COASTAL PROTECTION OF THE SUBSIDING DELTA

As already mentioned, about a thousand years ago in The Netherlands, man began to construct a coastal defence system to protect the area he had inhabited. These efforts were made in response to the changing natural conditions accompanying the most recent transgressive phase in this region in which the beach-barrier system was severely attacked and eroded in the southern part of the country. Sand which was so freed was transported northwards by long-shore currents and later accumulated through wind action on top of the existing older dunes to form the younger dune deposits. Thus, the process of erosion in the south led to some degree of stabilization further north.

The process of empoldering and dike construction implied also a substantial shortening of the coastline. The overflow capacity available in the extensive areas of salt marshes and flood basins was considerably reduced. Storm surges now forced the water to pile up in areas, still open to the sea, where consequently the peak water level rose gradually. In this situation the chances of breaching of the dikes increased and it is probable that the frequent breaches experienced in late Medieval times were partly caused by the reduction in overflow capacity.

In many other ways man has interfered in the natural balance of deltaic and coastal processes. In the hinterland rivers have been regulated and sand and gravel deposits have been dredged, with the result that the supply of coarser material to their delta has been restricted. Moreover many civil-engineering works, like construction of new harbour entrances have interfered with the natural transport of material by longshore currents.

It is, however, admitted, that man's influence on the coastal processes is not always easy to assess. For instance in the south-western part of The Netherlands the closure of a number of large estuaries is virtually complete. Still, it is not known what impact this situation will have on the adjoining shallow part of the offshore area.

In recent centuries a landward movement of the coastline has been observed. This process is occurring also in areas where the natural processes have not been influenced by man. Such an example can be seen on the northern coast of the island of Ameland.

CONCLUDING REMARKS

In the United States of America, a group of marine geologists have called for revision in the national shoreline protection policy (KERR, 1981). They contend that rising sea-level will make any form of protection ineffective. Although seawalls may halt shoreline erosion, beaches will be eroded by the rising sea. Coastal engineers state on the other hand, that much of the erosion can be related to man-made structures along the beaches.

From sea-level studies in The Netherlands we know that the rise amounts to about 0.1 m every 100 years. Periodically fluctuations in its trend curve occur, which may reflect either a momentary acceleration in sea-level rise or changes in the meteorological cycle. In the long term such processes could present further obstacles to providing adequate strategy for coastal protection. In the short term, man-induced land subsidence and his other activities in the coastal zone could accelerate the ongoing natural erosion process.

From the above it will be clear, that further studies are required, especially those with regard to the sea-level rise during the last 2000 years seem appropriate.

Acknowledgements

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The significance of explosive volcanism in the prehistory of Japan

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ABSTRACT

As studies advanced in the description of specific features of tephra, a number of voluminous tephra layers spread over extensive areas in and around Japan were disclosed. Present paper is largely focused in the two large eruptions in Kyushu, the Aira-Tn eruption (*ca.* 21,000 BP) and the Kikai-Akahoya eruption (*ca.* 6,300 BP), and on their possible impacts on the prehistoric world.

These big eruptions should have been responsible for forming the Aira and Kikai calderas as they are today with a diameter of 20 km. The Aira-Tn and Kikai-Akahoya ashes, which are confirmed to be as airfall part of pyroclastic flows, cover most of the Japanese islands as well as the floor of the northwest Pacific and the Sea of Japan, forming important time-markers in the upper Quaternary sequences.

These violent tephragenic eruptions should have certain features and impacts regardless of the specific environments in which they occur. The Aira-Tn ashfall would have given heavy impacts on the Japanese paleolithic world and the Kikai-Akahoya on the neolithic Jomon culture. Some archelogical evidences suggest that South Kyushu was abandoned temporarily after the Kikai-Akahoya event and was reoccupied several hundred years later by bearers of the different cultural tradition.

INTRODUCTION

In highly volcanic areas like Japan, the impact of explosive volcanism on human life and environment should be great. It fact it was documented that a number of historical eruptions supplied severe damages in this densly inhabited areas. Volcanic hazards in Japan are as great and significant as ones caused by earthquakes, water floods and so on. It seems rather lucky, however, that such historic eruptions were more or less limited in extent because they were less explosive caused by magmas composed of basaltic and andesitic compositions.

It is well known that a more or less continuous mantle of tephra exists over some 40 percent of the four main islands, and the widespread occurrence of patches clearly indicates that large-scale explosive volcanism took place several times in late Quaternary and produced firn-grained ashes mantling most parts of Japan.

In this paper I intend to deal with case studies on the cataclysmic eruptions of the prehistoric age and with the probable ecological significance of such events in Japan. Our studies are in their infancy as yet and field evidences are not so abundant as to reach some conclusions. Discussions on the past volcanic impact on human ecology described here are highly suggestive rather than conclusive.

EXTENSIVE TEPHRA DEPOSITS FROM LATE QUATERNARY ERUPTIONS AROUND JAPAN

Generally speaking, the amount of damage caused by volcanic eruptions depends on the nature and magnitude of eruptions, the distance from the volcanic center to inhabited areas, and the type and density of the settlements within the range of damaging effects. The damage caused by effusive and mixed type eruptions is usually fairly local or of short-range. In contrast, highly explosive activity of plinian and ignimbrite-forming types provides not only local or short-range very severe effects but also long-range and semi-global ones even though it doesn't occur frequently. Such events are exemplified in historic times by Santorini (BC 1500) Vesurius (AD 79), Tambora (AD 1815) and Krakatau (AD 1883) eruptions, which caused severe effects on human beings and their environments resulting in a lack of cultural continuity.

In Japan such highly explosive activity did not take place in historic times. When we turn to have a look at volcanic landforms and products of the prehistoric age, we have abundant records of highly explosive activity. Examples are very large Krakatauan calderas with extensive sheets of tephra deposits. All of them should be the products of plinian and ignimbrite-forming type eruptions.

MACHIDA and ARAI (1976 and 1978) reported two widespread tephras, the Aira-Tn (AT) and Kikai-Akahoya (K-Ah) ashes, which were produced by gigantic eruptions of the Aira and Kikai calderas respectively in southern Kyushu. They are of great significance in volcanology as well as Quaternary research because they occur throughout almost whole Japan.

These discoveries further encouraged identification and correlation of other widespread tephras. Petrographic characters of fine-grained tephras are thoroughly investigated not only on land but also in abyssal sediment cores around Japan (ARAI and MACHIDA, 1980; ARAI *et al.*,

Table 1 Representative late Quaternary

Source and Tephra	Age (10^3 yr. B.P.) Dating Method	Mode of emplacement	
Baegdusan-Tomakomai ash (B-Tm)	0.8–0.9 Archeology	p+c	Fine vitric ash
Kikai-Akahoya ash (K-Ah)	6.3 C-14	c+pp	do
Ulreung-Oki ash (U-Oki)	9.3 C-14	p	Micropumice
Aira-Tn ash (AT)	21–22 C-14	c+pp	Fine vitric ash
Shikotsu pumice fall-I ($Spfa_1$)	32 C-14	p	Pumice
Daisen Kurayoshi pumice (DKP)	45–47 Stratigraphy	p	do
Aso-4 ash (Aso-4)	70 Stratigraphy	c	Fine vitric ash
Kikai-Tozurahara ash (K-Tz)	75 Stratigraphy	c+pp	do
Ontake pumice-I (On. Pm-1)	70–90 Fission track	p	Pumice
Ata ash	85 Stratigraphy	c+pp?	Fine vitri cash
Toya ash	110–130 Fission track & Stratigraphy	pp+c	do

p, plinian eruption; c, coignimbrite ash eruption; pp, phreatoplinian eruption

1981; MACHIDA and ARAI, 1983a). Identification is successful on great numbers of tephras, of which very extensive ones of late Quaternary are shown in Table 1.

In practice we use every technique available for characterization of tephra. Accurate determinations of refractive indices of volcanic glass and phenocrysts are used as the first and most efficient parameter for quick characterization, together with crystal assemblages and micrographic features of constituent materials (ARAI 1972). The chemical composition of glass and crystals is also used for discriminating tephras which are similar in other respects.

Of the eleven late Quaternary widespread tephras listed in Table 1, the B-Tm and U-Oki ashes are distinctive in being alkali-feldspar bearing trachyte-rhyolite. They are confirmed from variations in thickness and grain-size to be of Korean origin. Other tephras are subalkalic rhyodacite in composition and of Japanese origin.

Most of the widespread tephras were supplied from large caldera volcanoes and not from strato-volcanoes. In other words, the eruptions causing the formation of large calderas were characterized by extraordinarily large and intense explosions producing extensive tephra sheets. Such tephras can be classified as follows, according to the difference in their modes of ejection, transportation and deposition: 1) coignimbrite ash-falls, 2) phreatoplinian ash-falls, 3) plinian pumice-falls, and 4) pyroclastic flows.

Coignimbrite ash (SPARKS and WALKER, 1977) is assigned to airfall deposits of fine-grained materials which occupied the upper part of convecting eruption column at the same time

widespread tephras in and around Japan

Characteristics of tephra Volcanic glass	Crystals	Distribution
pm > bw 1.506 – 1.516	af, (ho, cpx) afn$_1$ = 1.522 – 1.524	Northern part of Japan & Japan Sea
bw ⩾ pm 1.508 – 1.514	pl; opx, cpx opx γ = 1.709 – 1.712	Western and central Japan and adjacent seas
pm 1.514 – 1.524	af; bi, ho, cpx [af n$_1$ = 1.521 – 1.524 ho n$_2$ = 1.730 – 1.741	Southern part of Japan Sea and central Honshu
bw > pm 1.498 – 1.501	pl; opx, cpx, (ho, qt) opx γ = 1.728 – 1.734	Almost whole area around Japan
pm ≫ bw 1.499 – 1.502	pl, qt; opx opx γ = 1.731 – 1.734	Central to Eastern Hokkaido
pm ———	pl; ho, opx, bi opx γ = 1.702 – 1.708 ho n$_2$ = 1.673 – 1.680	Coastal areas facing the Japan Sea in Honshu
bw ⩾ pm 1.506 – 1.514	pl; ho, opx, cpx opx γ = 1.699 – 1.701 ho n$_2$ = 1.685 – 1.691	Almost whole area around Japan
bw > pm 1.497 – 1.500	pl, qt; opx, cpx opx γ = 1.705 – 1.709	do
pm 1.500 – 1.502	pl; ho, bi, opx opx γ = 1.706 – 1.711 ho n$_2$ = 1.681 – 1.690	Central Honshu
bw > pm 1.508 – 1.513	pl; opx, cpx opx γ = 1.704 – 1.708	Western Japan
pm > bm 1.494 – 1.497	pl; qt; opx opx γ = 1.756 – 1.761	Northern Japan

pm, pumiceous glass shard; bw, bubble walled glass shards; af, alkali feldspar; pl, plagioclase; qt, quartz; opx, orthopyroxene; cpx, clinopyroxene; ho, hornblende; bi, biotite.

as ejection of a huge pyroclastic flow (MACHIDA and ARAI, 1976). Their specific features are; 1) very abundant fine-grained glass shards generated by delayed vesiculation, 2) quantatively they are often equal to or in excess of the volume of pyroclastic flow deposits ejected during the same cycle of eruption. This type of tephra should be the dominant class of widespread tephra.

The second type is also very fine-grained widespread ashes of silicic composition, formed by the interaction of silicic magma and water. This type of activity was named phreatoplinian eruption by SELF and SPARKS (1978). Common features of such ashes are: 1) poorly sorted compared with plinian deposits, 2) contain accretionary lapilli commonly accompanied with base surges in proximal exposures, 3) composed of highly fractionated pumice clasts and shards and crystals, and 4) show rather irregular thickness distribution reflecting both their mode of emplacement and some contemporaneous erosion due to rains.

The third type of tephra is assigned to medium-to fine-grained pumice-fall deposits and show a gradual decrease in grain size and thickness with increasing distance from the vent. They are commonly distributed in a clear lobate shape on the lee side of the volcanoes. A great number of pumice layers of this type are known in Japan.

The fourth type of tephra is large-scale pyroclastic flow deposits (ignimbrite). They are generated by the collapse of a huge eruption column as thick and highly mobile ash flows, which spread in a concentric pattern around the source. They occur as valley ponds and as a veneer of pyroclastic flow material.

From the view point of volcanic hazards, it seems likely that hot pyroclastic flows might cause the greatest destruction in an area travelled. The ash-falls generated as coignimbrite or phreatolinian type, however, might also cause heavier impact because they occur in greatest area. In fact the AT ash covered almost whole Japan and the ash fall exceeds 10 cm thick over 10^5 km^2. In addition, phreatoplinian ashes should also cause serious damages over a vast area even if they occur in a modest thickness, because they commonly fall in a damp.

Of the extensive ashes shown in Table 1, the AT and K-Ah ashes should be very significant in analyzing volcanic impact on the prehistoric Japan, because they occur in every archeological site in western and central Japan and are used as an excellent time-markers (ODA, 1978; MACHIDA and ARAI, 1983b).

AIRA-TN ASH AND ITS POSSIBLE IMPACT ON PALEOLITHIC JAPAN

Figure 1 shows distribution of the Aira-Tn (AT) ash currently known. AT is probably one of the most extensive tephras in Quaternary. This ash is a distinctive white or light colored rhyolitic ash which is fine-grained even in near-source area, Kyushu, where it totals up to 100 cm thinkness (Plates 1, 2 and 3). At several localities in Kyushu and Shikoku this formation consists of three members. The lower is inversely-graded very fine compact ash, the middle is normally graded small pumice and ash, and the upper is fine-grained compact ash. They conformably occur on the Ito pyroclastic flow deposits and Kamewarizaka breccia near the source, Aira caldera.

More than thirty radiocarbon dates for AT and associated deposits indicate that the cataclysmic eruption of Aira caldera occurred 21,000–22,000 B.P. The Aira eruption started with the ejection of pluinian pumice-fall deposits, the Osumi pumice, followed by the two ignimbrite-forming eruptions. The Ito pyroclastic flows are the final and the biggest, covering whole area of south Kyushu, resulting in a formation of extensive pyroclastic plateau and eventual collapse into large calderas. The AT ash was formed as an airfall part of the Ito flows for most part and partly as a phreatoplinian ashes. A conservative estimate indicates that bulk volume of AT is at least 150 km^3 from its extensive distribution, which seems to be equivalent to that of the Ito pyroclastic flows.

The available paleo-environmental evidence shows that the world on which the AT ash

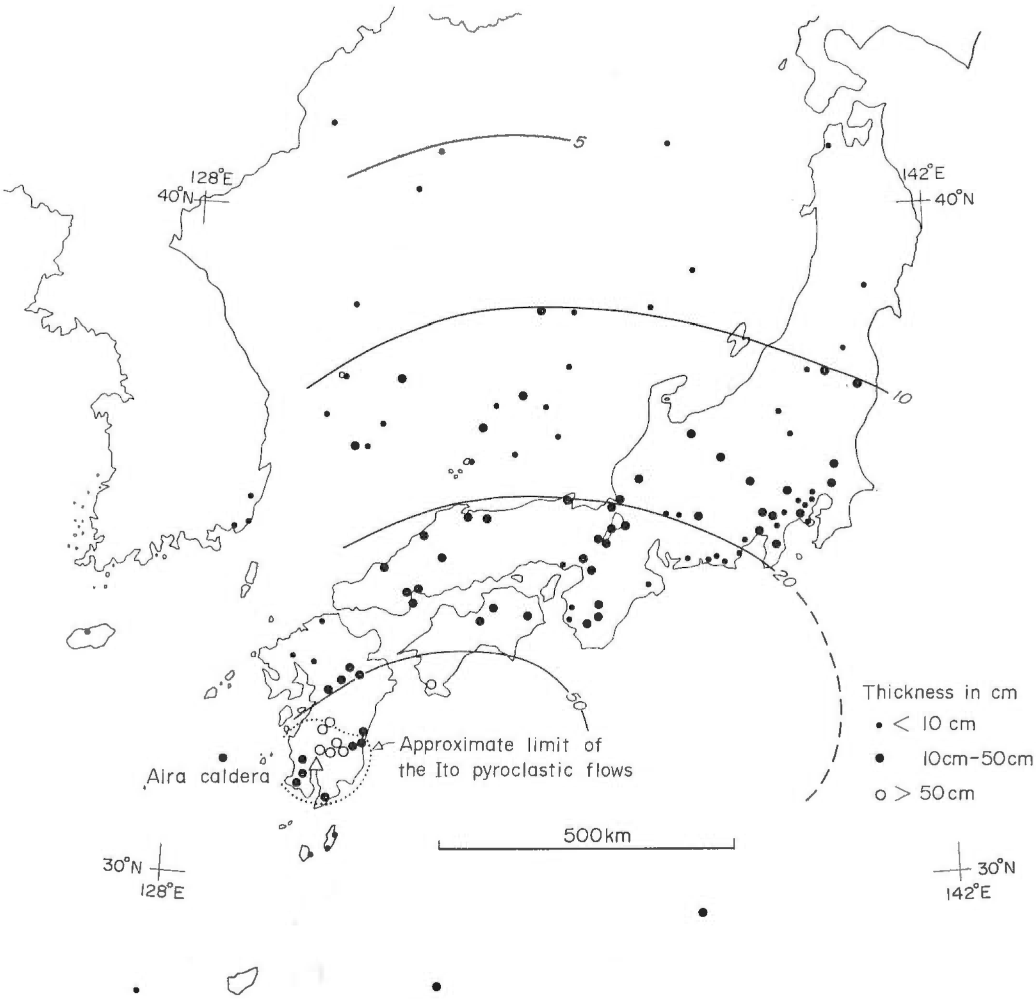

Fig. 1. Isopach map of the Aira-Tn ash with thickness in cm.

fell is asigned to the last glacial culmination (Fig. 2). Recent pollen analysis suggests that the forest assemblage in Kanto plain, central Japan, showed drastic change from temperate deciduous forest to boreal coniferous forest immediately after the eruption. Cooling in climate and lowering of sea-level reached their culminating phase immediately after the AT ash-falls.

Though few detailed studies on the effect of this volcanism on the ecosystem in Paleolithic Japan are available, it seems reasonable to suppose that this effect may have been drastic and extensive not only in proximal area but also distal Honshu and adjacent areas. A pollen analytical study was carried out on peat bogs bearing AT in northernmost part of Honshu, Tsugaru Peninsula, where AT is recognized as a thin layer with thickness of 0.5 cm, showing that a marked decline in vegetation occurred and recovery was delayed probably several hundred years or more (Tsuji, personal communication, 1981).

At the time when the eruption of Aira took place, Japan had already been occupied by the paleolithic people (Fig. 2). It is possible to suppose that paleolithic culture was obliged to change and decline temporarily. Oda and Keally (1975) classified paleolithic culture of the south Kanto district into four major stages from typology and stratigraphic sequence.

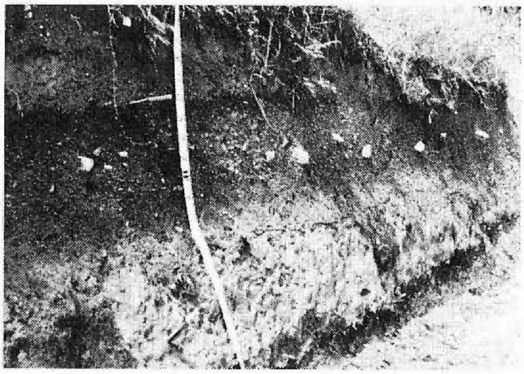

Plate 1 Exposure of K-Ah (top) and AT (bottom) at Sukumo, southwestern part of Shikoku.

Plate 2 Exposure of AT showing three members, sandwiched within fluvial gravels, at Mihama, 650 km to the northeast of the vent.

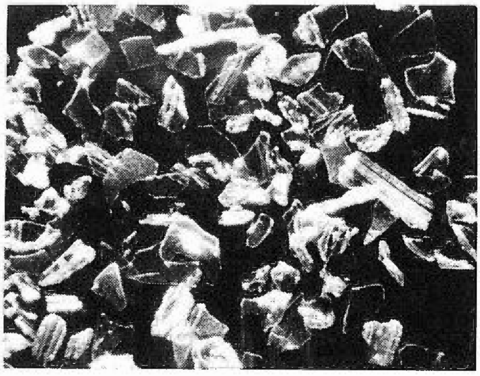

Plate 3 Photomicrograph of glass shards of AT from Daisen, San'in, ca. 500 km to the north-northeast of the vent. Maximum grain-size of bubble-walled glass shards is about 0.5 mm. Photo by F. ARAI.

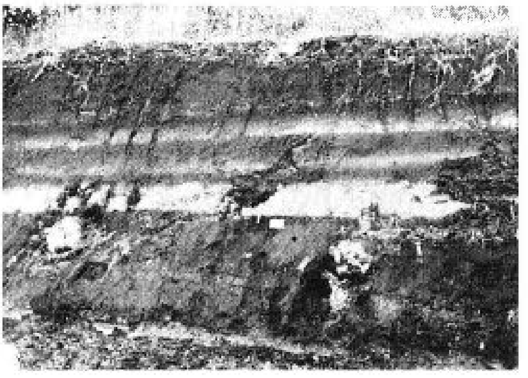

Plate 4 Exposure of K-Ah sandwiched within proximal tephras and soils at Kuju, central Kyushu, ca. 300 km to the north of the vent.

Plate 5 Photomicrograph of glass shards of K-Ah from Kuju. Maximum grain-size is about 0.7 mm. Photo by F. ARAI.

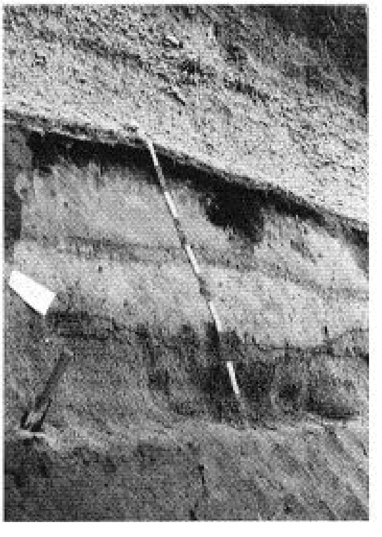

Plate 6 Exposure showing three members associated with K-Ah at Ohnejime, south Kyushu. Bottom is plinian Koya pumice-falls, middle is low-aspect ratio ignimbrite, Koya pyroclastic flows, and top is assigned to the coignimbrite ash-falls, K-Ah. A pumice layer overlying K-Ah is Ikeda pumice-fall deposits.

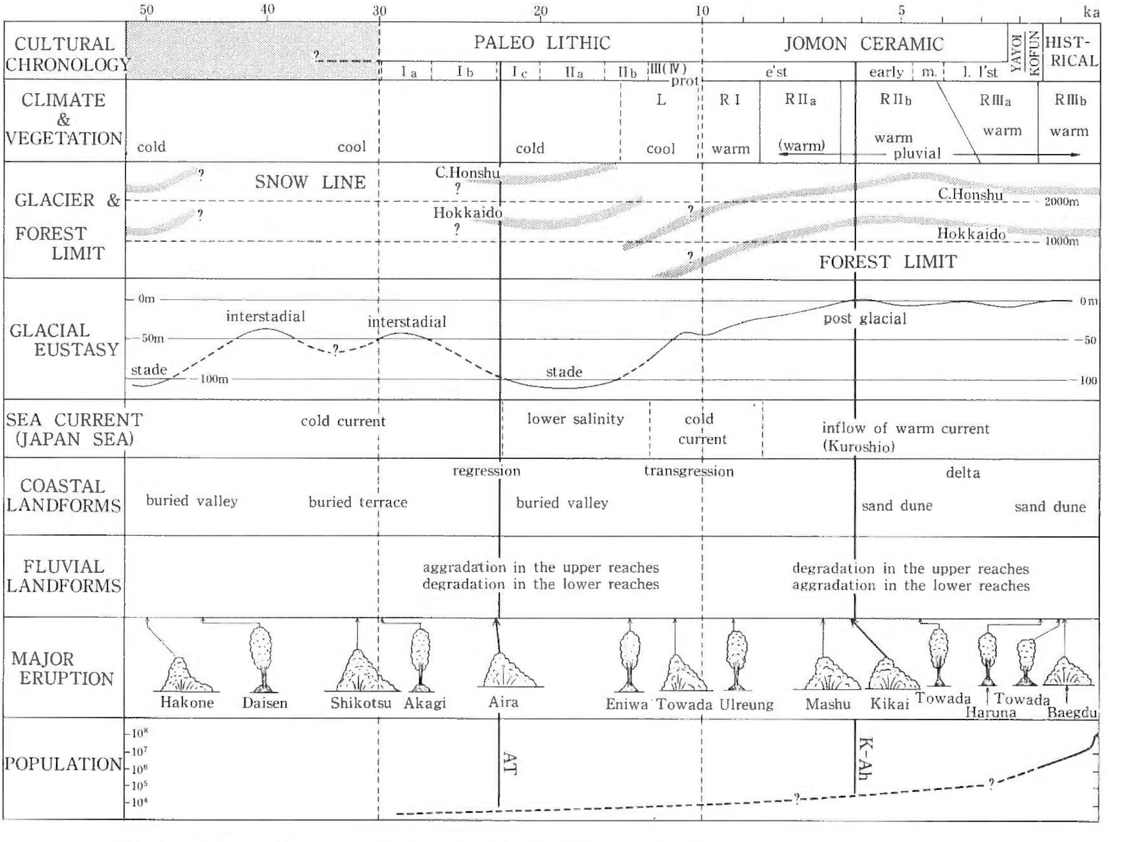

Fig. 2. Paleo-environment during the last 50,000 years in Japan.
prot, proto Jomon; e'st, earliest Jomon; m, middle Jomon; 1, late Jomon; 1'st, latest Jomon.

AT occurs in the cultural layer of the Ic stage and is useful for extensive correlation of artifacts of this stage throughout Japan. Several archeologists are currently discussing whether stone instruments changed their style between the pre-ash and the post-ash phases or not. At the present state it seems difficult to interprete some changes in paleolithic world in terms of identifying the impacts of this volcanic events in great detail.

KIKAI-AKAHOYA ASH AND ITS POSSIBLE IMPACTS ON JOMONIAN WORLD DEDUCED FROM ARCHEOLOGICAL DATA

The Kikai-Akahoya (K-Ah) ash represents the biggest explosive event in the Japanese Holocene. More than fifty radiocarbon dates of this ash have been obtained so far, indicating that the cataclysmic eruption occurred around 6,300 B.P.

'Akahoya' is named after its reddish color and appearance by farmers and pedologists in south Kyushu. It occurs as near-surface, soil-forming parent materials, comprising abundant fine-grained glass shards with maximum thickness up to 70 cm (Plates 4 and 5). Thickness varies from place to place mainly due to cultivation.

Its remarkable characteristics as a parent material of soil stimulated the interest of many pedologists to study its source, pedological features and distribution. However, opinions on its source and proper identification varied considerably from one author to another. Detailed petrographic observation and accurate determinations of refractive indices of the glass and several phenocrystal phases in the ash, together with extensive field work have led to the conclusion that the ash is the product of the Kikai caldera, largely submerged beneath the sea to the south of Kyushu (MACHIDA and ARAI, 1978).

The K-Ah ash is composed of bubble-walled glass shards and small pumice lumps of rhyodacitic composition and small amounts of orthopyroxene, clinopyroxene and opaques as mafic minerals. General feature is similar to that of the AT ash but the former can be distinguished by refractive indices (Table 1) and chemical compositions of the constituent materials.

Fallout area currently known is shown in Figure 3. The K-Ah ash occurs in extensive areas from Kyushu to central Honshu and is also recognized in several piston cores from southern part of the Sea of Japan, the Pacific Ocean and the East China Sea. The bulk volume of the deposits associated with this ash is estimated to be more than 100 km^3 (MACHIDA and ARAI, 1978).

Volcano-stratigraphical studies on the ejecta associated with the K-Ah ash show that parox-

Fig. 3. Isopach map of the Kikai-Akahoya ash with thickness of cm.

ysmal activity of the Kikai caldera *ca* 6,300 B.P. started with plinian-type eruption, producing the Koya pumice-falls, followed by the two ignimbrite-forming eruptions. The most extensive pyroclastic flow is that assigned to the Koya flows, which spread in a concentric pattern as a low-aspect ratio ignimbrite (WALKER *et al.*, 1980) reaching 100 km distant from the source (Fig. 3, Plate 6).

There are some evidences that the cataclysmic eruption of later stage took place in the shallow sea floor. The Koya flow deposits are characterized by highly vesiculted pumice lumps and fine-grained vitric ashes, and have a more varied lithic assemblage including rounded andesite clasts which would have deposited on the sea floor. Also, the K-Ah ash is fine-grained vitric ash with much of accretionary lapilli at its bottom. Generally speaking, the K-Ah ash was formed as a coignimbrite ash of the Koya pyroclastic flows, which were generated by the collapse of large eruption column with high mobility. Considerable part of the ash accumulated as agregates in wet condition.

At the time when the K-Ah ash fell, *ca.* 6,300 B.P., most of the Japanese Islands were occupied by neolithic Jomon people (Fig. 2). It seems reasonable to estimate that the culture in south Kyushu would have been perished in the holocaust by the pyroclastic flows and that almost whole areas of southwestern Japan, the area surrounded by the 20 cm isopach

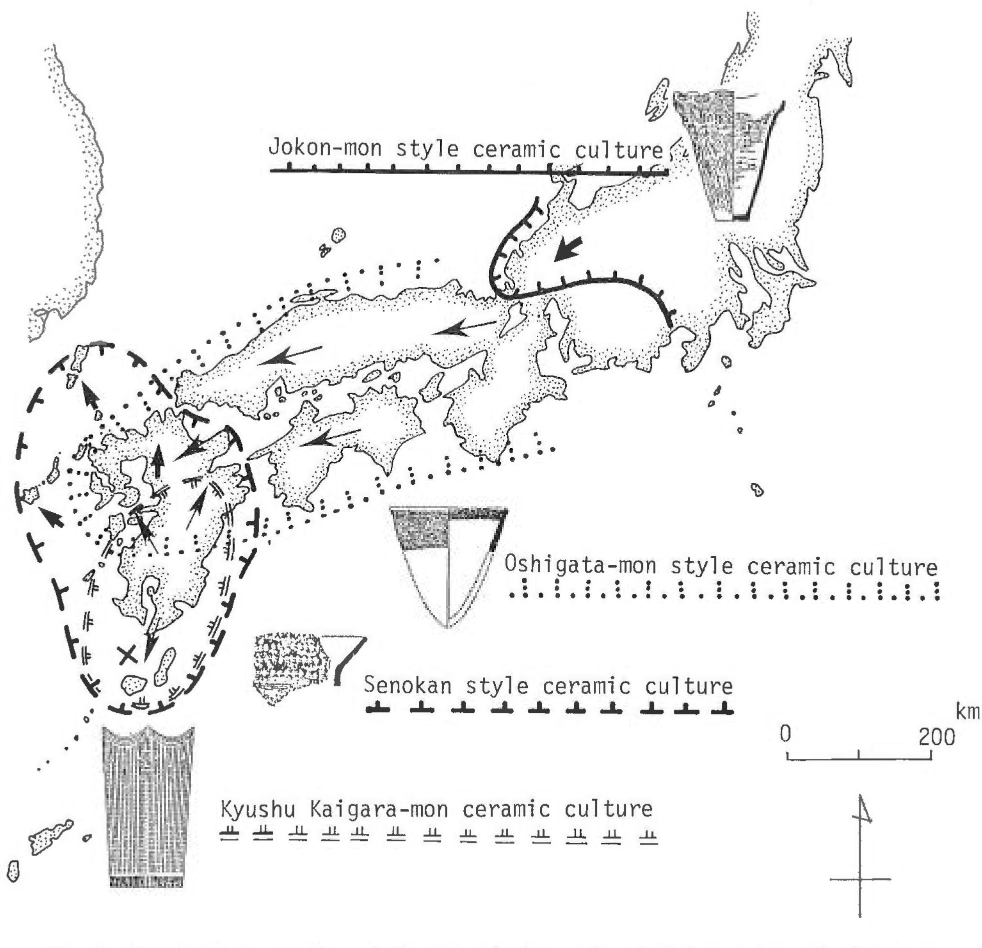

Fig. 4. Geographical extention of the regional phases of earliest Jomon immediately before the K-Ah eruption.

line (Fig. 3) would have been significantly devastated by ash-falls and associated events.

Neolithic Kyushu area has been studied in detail to permit the formation of archeological sequences. A few archeologists postulated a lack of cultural continuity between the pre-ash earliest Jomon phase of culture and the post-ash early Jomon phase (SHINTO, 1978). Figure 4 shows the general distribution pattern of ceramic cultures immediately before the K-Ah eruption. At that time, Kyushu was occupied by indigenous or native culture which was represented by the Kyushu-jokon-mon style potteries as illustrated in Figure 4, and by the imported Oshigata-mon style potteries (potteries with roller pattern). These potteries, however, are not found at all from the soil immediately above the K-Ah ash. This fact would indicate that people with such traditional culture either dispersed to the north area where volcanic impact was not so large or totally perished in the area.

Figure 5 shows the distribution pattern of Jomon ceramic culture after the Kikai eruption, based upon the assemblage of potteries and associated artifacts from the soil immediately above the K-Ah ash. A marked contrast between the pre-ash and post-ash situations (Figs. 4 and 5) shows drastic changes in the distribution of each phase of Jomon ceramic culture. An archeological interpretation suggests that the Jokon-mon ceramic culture (characterized by the potteries scraped with shell) had its origin in the east and/or central Honshu and emigrated westward. Todoroki style potteries represent such culture in Kyushu. Another culture represented by one with Sobata style potteries which was possibly originated in Korean Penin-

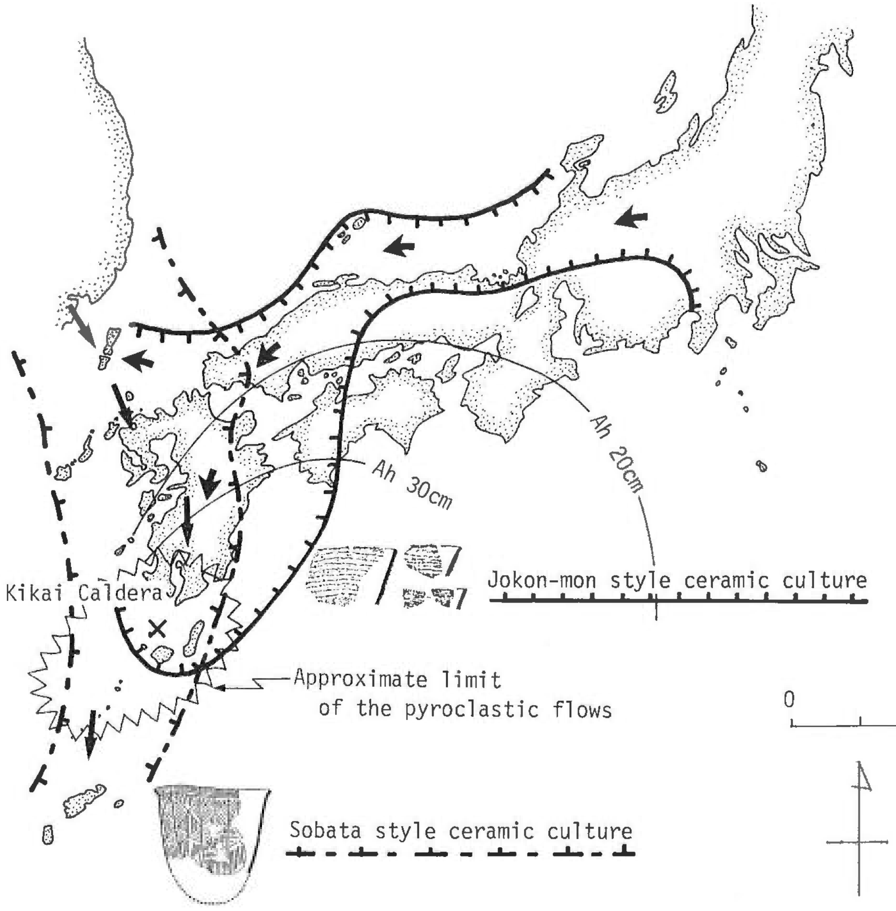

Fig. 5. Geographical extention of the regional phases of early Jomon after the K-Ah eruption.

sula also emigrated southward to Kyushu and Ryukyus after the Kikai eruption.

This archeological fact suggests that south Kyushu, if it was abandoned temporarily after the volcanic event, was reoccupied by bearers of the different cultural tradition. Several radiocarbon dates suggest that emigration into central and south Kyushu took place 300 to 800 years after the eruption. This interpretation is only one of possibilities available. Other factors such as social or other environmental pressures may have played a role in forming the new culture. But it seems very positive in correlating the timing of the archeological events in Kyushu with the cataclysmic eruption of Kikai.

There have been few archeological data on the volcanic impact as yet in Shikoku and adjacent areas. However, the effect of the ash-fall can be interpreted as great from some geological evidences. One is the occurrence of the ash induced severe landslide or slope erosion in every mountainous area. There are patches of the K-Ah ash scattering within debris avalanche deposits. This fact indicates that extensive devastation of forest occurred by ash-fall and associated phenomena. As mentioned earlier, considerable part of the K-Ah ash was generated from phreatoplinian eruptions. Torrential mud-rain and perhaps, eruption-induced storms might have taken place and caused the death or decline of plants. In fact the ash of this type may fall dry or wet, become sticky after deposition due to absorbed moisture, and then harden.

Another evidence exists in coastal areas of central Honshu. Archeological excavations from shell mound sites in Aichi prefecture revealed that there is a conspicuous decline in size and number of shells immediately after the Kikai event. This fact may suggest extensive devastation even in shores by ash deposition and associated phenomena.

It seems doubtless that the K-Ah eruption induced a significant decline in natural productivity over a vast area.

CONCLUSION

Joint studies from volcanology, archeology and other related sciences on the two widespread ashes of south Kyushu origin led to the conclusion that these ashes were supplied from the large-scale explosive activities of exceptional magnitude and that the eruptions induced a significant damage on human beings and environment over a vast area. The recurrence of such a volcanic event would be of severe consequence anywhere in the world.

Such highly explosive volcanism does not occur frequently as far as concerning in a particular volcanic center. Eruptive history of the Aira and Kikai calderas suggests that such cataclysmic volcanism occurred at intervals of tens of thousand years in late Quaternary.

The major per-AT explosive volcanism in the Aira caldera is assigned to the eruption of the Iwato pyroclastic flow deposits and associated ejecta, *ca*, 50,000–60,000 B.P. Its magnitude was smaller than that of the Ito-AT events. The last but one eruption of the Kikai caldera is correlated with the eruption of the Kikai-Tozurahara ash *ca*. 75,000 B.P. (Table 1). It should have been of phreatomagmatic type and of exceptional volume and dispersive power, because it mantles extensive areas approximately same as K-Ah. It is noted that such major eruptions in volcano-tectonic depression of south Kyushu have occurred in the shallow sea floor or lake basin, and hence of devastating type in most cases.

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Volcanoes and Volcanic Hazards in Papua New Guinea

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ABSTRACT

Papua New Guinea has fourteen active and 22 dormant volcanoes which are a danger to the lives of 204,000 people living in a total area of 16000 square kilometres — that is 6.8 percent of the total population over 3.8 percent of the total land area of the country.

This paper describes the distribution of all the active and dormant volcanoes and details are given of their geographic locations, the sizes of the hazardous areas surrounding them and the numbers of people living within these.

A historical summary showing the frequency of recorded eruptions from the active volcanoes is presented, the eruption types are described, the percentages of active volcanoes showing the differenct eruption types have been calculated and a tabulated synopsis of the recorded hazardous eruptions of the volcanoes that have caused destruction and death and/or required evacuation has been drawn up.

The hazards presented by all the active and dormant volcanoes are considered and danger scores based on factors which reflect the likelihood of dangerous volcanic activity have been calculated and used together with the size of the population thought to be at risk in each case to produce a hazard rating for each volcano. The hazard ratings for the active and dormant volcanoes have then been listed in descending order of hazard rating to indicate which are the most potentially dangerous and which therefore most urgently require surveillance.

DISTRIBUTION OF THE VOLCANOES

Papua New Guinea has 14 active and at least 22 dormant volcanoes (Fig. 1, Table 1) which are a potential danger to the lives of 204,000 people living in a total area of 16,000 sq km (Tables 2, 3). The distribution of the active, dormant and extinct Quaternary volcanoes in this country is shown in Figure 1. There are, in addition, two submarine centres, A and B, at which disturbances of possible volcanic origin have taken place in recent times.

The active volcanoes (Table 1 and Fig. 1) are those at which historical eruptions have taken place, but the criteria used for classifying the dormant volcanoes are less specific. These criteria are;

(1) particularly youthful morphological features;
(2) active or recently active fumaroles or solfataras; and
(3) indigenous stories or legends of eruptions.

Those dormant volcanoes which may have been recently active are distinguished in Table 1 and on Figure 1 as they are considered to be of greater potential hazard than those for which there are no legends of eruptions.

The extinct volcanoes are those having no historic record of eruptive or solfataric activity and are unlikely to erupt again.

LOCATION, POPULATION AND SIZES OF HAZARDOUS AREAS

If the active volcanoes are considered to be the most likely to be a hazard followed by the dormant volcanoes which could become active again in the near future, then it can be seen from Tables 2 and 3 that 148,000 people living in an area of 7,418 sq km run a high

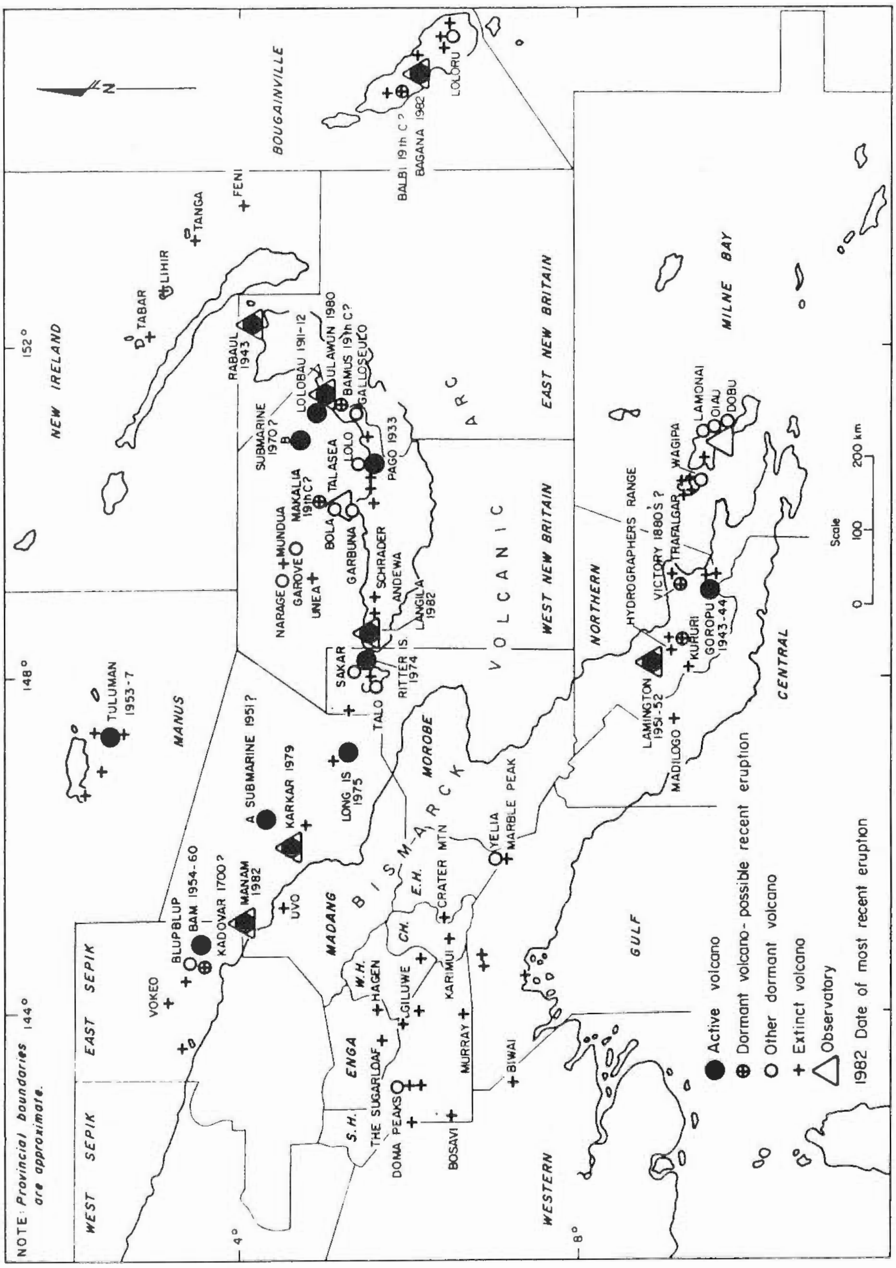

Fig. 1. Quaternary volcanoes and volcano observatories in Papua New Guinea.

Table 1. Active and dormant volcanoes of Papua New Guinea.

REGION	ACTIVE VOLCANO	DORMANT VOLCANO POSSIBLY RECENTLY ACTIVE	OTHER DORMANT VOLCANO
Admiralty Islands	Tuluman	—	—
Bismarck	Bam	Kadovar	Blupblup
Volcanic Arc	Manam	Makalia	Talo
	Karkar	Bamus	Sakar
	Submarine Centre A?		Narage
	Long Is		Garove
	Ritter Is		Garbuna
	Langila		Bola
	Pago		Lolo
	Lolobau		Galloseulo
	Submarine Centre B?		
	Ulawun		
	Rabaul- Vulcan Is Vulcan Tavurvur Rabalanakaia Sulphur Creek		
Bougainville	Bagana	Balbi	Loloru
East Papua	Lamington	Kururi	—
	Goropu	Victory	
D'Entrecasteux	—	—	Wagipa
Islands			Lamonai
			Oiau
			Dobu
New Guinea	—	—	Doma Peaks
Highlands			Yelia
TOTAL	14	6	16

Table 2. Population figures for active volcanoes in Papua New Guinea.

REGION	VOLCANO	HAZARD AREA (sq km)	1980 POPULATION
Admiralty Islands	Tuluman	<1	0
Bismarck Volcanic Arc	Bam	7	674
	Manam	79	5 046
	Karkar	380	23 143
	Long Is	452	1 010
	Ritter Is	<1	0
	Langila	314	2 270
	Pago	1 257	10 989
	Lolobau	79	493
	Ulawun	452	1 018
	Rabaul	804	68 964
Bougainville	Bagana	452	147
East papua	Lamington	2 828	34 467
	Goropu	314	0
	TOTAL	7 418	148 221

Table 3. Population figures for dormant volcanoes in Papua New Guinea.

REGION	VOLCANO	HAZARD AREA (sq km)	1980 POPULATION
Bismarck Volcanic Arc	Blupblup	7	379
	Kadovar	1	291
	Talo	908	7 509
	Sakar	50	200
	Narage	3	0
	Garove	79	2 361
	Garbuna	154	815
	Bola	50	0
	Makalia	314	451
	Lolo	28	552
	Galloseulo	380	4 343
	Bamus	616	703
Bougainville	Balbi	707	2 408
	Loloru	1 257	14 733
East Papua	Kururi	314	4 150
	Victory	1 257	2 630
D'Entrecasteaux Islands	Wagipa	3	864
	Lamonai	154	775
	Oiau	50	1 599
	Dobu	13	843
New Guinea Highlands	Doma Peaks	1 964	6 166
	Yelia	314	3 652
	TOTAL	8 623	55 424

Table 4. Land areas and population of Papua New Guinea at risk from volcanic hazards.

	LAND AREA (sq km)	POPULATION	PERCENTAGE OF TOTAL LAND AREA	PERCENTAGE OF TOTAL POPULATION
High risk from active volcanoes	7 418	148 221	1.7	4.9
Moderate risk from dormant volcanoes	8 623	55 424	2.0	1.8
Mod & high risk from all volcanoes	16 041	203 645	3.8	6.8

Total 1980 population of PNG=3,006,799 persons
Total land area of PNG = 426,840 sq km

risk of being endangered by an eruption of an active volcano in the near future and a further 55,000 people living in an area of 8,623 sq km run a somewhat lower risk of being endangered by resumption of activity by a dormant volcano. The total number of people at risk is 204,000.

As the total land area of Papua New Guinea is known to be 426,840 sq km and the total population (in 1980) is 3,006,799, the percentage of the land area and population at risk can be calculated (Table 4). From this it can be seen that a significant proportion of the land area of this country (3.8%) and its population (6.8%) are in some risk of being endangered by volcanic activity in the near future.

It is however clear from Figure 1 that the distribution of volcanoes in Papua New Guinea is not uniform. For example, the Bismarck Volcanic Arc, which extends from Vokeo Island in the west to Rabaul in the east, contains the majority (10 out of 14) of the active and over half (12 and of 22) of the dormant volcanoes in the country and the percentages of the land area and population at risk in this area will be very much higher than that for the country as a whole. On many of the volcanic islands situated in the western portion of the Bismarck Volcanic Arc 100 percent of the population are at a risk of being endangered by volcanic activity in the near future.

Other regions of volcanic risk are Bougainville Island, East Papua and possibly the D'Entrecasteaux Islands.

Within the region of volcanic risk are individual hazardous areas which are situated at or in the vicinity of the active and dormant volcanoes (Tables 2, 3). The exact sizes of the hazardous areas are difficult to determine except for the volcanoes with well documented recent eruptive histories.

In many cases the estimated sizes of the hazardous areas are based on the physical sizes of the volcanic edifices and the outer limits coincide with coastlines, major valleys, abutments against other topographic features or the maximum extent of known lava and pyroclastic flow deposits.

In all cases the areas shown are the *maximum* in which hazards based on previous eruptive activity are considered likely to occur and the population figures are the total number of people (based on the 1980 census) that could be involved if the entire areas were affected in the immediate future.

In the event of future eruptions, many of the areas will prove to be much smaller and a few may be much larger than shown, but the figures chosen do at least enable a rough assessment of the potential danger to lives and property.

FREQUENCY OF ERUPTIONS

The sequence of volcanic eruptions in Papua New Guinea since the 1870's is represented diagrammatically in Figure 2 (modified after COOKE and JOHNSON, 1978). Information of earlier events in too incomplete to contribute usefully to a comprehensive eruptive history. The record is only reliable and complete after 1950 when the Rabaul Volcanological Observatory was re-established after the war.

Increased levels of volcanic activity appear to have occurred during the 1870's–1880's, the 1940's–1950's and in the 1970's, and only a low level appears to have occurred during the 1920's and early 30's. The higher level of activity apparent since the late 30's may in fact reflect better reporting and more complete collection of data, resulting from the establishment of the Rabaul Observatory in 1937 and the major expansion of aircraft operations (from which first reports are often obtained) during and after the Second World War.

Volcanoes have been active in four regional groups during the peaks of activity in the 1870's–1880's and the 1950's: — East Papua, the Admiralty Islands, the Bismarck Volcanic Arc and Bougainville Island. Volcanoes in only the Bismarck Volcanic Arc and Bougainville Island were active during the marked time — cluster of eruptions in the 1870's. The activity in the Bismarck Arc was strikingly concentrated in its western part and was more prolific than at any earlier recorded period.

A local upsurge in volcanism is apparent in East Papua during the 1940–50's regional upsurge when the first recorded eruption in history took place at Mount Lamington Volcano and a new volcano (Goropu) was born within a period of seven years.

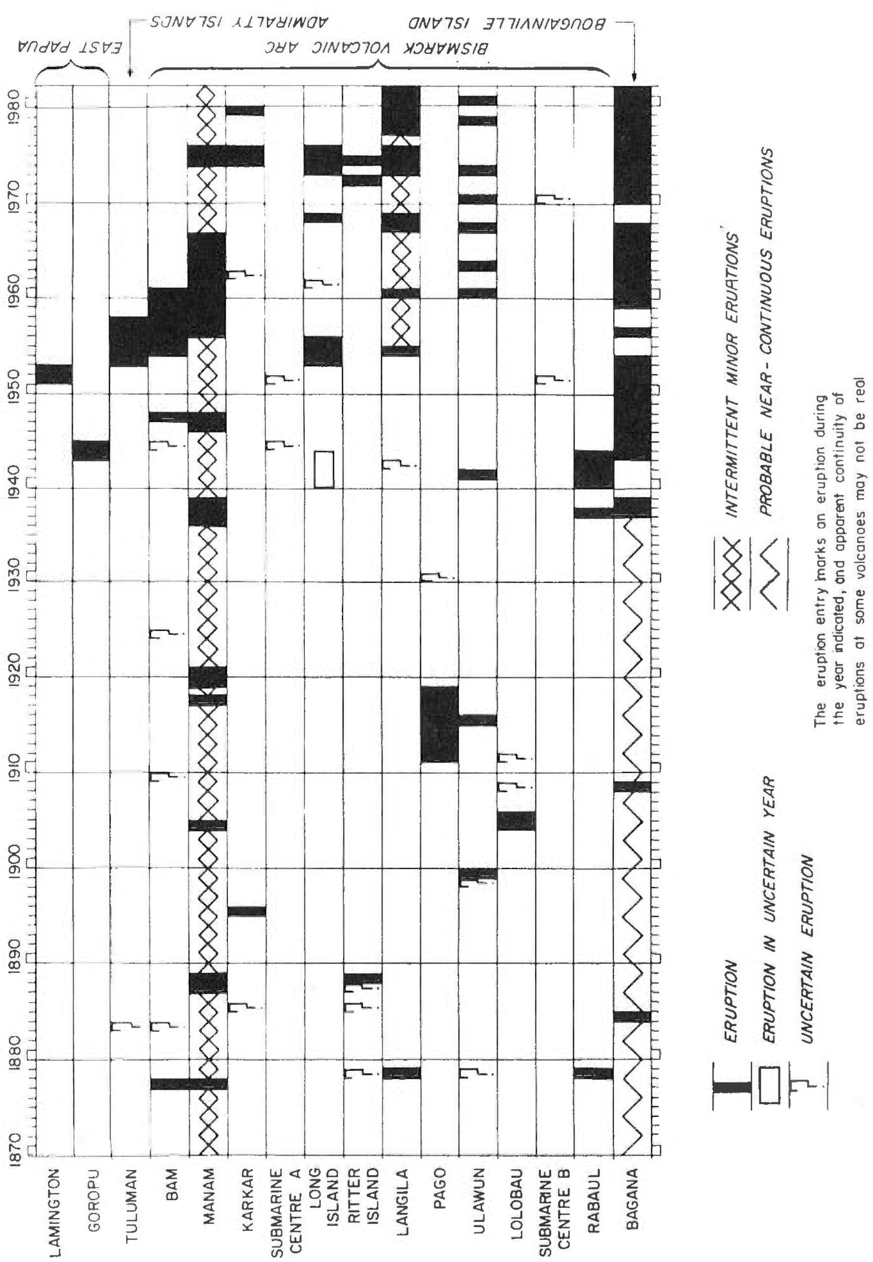

Fig. 2. Eruptive history of active volcanoes in Papua New Guinea, 1870–1981.

The apparent increase in activity in the period after 1935 as compared with the previous period has been considered to be real (MICHAEL, 1969) and to be related to a local fluctuation in the rate of extension of the mantle. Short pulses of volcanic activity with intervening quiet periods were proposed by Michael to be caused by variations in the rates of movements in elements of the Melanesian Shear Zone (CAREY, 1958).

The length of time for which written records of direct observation of the volcanoes in Papua New Guinea is too short to enable any long term periodicity to be detected.

During the 100 years or so for which written records of direct observations are available, no regular short term periodicity has been detected at any of the volcanoes and prediction on this basis is impossible.

TYPES OF ERUPTIONS

The principal types and dates of most recent eruptions of the active volcanoes in Papua New Guinea are shown in Table 5. The principal eruption types are defined in accordance with the scheme of MACDONALD (1972) but with some differences. The term "Strombolian" indicates frequent to near continuous explosions (typically one or more per minute) producing pasty bombs, normally incandescent in daylight, with greater or lesser amounts of ash, whereas "Vulcanian" indicates less frequent explosions (typically several hours apart), commonly with solid bombs which may be incandescent at night; Strombo-Vulcanian activity has intermediate character.

"Peléan" here indicates the expulsion of nuées ardentes from a crater, with or without dome

Table 5. Principal eruption types and dates of latest eruptions of the active volcanoes in Papua New Guinea.

ACTIVE VOLCANO	PRINCIPAL RECENT ERUPTION TYPE	DATE OF MOST RECENT ERUPTION
Tuluman	Underwater and Strombo-Vulcanian	1953–7
Bam	Vulcanian	1954–60
Manam	Strombolian and Peléan	1982
Karkar	Strombolian and Phreatic	1979
Submarine Centre A	Underwater	1951?
Long Island	Underwater and Strombolian	1975
Ritter Island	Underwater, Strombolian and Peléan	1974
Langila	Strombo-Vulcanian and Vulcanian	1982
Pago	Strombo-Vulcanian	1933
Lolobau	Vulcanian	1911–12
Submarine Centre B	Underwater	1970?
Ulawun	Strombolian and Peléan	1980
Rabaul:		
Vulcan Is	Underwater and Plinian	1878
Vulcan	"	1937
Tavurvur	Strombo-Vulcanian	1937–43
Rabalanakaia	?	19th Century
Sulphur Creek	Vulcanian	1850
Bagana	'Baganian', Vulcanian and Peléan	1982
Lamington	Vulcanian and Peléan	1951
Goropu	Vulcanian and Peléan?	1943–44

Table 6. Percentages of active PNG volcanoes showing different eruption types

DEGREE OF HAZARD	ERUPTION TYPE	NO. OF ACTIVE VOLCANOES SHOWING THIS TYPE	PERCENTAGE OF ACTIVE VOLCANOES SHOWING THIS TYPE
Very high	Plinian	1	7
	Peléan	6	43
	Vulcanian	7	50
	Strombo-Vulcanian	4	29
	Strombolian	5	36
	'Baganian'	1	7
Low	Underwater	4	29

Total number of active volcanoes for which information available=14

building (excluding nuées produced merely by collapse of a dome or lava flow), and "Plinian" indicates voluminous and more or less continuous outpourings of pumice, with or without caldera collapse. Existing classifications do not provide an equivalent name for purely effusive (non-explosive) eruptions such as those observed at Bagana and the term "Baganian" has been used for this type (COOKE and JOHNSON, 1978). The under-water eruptions include several different types including frequent eruptions of the type distinguished as "Surtseyan" (Long Island), non-explosive rise of pumice to the surface (Tuluman) and submarine disturbances and water discolouration for which volcanic origins are not certain (Submarine Centres A and B).

One of the striking features in Table 5 is that most of the volcanoes have shown different types of eruption at different times and this makes hazard prediction all the more difficult.

If the eruption types are listed in the order of hazard that they present from very high for Plinian and Peléan to low for under-water (Table 6) it is evident that some 50 percent of the active volcanoes in Papua New Guinea have exhibited very dangerous activity in recent times.

RECORDED HAZARDOUS ERUPTIONS

Of the fourteen active volcanoes in Papua New Guinea, eight have produced dangerous eruptions that have caused destruction and death and/or have required evacuation of the people living near them. These are Ritter Island, Rabaul, Goropu, Bagana, Mount Lamington, Manam, Ulawun and Karkar Island.

A synopsis of recorded hazardous eruptions at these volcanoes which lists the types of dangerous eruption that have occurred, their dates, the amount of damage done, the number of fatalities caused and the numbers of people evacuated, is presented in Table 7. Also provided are principal references from which details of the eruptions can be obtained.

From Table 7, it can be seen that in the 282 years from 1700 to 1982, for which historical records of disastrous eruptions are available, there have been over 3600 people killed and several hundreds of square kilometres of land destroyed. Most of this damage was caused by just three eruptions — Ritter Island 1888, Rabaul 1937 and Mt Lamington 1951.

It is also evident from the recorded information available on the other volcanoes, that although catastrophic eruptions have not occurred recently, they have the potential to produce them in the near future. This may apply in the case of Mt Ulawun which has erupted three times at closely spaced intervals during the past ten years, and on each successive occasion (1973, 1978 and 1980) the new eruption has been more violent and has destroyed an area four or five times as large as did its predecessor.

It is, however, not possible from the historical record alone to establish the likelihood of

Table 7. Recorded hazardous eruptions of active volcanoes in Papua New Guinea that have caused destruction and death and/or have required evacuation.

VOLCANO	DANGEROUS ERUPTION TYPE	LAVA TYPE	DATE	REFERENCES	AREA DESTROYED (sq km)	CAUSE OF DESTRUCTION	NO. OF FATALITIES RECORDED	CAUSE OF DEATHS	NO. OF PEOPLE EVACUATED
Ritter Island	Peléan	Basalt	1700	Cook and Johnson, 1978	?	Nuées ardentes	—	—	—
	〃	Basalt	1793	Cooke, 1981a	?	〃 〃	—	—	—
	Caldera formation	?	1888	〃 〃	100's	Tsunami	100's	Drowning	—
Rabaul									
Vulcan Is	Plinian	Dacite	1878	Cooke, (Unpubl manusc)	?	Airfall tephra	—	—	—
Vulcan	〃	〃	1973	Fisher, 1939	155	Airfall tephra and nuées ardentes?	506	Crushing asphyxiation and burial	7500
Goropu	Peléan	Trachy-basalt	1943–44	Baker, 1946	30	Nuées ardentes	—	—	—
Bagana	Peléan	Low silica andesite	1950	Bultitude, 1976 and 1979	5	Nuées ardentes	—	—	—
	〃	〃	1952	〃 〃	1	〃 〃	—	—	—
	〃	〃	1966	〃 〃	10	〃 〃	—	—	—
Mount Lamington	Peléan	Andesite	1951	Taylor, 1958b and 1966	230	Nuées ardentes	3000	Burning asphyxiation and cadaveric spasm	?
Manam	Peléan	Basalt	1936	Palfreyman & Cooke, 1976	?	Nuées ardentes	—	—	—
	〃	〃	1957–58	Taylor, 1958a and 1966	36	〃 〃	—	—	3200
	〃	〃	1960	Taylor, 1963	5	〃 〃	—	—	100's
	〃	〃	1974	Cooke et al., 1976	<5	〃 〃	—	—	—
Ulawun	Peléan	Basalt	1898	Cooke, 1981b	?	Nuées ardentes	—	—	—
	〃	〃	1970	Johnson & Davies, 1972 Melsom et al., 1972	2	〃 〃	—	—	—
	〃	〃	1973	Cooke et al., 1976	1	〃 〃	—	—	—
	〃	〃	1978	McKee et al., 1981a	5	〃 〃	—	—	—
	〃	〃	1980	Mckee (in press)	20	〃 〃	—	—	1018
Karkar Island	Phreatic explosion	Low silica andesite	1979	McKee et al., 1981b	5	Directed tephra blast	2	Crushing asphyxiation and burial	—

future dangerous eruptions occurring but if all the known hazardous features of each of the active and dormant volcanoes in Papua New Guinea are listed and compared, it is possible to derive semi-quantitative hazard ratings which provide at least an empirical estimate of the dangers presented in each case.

HAZARD RATINGS OF THE VOLCANOES

In determining the likelihood of future dangerous eruptions from any of the volcanoes in Papua New Guinea a number of factors have to be taken into consideration.

1) The volcano type and composition of recent eruption products.
2) The geological record of recurrent dangerous activity of the volcano.
3) The geological record of volcanic activity in the region in which the volcano is situated.
4) The historical records of recent dangerous eruptions of the volcano and the amount of damage and fatalities caused.
5) The present stage of development of the volcano.
6) The present level of activity of the volcano.

A number of these factors may be used directly to calculate a danger score for individual volcanoes (Figs. 3, 4) and others may give some less easily quantifiable indication of additional dangers that could arise.

Volcano Type

It is well known that composite volcanoes particularly those in which recent eruption products have been derived from viscous silica-rich magma that is andesitic, dacitic or rhyolitic in composition, are much more likely to erupt violently and cause widespread destruction than volcanoes in which the eruption products are derived from more fluid, silica-poor basaltic or low silica andesitic magma.

On this basis it can be seen (Figs. 3, 4) that 11 of the 14 active volcanoes and 18 out of 22 of the dormant volcanoes have erupted moderate to high silica products.

Geological Record of Dangerous Activity

The presence of lava domes, calderas or extensive pyroclastic flow or outlying or strongly aligned satellite centres can all be taken to indicate that a volcano has previously experienced and may again show dangerous or more widespread activity.

Lava domes indicate that viscous magma was emplaced in a previous eruptive episode. It is well known that the formation of lava domes is frequently preceded by violently explosive activity and the production of nuées ardentes and the presence of well preserved lava domes is fairly good evidence for the occurrence of relatively recent (geologically) explosive activity.

One active volcano (Lamington) and six dormant volcanoes (Kadovar, Bamus, Loloru, Victory, Doma Peaks and Yelia) show this feature (Figs. 3, 4).

Calderas indicate that relatively recent (geologically) catastrophic collapse or explosion of a volcanic edifice has occurred. It is well known that further collapse and subsidence and enlargement of existing calderas can occur with very serious consequences. Six of the active and six of the dormant volcanoes have well developed calderas (Figs. 3, 4).

Pyroclastic flow deposits which have been deposited as a result of historically or geologically recent violently explosive eruptions are known to occur at 9 out of the active and 10 of the dormant volcanoes in Papua New Guinea. The number of dormant volcanoes with these deposits may be higher as tephrochronological studies have not been carried out at all of them (Figs. 3, 4).

In a few cases (Karkar Island, Long Island and Rabaul) tephrochronological studies have revealed a history of repeated deposition of pyroclastic flow deposits derived from catastrophic events, and in these cases there is a disturbing possiblity that a repetition may occur in the distant if not near future.

		GEOLOGICAL FEATURES					HISTORICALLY RECORDED FEATURES													
REGION	ACTIVE VOLCANO	ANDESITE, DACITE OR RHYOLITE (MOD-HIGH SILICA PRODUCTS)	LAVA DOME	CALDERA	PYROCLASTIC FLOW DEPOSITS	ALIGNMENT OF SATELLITE CENTRES	CONTINUOUS VAPOUR EMISSION	MAJOR VIOLENT EXPLOSIVE ACTIVITY	NUÉES ARDENTES	MUDFLOWS OR LAHARS	DESTRUCTIVE TSUNAMI	AREA OF EXPLOSIVE DESTRUCTION >10 SQ KM	RECORD OF FATALITIES	EVACUATION AS RESULT OF ERUPTION	DANGER SCORE /13	POPULATION >100	POPULATION >1000	POPULATION >10000	HAZARD RATING /16	ACTIVE VOLCANO
Admiralty Islands	Tuluman	●													1				1	Tuluman
Bismarck Volcanic Arc	Bam	●					●								2	●			3	Bam
	Manam	●			●	●	●	●	●	●		●		●	9	●	●		11	Manam
	Karkar	●		●	●	●	●	●		●			●		8	●	●	●	11	Karkar
	Long Is			●	●	●	●								4	●	●		6	Long Is.
	Ritter Is			●				●			●	●	●		5				5	Ritter Is.
	Langila	●				●	●	●	●						5	●	●		7	Langila
	Pago	●		●	●		●								4	●	●	●	7	Pago
	Lolobau	●		●		●									3	●			4	Lolobau
	Ulawun				●	●	●	●	●	●		●		●	8	●	●		10	Ulawun
	Rabaul	●		●	●	●	●	●	●	●	●	●	●	●	12	●	●	●	15	Rabaul
Bougainville	Bagana	●			●		●	●	●			●			6	●			7	Bagana
East Papua	Lamington	●	●		●		●	●	●	●		●	●	●	10	●	●	●	13	Lamington
	Goropu	●			●			●	●			●			5				5	Goropu

Fig. 3. Hazardous features, danger scores and hazard ratings for the active volcanoes of Papua New Guinea.

		GEOLOGICAL FEATURES					PRESENT FEATURES							
REGION	DORMANT VOLCANO	ANDESITE, DACITE OR RHYOLITE (MOD - HIGH SILICA PRODUCTS)	LAVA DOME	CALDERA	PYROCLASTIC FLOW DEPOSITS	ALIGNMENT OF SATELLITE CENTRES	THERMAL ACTIVITY	STRONG FUMAROLES	DANGER SCORE /7	POPULATION >100	POPULATION >1000	POPULATION >10000	HAZARD RATING /10	DORMANT VOLCANO
Bismarck Volcanic Arc	Blupblup	●				●	●		3	●			4	Blupblup
	Kadovar	●	●				●	●	4	●			5	Kadovar
	Talo	●		●	●		●		4	●	●		6	Talo
	Sakar	●				●	●		3	●			4	Sakar
	Narage						●		1				1	Narage
	Garove			●	●		●		3	●	●		5	Garove
	Garbuna	●					●	●	3	●			4	Garbuna
	Bola	●					●		2				2	Bola
	Makalia	●		●	●	●	●		5	●			6	Makalia
	Lolo	●							1	●			2	Lolo
	Galloseulo	●		●	●	●	●		5	●	●		7	Galloseulo
	Bamus	●	●		●	●	●		5	●			6	Bamus
Bougainville	Balbi	●			●	●	●	●	5	●	●		7	Balbi
	Loloru	●	●	●	●		●	●	6	●	●	●	9	Loloru
East Papua	Kururi								0	●	●		2	Kururi
	Victory	●	●		●	●	●		5	●	●		7	Victory
D'Entrecasteaux Islands	Wagipa								0	●			1	Wagipa
	Lamonai	●					●		2	●			3	Lamonai
	Oiau	●					●		2	●	●		4	Oiau
	Dobu	●					●		2	●			3	Dobu
New Guinea Highlands	Doma Peaks	●	●	●	●	●	●		6	●	●		8	Doma Peaks
	Yelia	●	●		●	●	●		5	●	●		7	Yelia

Fig. 4. Hazardous features, danger scores and hazard ratings for the dormant volcanoes of Papua New Guinea.

The presence of satellite centres particularly can be taken to indicate that the volcano has in the past and may again in the future, erupt outside the present main centre of activity, causing more widespread destrucion than would otherwise occur. Flank eruptions are likely on any large stratovolcano which has satellite centres particularly if there is a structurally controlled allignment. Satellite centres showing same form of alignment occur at seven of the active and nine of the dormant volcanoes in Papua New Guinea (Figs. 3, 4).

Large volcanic edifices on which satellite centres that are related to major structural alignments occur are additionally dangerous in that sector collapse with catastrophic consequences can occur along these lines of weakness. Sector collapse may have already occurred in the past at Ulawun and Bam and could probably occur in the future at Ulawun, Galloseulo and Bamus volcanoes (JOHNSON, in press).

In the case of volcanoes with calderas, the development of satellite centres showing arcuate alignment could be the forerunner of further caldera collapse. Rabaul is an example of a caldera where satellite centres show arcuate alignment, and volcano seismicity also occurs along arcuate zones. Further caldera collapse is therefore considered to be a distinct possibility.

Historical Record of Dangerous Eruptions

This is by far the most useful criteria that can be used in determining the likelihood of future dangerous eruptions but only applies to volcanoes that can be classified as active (Figs. 3).

If it is accepted that past behaviour is likely to be the key to future activity, then the longer and more complete the record of past activity is, the better the prediction of future dangerous activity will be.

In Papua New Guinea the use of this technique is handicapped by the very short period of 44 years (since 1937 when the Rabaul Observatory was established) for which fairly complete records of eruptive activity are available.

In spite of this however, some indication of the likelihood of future dangerous activity of the volcanoes can be obtained by listing all recorded instances of violent explosive activity, generation of nuées ardentes, formation of mudflows, the areas of destruction produced, the number of fatalities caused and the numbers of people that have had to be evacuated (Fig. 3). The numbers of these features for which positive answers are obtained can then be used in conjunction with the scores obtained for other factors listed in Figure 3 to show which of the volcanoes are most likely to produce dangerous eruptions in the future (high danger score).

The Geological Record of Regional Volcanic Activity

An active or dormant volcano that is situated in a geotectonic region in which volcanic activity is currently widespread and vigorous is more likely to be a threat in the future than one situated in an area in which the majority of volcanoes are either dormant or extinct.

On this basis active and dormant volcanoes in the Bismarck Volcanic Arc are more likely to erupt again in the near future than those in East Papua, the New Guinea Highlands or D'Entrecasteaux Islands regions.

That this is so is borne out by the larger number of active volcanoes and the higher frequency of eruptions in th Bismarck Volcanic Arc than in any of the other regions (Fig. 2).

In addition a recent study (MCKEE and LOWENSTEIN, 1981) has shown that within a given active area (The Western Bismarck Volcanic Arc) there may be a geographic variation in the sizes of and total amount of eruptive material that occurs in the volcanoes in different parts of the region.

In the Western Bismarck Volcanic Arc, the amount of eruptive material that may have been involved in the development of the volcanic centres shows an apparent increase from west to east and from this it can be predicted that the eastern portion of the area is subject to greater volcanic risk with more voluminous generation of volcanic rocks than the western one.

Although it is not possible to use this type of information quantitatively to derive danger scores for the individual volcanoes it should be borne in mind when considering the likelihood and possible locations of hazardous eruptions within the regions as a whole.

Current Stage of Development

One of the factors to be taken into consideration in determining the likelihood of a future dangerous eruption is the stage at which a volcano is in its development i.e. youthful, mature or senile.

Some volcanoes that have been born geologically very recently show less violent eruptive activity than others which have reached a mature stage and have built up an edifice to the point where it becomes unstable and could collapse or where the height of magma column required for summit eruption is so great that flank eruptions from satellite centres become more probable.

The magma feeding youthful volcanoes may also have had less time to differentiate and therefore have a lower silica and volatile content and a lower viscosity and be less likely to produce explosive eruptive activity.

Bagana on Bougainville is a good example of a youthful volcano in which unusually quiet emission of relatively fluid low-silica andesite has been occurring continuously throughout historical times and has so far only built up a relatively small edifice.

Other youthful volcanoes (Goropu) have come into existence with violent explosive activity so there are clearly exceptions.

Mature volcanoes, especially those with relatively long periods of inactivity (dormancy) present the greatest threat as there may be an insufficient number of historical eruptions to indicate what type of eruption is to be expected. Many of these have deposits (pyroclastic flows) and features (lava domes, calderas and satellite centres) that indicate a potential for very violent activity even though they may be dormant or have a historical record of mild eruptions. Many of the large active and dormant volcanoes in Papua New Guinea fall into this category.

Senile volcanoes that have approached the end of their life-span are also very unpredictable in terms of producing violent eruptions. Large dormant volcanoes such as Doma Peaks and Mt Yelia which occur in areas containing many extinct Quaternary volcanoes, may belong to this category. They may only erupt very infrequently but when they do, activity may be very explosive in nature. The probabiliy of a major eruption occurring at these in the forseeable future is low and as such they present less of a hazard than the mature active volcanoes. Some volcanoes now regarded as extinct fall into this category.

Present Level of Activity

Obervation of the present level and kind of activity is also important in assessing the likelihood of further eruptions in the near future although it will not always indicate whether these will be dangerous.

A volcano that is at present in a continuous state of eruption is perhaps less likely to produce an extremely violent explosion than one that is not and is therefore less of a hazard. Volcanoes in continuous activity can be monitored visually and trends of increasing or decreasing violence can often be detected and changes predicted (Bagana and Langial).

Active volcanoes that are not now erupting but produce continuous emissions of vapour are considered to be more likely to produce dangerous eruptions in the near future than those which are at present completely quiet and this is taken into consideration in arriving at danger scores for the active volcanoes (Fig. 3). Similarly dormant volcanoes with fumaroles can be considered more likely to erupt and be a danger in th near future than those on which only mild or no thermal activity occurs and these factors are taken into consideration is arriving at danger scores for the dormant volcanoes (Fig. 4).

Danger scores, i.e. empirically derived figures to indicate the likelihood of future dangerous eruptions from each of the active and dormant volcanoes in Papua New Guinea, are presented in Figures 3 and 4.

These are based on yes/no answers to the questions raised by the factors 1–6 just discussed and give a fairly realistic if not entirely reliable assessment of the potential danger of each volcano.

However in attempting to quantify the potential dangers of the volcanoes in terms of a threat to life and property (i.e. arrive at a true hazard rating), it is necessary also to take into account the numbers of people living within the maximum predictable areas of destruction around each one.

Additional points are therefore added to the danger cores in Figures 3 and 4 depending on whether the population are >100 (1 point) >1000 (2 points) or >10000 (3 points) to arrive at a figure (hazard rating) that is more likely to reflect the true potential hazard of each volcano.

In the event that a volcano has no population within the maximum radius that is likely to be affected by a dangerous eruption the hazard rating is the same as the danger score.

Table 8 lists all the active and dormant volcanoes in Papua New Guinea ranked in descending numerical order of their hazard rating and indicates which ones are currently under surveillance. This has value in that it not only indicates where the greatest potential hazards lie, but may also be used to assign priorities for future surveilance.

It is for example clear that among the active volcanoes, Pago *must* be placed under surveillance as soon as possible and that there are a number of dormant volcanoes, particularly Loloru, Doma Peaks, Galloseulo, Balbi, Victory and Mt Yelia which should be included in any expan-

Table 8. Active and dormant volcanoes of Papua New Guinea in descending order of hazard rating.

ACTIVE VOLCANO	HAZARD RATING /16	DORMANT VOLCANO	HAZARD RATING /10
Rabaul*	15	Loloru	9
Lamington*	13	Doma Peaks	8
Manam*	11	Galloseulo	7
Karkar*	11	Balbi	7
Ulawun*	10	Victory	7
Langila*	7	Yelia	7
Bagana*	7	Talo	6
Pago*	7	Makalia*	6
Long Is	6	Bamus	6
Ritter Is*	5	Kadovar	5
Lolobau	4	Garove	5
Goropu	4	Blupblup	4
Bam	3	Sakar	4
Tuluman	1	Garbuna*	4
		Oiau*	4
		Lamonai	3
		Dobu*	3
		Bola*	2
		Lolo	2
		Kururi	2
		Narage	1
		Wagipa	1

*Under surveillance

sion of our surveillance program.

It is also evident that the dormant volcanoes Oiau and Dobu in the D'Entrecasteaux Islands region have only a low hazard rating and that with the limited resources available, surveillance of these should be reduced in favour of more dangerous targets.

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The Importance of an Internationl Earthquake Data Bank

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ABSTRACT

Three strategies for mitigating earthquake hazards are: (1) avoid building in high seismic risk areas, (2) build structures that can withstand the effects of earthquakes, and (3) plan for earthquake emergencies, especially to predict earthquakes well in advance to minimize damage. In all these cases, we need accurate data concerning earthquakes. This can be accomplished by systematically consolidating old data and collecting new data.

The idea of creating a global seismic data bank has been studied by a group of IASPEI/UNESCO experts. V. KARNIK completed a feasibility study, but so far funding for this multi-million dollar project has not been found. In this paper I will report my analysis of the data consolidation problem, and efforts towards organizing an international earthquake data bank. Such a bank should include every level of earthquake data, from seismograms to published papers. Implementation of this data bank is technically feasible and can be done in one to two decades.

During the past 5 years, significant progress has been made towards an international earthquake data bank. For examples, about 400,000 seismograms have been copied under the Historical Seismogram Filming Project; the bulk of seismograph station bulletins (about 300,000 pages) has been microfilmed; over 10,000 papers has been indexed in the Current Earthquake Literature database; and a computer-based system for organizing earthquake-related data has been developed.

When sufficient data are accessible, an accurate global earthquake catalog of the past 100 years can be rapidly produced. Such a catalog and the source materials in the data bank will provide valuable information to make better decisions and to aid research on earthquake hazards reduction.

INTRODUCTION

Ever since civilization began, earthquakes have caused mankind much suffering. For example, Table 1 lists earthquakes that caused over 1,000 fatalities or over 100 million dollars of damage since 1970. This list is by no means complete, but will serve as a reminder that, from 1970 to 1980, earthquakes have killed over 400,000 persons and caused over 11 billion dollars in damage. There are three basic strategies for mitigating earthquake hazards: (1) avoid living in high seismic risk areas, (2) build structures that can withstand the effects of earthquakes, and (3) plan for earthquake emergencies, especially to predict earthquakes well in advance to minimize damage.

The first strategy is not practical because many productive lands are located in high seismic risk areas. However, by mapping active faults and studying past earthquakes, we may estimate the hazard potentials from earthquakes, and plan our land use accordingly. The second strategy depends on the skills of engineers, but also requires seismologists to provide realistic estimates of the ground motions from expected earthquakes. The third strategy involves the cooperation of the entire society, and also depends on the ability of seismologists to predict earthquakes reliably. Unfortunately, the science of earthquake prediction (see, e.g., RIKITAKE, 1976) is in the developing stage, and our ability to predict earthquakes is very limited.

In all three strategies, we need accurate data concerning earthquakes, especially, accurate and homogeneous earthquake catalogs which contain information on origin times, hypocenter

Table 1. Examples of "Bad" earthquakes (1970–80) (after Ganse & Nelson, 1981).

Year	Date	Place	Magnitude	Deaths	Damage*
1970	May 31	Peru	7.8	66,000	500
1971	Feb 9	San Fernando, USA	6.5	60	500
1972	Apr. 10	Ghir, Iran	7.1	5,400	5
1972	Dec. 23	Managua, Nicaragua	6.2	5,000	800
1974	May 10	Yunnan-Szechwan, China	6.8	20,000	--
1974	Dec. 28	Pakistan	6.2	5,300	--
1975	Feb. 4	Haicheng, China	7.4	10,000	--
1975	Sep. 6	Lice, Turkey	6.7	2,300	17
1976	Feb. 4	Guatemala	7.5	23,000	1,100
1976	May 6	Friuli, Italy	6.5	1,000	8,000
1976	Jun. 25	West Irian, Indonesia	7.1	6,000	--
1976	Jul. 27	Tangshan, China	7.8	240,000	--
1976	Aug. 16	S. Mindagao, Philippines	6.9	8,000	130
1976	Oct. 29	West Irian, Indonesia	7.2	6,000	--
1976	Nov. 24	East Turkey	7.3	5,000	--
1977	Mar. 4	Rumania	7.2	1,500	800
1978	Sep. 16	Tabas-e-Golshan, Iran	7.4	20,000	--
1980	Oct. 10	El Asnam, Algeria	7.3	3,500	--
1980	Nov. 23	South Italy	6.8	3,000	--

* in million of U.S. dollars.

coordinates, magnitudes, etc. This can be accomplished by (1) systematically consolidating old data and collecting new data, (2) making earthquake data easily accessible, and (3) encouraging seismologists to develop accurate earthquake catalogs. I believe that it is important to implement an international earthquake data bank because it can serve as the focal point for collecting and distributing earthquake data, and improving our knowledge about past earthquakes.

When an international earthquake data bank is fully implemented, it will serve scientific, educational, and industrial needs of the entire world community. In the scientific areas, the bank will provide all kinds of earthquake data for research purposes. In particular, it will supply the basic data for (1) preparing seismicity maps showing the distribution of earthquakes in space and time, and (2) studying seismotectonic features and earthquake recurrence to aid hazards evaluation and earthquake prediction. From the educational point of view, the bank will provide data for (1) training students, (2) inform the public, and (3) assist officials in preparing plans to cope with earthquake hazards. In industrial applications, the bank will provide data for (1) earthquake-resistant design, (2) urban and regional planning, and (3) siting critical structures, such as nuclear power plants and dams.

In this paper, I will first discuss the historical background for creating an international earthquake data bank. I will next discuss what materials such a bank should have, and whether or not our current data processing technology can handle the amount of data involved. Finally, I will report to you some of the current activities which may eventually lead to an international earthquake data bank.

HISTORICAL BACKGROUND

The idea of an international earthquake data bank is almost as old as instrumental seismology itself. In fact, the early pioneers in seismology recognized the importance of organizing earthquake data world-wide, and formed the International Association of Seismology in 1901 (ROTHE, 1981). This association later became the International Association of Seismology and Physics of the Earth's Interior (IASPEI). In particular, John Milne began systematic collection of arrival times of earthquakes from stations around the world in the late 1890's. Milne's effort later became the well know International Seismological Summary (ISS) in which arrival times were compiled and origin time and hypocenters were given. By 1964, the International Seismological Center (ISC) was established and its Bulletins succeeded the ISS. Recently, Robin Adams has summarized the activities of the ISC (ADAMS, 1982). It is amazing that the ISC is producing many fine products with a staff of only seven members.

The major task of the ISC is to produce a basic world-wide bulletin of earthquake information at a time lag of about 2 years. Since it is an ongoing task and ISC is limited by funding and staff, they do not have the luxury of going back to improve upon their previous results. Nor do they have the original seismograms to correct for errors or omissions. Although many special studies have been made, the majority of earthquakes prior to 1964 have not yet been systematically relocated by computer methods. It is well known that many earlier earthquakes are mislocated by tens or hundreds of kilometers (DEWEY, 1979; UTSU, 1982), and their magnitudes may be poorly determined or not determined at all (ABE, 1982).

The desire for an accurate and homogeneous set of earthquake data has long been recognized. For example, the idea of creating a comprehensive and homogeneous seismic data bank on a world-wide scale was supported by IASPEI at its General Assembly in 1977. A group of experts met in 1978 under UNESCO sponsorship to consider this idea. Subsequently, Dr. Vit KARNIK of Czechoslovakia performed a feasibility study on the establishment of a global seismic data bank (KARNIK, 1980), and a group of experts met again in 1980 for the same purpose. They produced a well documented report, "Creation of a Global Seismic Data Bank" (UNESCO, 1980). In this UNESCO report, the following actions were proposed to create a global seismic data bank:

"(a) collection of all existing national, regional and world earthquake catalogues and their reformating into one uniform data base;

(b) compilation of sublists of additional information on earthquakes (fault plane solutions and other source parameters, tsunamis, macro-seismic observations, geological effects, unusual phenomena, strong-motion records, casualties, extent of damage, collections of seismograms for particular events);

(c) revision and completion of earthquake parameters, particularly for years prior to 1964 with attention to parameters giving the size of event (magnitude, intensity). For this purpose, all available sources of instrumental and macroseismic information should be collected, i.e., (i) bibliography of literature on individual earthquakes; (ii) full set of station reports (or copies) from all existing stations; and (iii) inventory of collections of records of the medium and large events, particularly from stations with defined instrumental constants and long series of observations;

(d) relocation of hypocentres whose parameters are known to have been set arbitrarily (e.g. some ISS epicentres 1918–1963);

(e) continuous search for additional historical (before 1900) information in archives, chronicles, reports, etc., revision and completion of earlier determinations.

The work defined above can be implemented only by co-operation with existing World Data Centers, national and regional centres, securing the most effective combination of national and international resources;

(f) creation of a summary catalogue with single values of time, spatial co-ordinates for earthquakes, but with all magnitudes to act as an index to the basic file and immediately aid prediction and risk analysis programmes. This master event file is to be held in fixed format for simple manipulation."

The UNESCO experts concluded that such a data bank could be implemented within a five-year period provided that adequate funding was available. They strongly recommended it to proceed. Unfortunately, funding for this multi-million dollar project has not yet been found.

Although I agree with the UNESCO experts in general, I world like to propose implementing an international earthquake data bank with a larger scope. To me, such a data bank should include, as much as possible, all earthquake data—from raw obserbations to final scientific papers. Instead of waiting for funding to come, we should proceed to do whatever we can. I think the first step is to organize all existing earthquake data and make them accessible. Unlike the UNESCO proposal, I would include seismograms in the data bank, and I would also encourage seismologists all over the world to participate in organizing, processing, and analyzing earthquake data for an international earthquake data bank.

CONTENTS OF AN INTERNATIONAL EARTHQUAKE DATA BANK

Because I like to analyze the data problem at least semi-quantitatively, I will provide many numbers. Although the values of these number are rough estimates, they will be adequate for my order of magnitude arguments. Before I go on to discuss the contents of an international earthquake data bank, I would like to introduce some information terminology first.

A basic unit of information is 1 bit (either 0 or 1). A letter in the English alphabet is commonly represented by 8 bits or 1 byte. A number usually takes from 10 to 60 bits, depending on the precision required. We will use "byte" as our data unit. For simplicity, we assume the following approximations:

$$1 \text{ bype} \simeq 10 \text{ bits}$$
$$1 \text{ integer number} \simeq 2 \text{ bytes}$$
$$1 \text{ real number} \simeq 4 \text{ bytes}$$
$$1 \text{ English word} \simeq 6 \text{ bytes}$$

Let us consider the information contained in a typical book: it may have 300 pages, each page has 60 lines, and each line has 12 words. Therefore, one page contains about 4,000 bytes, and a book contains about 1,000,000 bytes or 1 megabyte. A television screen usually contains about 250,000 pixels. Thus it requires about 100,000 bytes to display a color picture on the television screen. This agrees with the old saying that a picture is worth 10,000 words. Figure 1 illustrates the amount of information contained in various common objects. Please note the use of a logarithmic scale.

Now I would like to explain why I propose to include seismograms in an international earthquakes data bank.

Importance of Seismograms

Seismograms are the basic observational records in seismology for studying earthquakes and the earth's interior. They are recorded at seismograph stations all over the world and are usually stored locally. Since seismic waves from earthquakes propagate throughout the earth without regards to national boundaries, seismologists face a potential problem when they wish to use seismograms recorded in other observatories to study earthquakes. In other words, seismologists need each other's seismograms, but currently seismograms are not easily accessible to them. This situation is very different from many other branches of sciences, where one could set up a laboratory and carry out his research without needing data from outside sources.

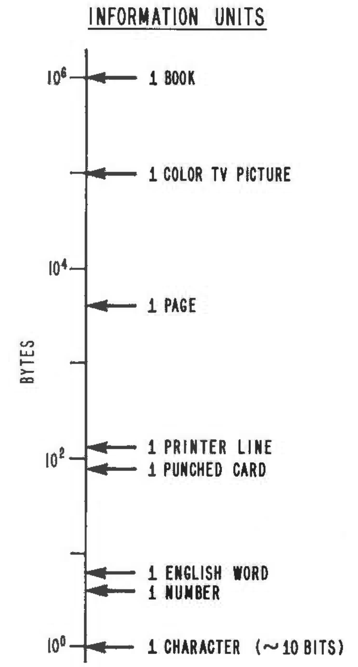

Fig. 1. Amount of information contained in various common objects.

Seismograms are not easy to copy because of their size (typically 30 cm by 90 cm) and fine resolution, and thus they are not readily available to others. Consequently, seismologists must spend large amounts of time and effort to collect significant sets of seismograms for their studies. Therefore, the inaccessibility of seismograms is the major bottle neck in earthquake research. This fact has been recognized for a long time, but little progress was made until the early 1960's. In 1963, the World-Wide Network of Standardized Seismographs (WWNSS) was set up by the United States, with over 100 stations covering a large part of the earth, and a scheme to copy and distribute WWNSS seismograms was implemented (OLIVER and MURPHY, 1971). The impact of WWNSS in seismology is astonishing. Because of easy access of WWNSS seismograms, great advances in seismology were accomplished within a few years. For example, WWNSS seismograms contribute directly to the development of the concept of plate tectonics, which revolutionized the earth sciences (see, e.g., SYKES, 1967; ISACKS, OLIVER, and SYKES, 1968).

Despite its great success, WWNSS includes only a small fraction of the seismograph stations in operation. For example, seismograms from stations in major countries, such as China and the USSR, and seismograms from local networks in the United States and many other countries remain relatively inaccessible. Furthermore, the WWNSS seismograms cover only the last 20 years, whereas instrumental seismology began nearly 100 years ago. In other words, the bulk of seismograms are still unavailable to seismologists. It does not make sense to have a global seismic data bank that does not contain a significant number of seismograms, the basic observational records of seismology. Therefore, I believe that we must make an effort to copy seismograms and include them as the first priority in any international earthquake data bank.

Classification of Earthquake Data

Although there are many different kinds of instruments monitoring earthquakes and related phenomena, the bulk of earthquake data are derived from seismograph stations. We may classify data associated with seismograph stations as follows:

(1) Level 0: Instrument location, characteristics, and operational details.

(2) Level 1: Raw observation data, i.e., seismograms containing the continuous signals from seismometers.

(3) Level 2: Earthquake waveform data, i.e., parts of the seismograms that contain seismic events.

(4) Level 3: Earthquake phase data, such as P- and S-arrival times, maximum amplitude and period, first motion, signal duration, etc.

(5) Level 4: Event lists containing origin time, epicenter coordinates, focal depth, magnitude, source parameters, etc.

(6) Level 5: Scientific reports describing seismicity, focal mechanisms, etc.

There are, of course, many different types of seismograph stations. We may broadly classify them into:

(1) Long-period (~10 sec) stations, primarily to record teleseismic events occurring, say, at 1,000 km or beyond.

(2) Short-period (~1 sec) stations, primarily to record local events occurring, say, within, 1,000 km or less.

(3) Strong-motion stations, to record nearby large events when they are triggered.

(4) Special arrays designed to improve signal-to-noise rations for monitoring nuclear explosions. Although these arrays are very interesting, we will not discuss them any further.

(5) Digital seismograph networks which became operational in the last few years (ENGDAHI *et al.*, 1982; Center for Seismic Studies, 1982).

I will not discuss them because many experts are now working on the data processing and analysis problems of the digital networks.

Amount of Earthquake Data

Let us now make some rough calculations on the amount of data we have. Let us consider the long-period stations first and let us make two estimates: the data we already have, and the data we are now collecting. Instrumental seismology began in the 1880's. Although very few of the early records survived, we may take, for a first approximation, T = 100 years as the total time period. At present, there are about 1,500 long-period stations. They were built up over the years, and we may take N = 500 as the average number of stations over the past 100 years. There are usually three records per day per station; and in one year, we have roughly R = 1,000 seismograms. Therefore, the total number of seismograms we have from long-period stations is approximately 50 million. Because of wars, fires, floods, and other disasters, we may have lost half of the seismograms. Thus, we may have 25 million seismograms to deal with or about 20 million seismograms prior to the WWNSS era.

Nearly all the existing long-period seismograms are in the analog form, i.e., we can see the seismic traces recorded on a piece of paper. If we use computers for processing, we must first digitize the seismograms. Long-period seismograms may be digitized at a data rate of 10 samples per second. The amount of digital data, equivalent to 25 million seismograms, is about 40 trillion bytes. If we digitize only the earthquake waveform, we have about 1 trillion bytes for the Level 2 long-period data.

We may estimate the corresponding Levels 3 and 4 data by noting that the ISC hypocenter file contains data on about 300,000 events. If we assume that each event has 100 stations reporting on the average, and each station contributes about 100 bytes of phase data per event, then the total Level 3 or phase data equal approximately 3 billion bytes. Since each event in the hypocenter file contains about 100 bytes of data, the total Level 4 or event list data equal approximately 30 million bytes.

Now, let us turn to short-period seismic data. Most short-period stations were set up in the last 20 years because of the popularity of microearthquake networks (see, e.g., LEE and STEWART, 1981). At present there are about 3,000 such stations and most of them are single-component seismographs. To estimate the amount of short-period data in existence, we may simply take T = 20 year, N = 1,000, and R = 400. Thus, approximately 8 million short-period seismograms exist. Since we have to digitize at a higher data rate (say, 100 samples per second) for short-period seismograms, the digital data equivalence is about 100 trillion bytes. If we consider only the earthquake waveform data, we may have about 1 trillion bytes.

The short-period seismic data are quite different from the long-period data. Although some short-period data are recorded just like the long-period data, the bulk of data are derived from microearthquake networks established in the last 20 years. In most microearthquake networks, data are recorded on microfilms and/or analog magnetic tapes which can be digitized by computers. Some microearthquake networks even record digitally.

To estimate the amount of phase data from short-period stations, I will take the total number of local events for the past 20 years to be approximately 1 million. If we assume about 20 stations reporting each event and each station contributes 100 bytes of phase data per event, then the total amount of phase data from short-period stations is approximately 2 billion bytes. Again, if we assume each local event contributes 100 bytes of data for the event list, then we have approximately 100 million bytes in the hypocenter file for local earthquakes.

As I know very little about strong-motion data, I will just make a few comments. Under UNESCO sponsorship, a group of experts in strong ground motion had met, and a feasibility study to establish a strong-motion data center had been made by BRADY (1975). The amount of strong-motion records and associated data are about 3 orders of magnitude lower than the long-period seismological data. Hence strong-motion data are relatively easy to handle.

To complete my discussion on earthquake data, I must add that the Level 0 data, i.e., data concerning station location and operation details, are rather small but very critical if we are to make any sence out of the seismograms. I estimate that each station may contribute 100 bytes of data per year. Thus, we have approximately 5 million byte for long-period sta-

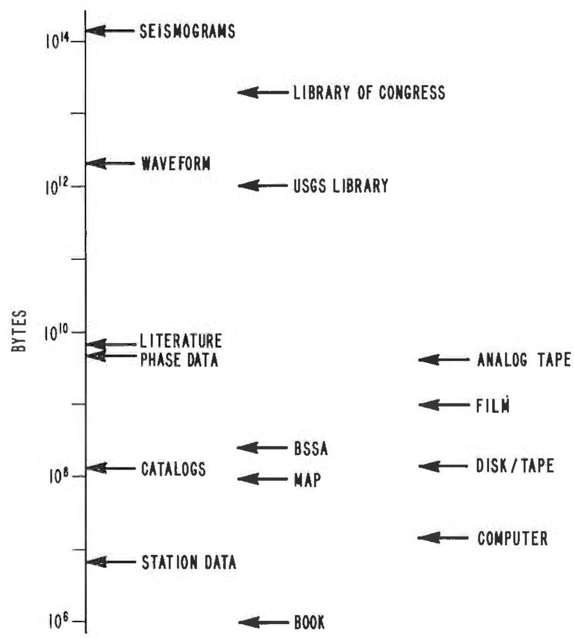

Fig. 2. Comparison of amount of earthquake data in various levels with that contained in existing libraries and computer storage media.

tions and 2 million bytes for short-period stations. Finally, the amount of scientific literature on earthquakes may be estimated from the amount already published in the Bulletin of the Seismological Society of America (BSSA) and the approximate share of BSSA in the Current Earthquake Literature (CEL) database. A total of about 60,000 pages have been published in BSSA so far. If we assume each page contains 4,000 bytes, then we have 240 million bytes for BSSA alone. The share of BSSA in the CEL database is about 5 percent, so the total indexed earthquake literature is approximately 5 billion bytes. To this amount, we must add about 5 billion bytes for stations bulletins and other materials which are not indexed in the CEL database. Thus the total amount of earthquake literature is approximately 10 billion bytes. If one reads 200 words/minute, 8 hours a day, 5 days a week, then one can read about 144 million bytes a year. Thus, it would take 1.7 years of reading to go over BSSA once, and about 70 years to read the total earthquake literature.

To sum up, we may illustrate the amount of earthquake data in various levels in Figure 2, and compare them with the amount of information contained in existing libraries and computer storage media. It is interesting to note that the amount of information contained in existing seismograms greatly exceeds that contained in one of the world's largest library, i.e., the U.S. Library of Congress.

Because I scale the existing data from the present situation by choosing approximate scaling factors, I can quickly obtain the current annual output of earthquake data. The results are given in Table 2. I would like to propose an international earthquake data bank which includes, as much as possible, all the data listed in Table 2. The question is then can such a data bank be implemented using current data processing technology. I will examine this question next.

Table 2. Amount of earthquake data

		EXISTING AMOUNT (bytes)		CURRENT ANNUAL OUTPUT (bytes)	
LEVEL	TYPE	LONG-PERIOD	SHORT-PERIOD	LONG-PERIOD	SHORT-PERIOD
0	Station data	5×10^6	2×10^6	2×10^5	3×10^5
1	Raw data	4×10^{13}	1×10^{14}	1×10^{12}	2×10^{13}
2	Waveform data	1×10^{12}	1×10^{12}	3×10^{10}	2×10^{11}
3	Phase data	3×10^9	2×10^9	1×10^8	3×10^8
4	Hypocenter data	3×10^7	1×10^8	1×10^6	2×10^7
5	Papers & bulletins	1×10^{10}		4×10^8	
Equivalent seismograms		25 million	8 million	1.5 million	1.2 million
Time period		100 years	20 years	1 year	1 year

CURRENT DATA PROCESSING TECHNOLOGY

We will first examine some typical rates of processing information. We get a pretty good estimate of the human procession rate by asking how fast we can read or write. The reading speed for a human being is typically 200 words per minute or 20 bytes per second. A typist clerk is usually required to type 50 words per minute; thus our writing speed is no better than 5 bytes per second. Let us now tabulate some typical processing rates for machines and compare them to those of a human in Table 3.

It is clear from Table 3 that if we have large amount of data to be processed and analyzed, we must rely on machines. At present, a large computer can process over several trillion bytes of data per year. We, however, cannot assimilate more than a few million bytes of information. Even if the relevant information is present in our data, it is not clear that we will be able to extract it, although interactive computer graphics (e.g., FOLEY and VAN DAM, 1982)

Table 3. Some typical processing rates of human and machines

	Processing rate (bytes/sec)
Human	~ 10
Punched card machine	~ 10^3
Line printer	~ $2x10^3$
Micro-computer	~ 10^5
Tape drive	~ $2x10^5$
Disk drive	~ 10^6
Mini-computer	~ 10^6
Main frame-computer	~ 10^7
Super computer ·	~ 10^8
Speed of light limit	~ 10^9

Table 4. Comparison of various storage media

STORAGE MEDIA	INFORMATION DENSITY (Kilobytes/cm^3)	INFORMATION PER UNIT STORAGE (megabytes)	COST PER MEGABYTE (U.S. $)
Punched card (1 box)	0.03	0.16	$ 60
Book	1	1	30
800 BPI magnetic tape	15	15	1
Computer memory chip	16	0.06	25,000
Standard seismogram	50	1.7	0.6
Microfilm of text	60	12	1
6250 BPI magnetic tape	150	150	0.1
High density disk	200	500	50
Microfilm of seismogram	500	1000	0.01
Analog magnetic tape	800	4500	0.02
Geologic map	1000	100	0.01

will help. The problem is human limitations and not computers.

Let us now examine different ways of storing information. I know roughly how many bytes each unit of storage medium can hold. In order to make comparison, I need to compute the information density for different storage media, so I just measure their physical sizes. The results are tabulated in Table 4 and illustrated in Figure 3. It is clear that microfilms and high density magnetic tapes are compact in size and economical. This is precisely what we are practicing. It is also interesting to note that recording in analog form is far more efficient than in digital form. This confirms the old saying that pictures are worth more than words. Unfortunately, analog data cannot be directly processed by computers.

As I said earlier, modern large computers have a processing rate of the order of 10 million bytes per second, or roughly 10 MIPS (millions of instructions per second). There are roughly 30 million seconds per year, so a large computer can execute about 300 trillion instructions in a year. The amount of raw seismic data we are now producing is of the order of 10 trillion bytes per year. Although several or several tens of instructions are needed to process each

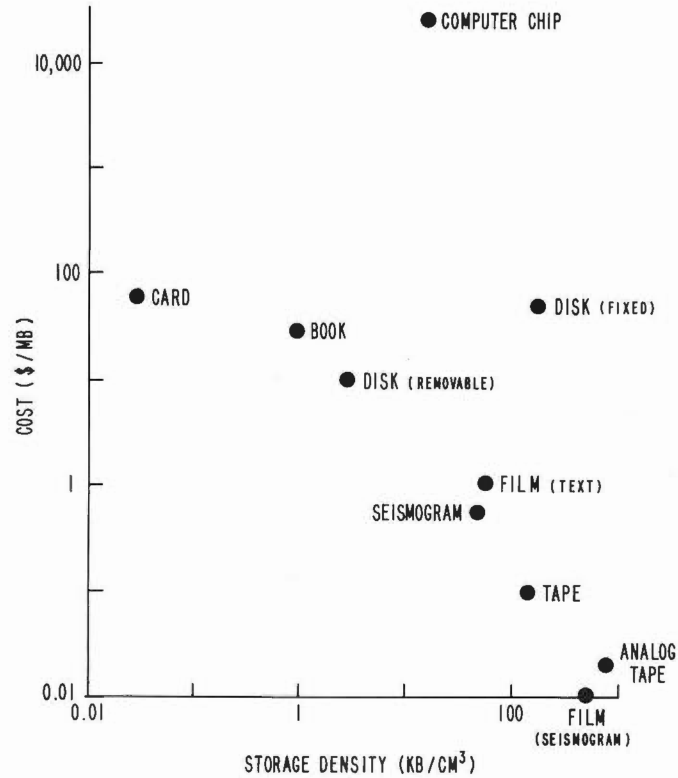

Fig. 3. Cost of various storage media versus their storage capacity.

data point, we can process our data with a large computer. In reality, we do not process data in a central place. If we note that mini-computers, or at least the super mini's, have rates on the order of 1 million of instructions per second, we will need at least one mini to process data from a typical network of about 100 stations. So we can now process our raw data at about the rate it accumulates. However, we are a little short on storage technology, especially if we wish to put all the past raw earthquake data on computers for processing.

In summary, the current data processing technology is capable of handing all our earthquake data if we use it wisely. Seismograms and literature are best stored on microfilms. Waveform data, phase data, and event lists are best stored on magnetic tapes and disks so that they can be readily accessible and to be processed by computers.

ACTIVITIES FOR CREATING AN INTERNATIONAL EARTHQUAKE DATA BANK

As I said earlier, we should not wait for a multi-million dollar funding to begin an international earthquake data bank. In the last 5 years, I have tried very hard to carry out a few projects that may contribute to the creation of an international earthquake data bank. I would like to report to you the progress so far.

Historical Seismogram Filming Project

Instrumental seismology is nearly 100 years old, while WWNSS seismograms cover only the last 20 years. Naturally, it is very desirable to consolidate the seismograms collected before the WWNSS era (i.e., prior to 1963). The Historical Seismogram Filming Project directly addresses this problem (UNESCO 1981), and a personal history of this project has been given by LEE (1982). This project is being carried out under the scientific guidence of a joint IASPEI/UNESCO Working Group on Historical Seismograms. The importance of historical seismograms for geophysical research has been discussed by KANAMORI (1982).

It costs approximately 1 U.S. dollar to microfilm a seismogram. Because of financial limitaions, only a few percent of existing seismograms will be filmed. The Working Group has adopted a strategy that carries out two types of filming: (1) all seismograms at about 20 selected stations around the world will be filmed chronologically, and (2) seismograms of about 2,000 selected earthquakes will be filmed at as many stations as practical. For the past 4 years, about 400,000 seismograms from U.S. stations have been copied under this project (MEYERS and LEE, 1979; GLOVER, 1980; GLOVER and MEYERS, 1981; and MEYERS, 1982). We intend to build up a microfilm library of a few million seismograms which were recorded prior to 1963. Such a library will be a major component of an international earthquake data bank.

As the task for filming the selected U.S. seismograms are drawing to a close, the Working Group is now considering filming seismograms in other contries. In particular, the Workong Group held a workshop at the Earthquake Research Institute of the University of Tokyo from December 20–22, 1982 to discuss filming seismograms from Asian observatories (IASPEI/UNESCO Working Group on Historical Seismograms, 1983). A similar workshop will be held during the IUGG General Assembly in Hamburg, August, 1983, to consider the European and Latin American seismograms.

It is important to recognize that the Historical Seismogram Filming Project can not succeed without international cooperation. The IASPEI/UNESCO Working Group on Historical Seismograms, urges every nation to join in this project. We believe that this task is critical as clearly stated by a resolution of the IASPEI General Assembly in 1977:

> "Noting that seismograms recorded at observatories around the world are basic for research on earthquakes and the structure of the Earth and that many of the early seismograms have been lost in war, though natural hazards and deterioration and, therefore, it is essential that seismograms of significant earthquakes be systematically collected and preserved by making photographic copies at observatory sites, and be made available through the World Data Centres. IASPEI urges that seismological observatories around the world cooperate with a copying programme by providing access to historical seismograms to be photographed on site and by preparing supporting observatory data to accompany the copies."

Seismograph Bulletins Microfilming Project

Many seismograph stations publish bulletins which describe instrumentation characteristics, report phase data, and summarize observational results. Thus station bulletins contribute directly to Level 0, 3, and 4 data as described in the subsection on classification of earthquake data previously. Although the *International Seismological Summary* (1913–1963) and the Bulletins of the *International Seismological Center* (1964-present) summarize many obsrvations made by seismograph stations throughout the world, this effort is by no means complete. For example, in their classic work on the seismicity of the earth, GUTENBERG and RICHTER (1954) made extensive use of station bulletins.

The Working Group on Historical Seismograms recognized the importance of seismograph station bulletins, and has initiated a systematic microfilming of these bulletins. This work is under the direction of Robert Herrmann of the St. Louis University, using primarily the collection of the Jesuit Seismological Association. We intend to supplement this effort with collections of the World Data Center A and the New Zealand Seismological Observatory. We also hope that, with helps from others, we will be able to microfilm a nearly complete collection of all existing seismograph station bulletins. We estimate that we will microfilm approximately 500,000 pages of station bulletins. We believe that these materials will greatly facilitate the use of historical seismograms and provide data for relocation of earthquakes and improved determination of earthquake magnitudes. A microfilm library of seismograph station bulletins will also be a major component of an international earthquake data bank.

Current Earthquake Literature Database

In the last 20 years, there has been a great increase of earthquake literature. Part of the reason is that funding for earthquake research has increased. But another important factor is the "publish or perish" policy. In the United States, funding for research is mostly through submission of proposals on yearly basis. Emphasis is thus placed on short-term projects that yield published results quickly.

With the rush to print, it is not surprising that most published papers are rarely used by anyone, and that no one has the time to read the increasingly thick journals. The *Institute of Scientific Information* (1961-present) in Philadelphia, U.S.A., has been publishing the Science Citation Index for about 20 years. The average annual number of citations for a given cited paper is less than two. This means that most existing papers are not referenced at all. I did a citation analysis for solid-earth geophysics some 14 years ago (LEE, 1968), and found the following:

(1) About 50 percent of the citations refer to works published within the last 4 years, and over 75 percent within the last 10 years. I suspect that few authors bothered to look up older literature as literature searching becomes more and more tedious as one goes back in time.
(2) During a 2-year period, 75 percent of the cited articles received only one citaion, often by the same author; 12 percent received two citations; and only 1 percent of the cited articles received over 10 citations.

Becasue I was not happy with the existing indexing services, I launched in 1978 the Current Earthquake Literature (CEL) database, which was quite different from those already available (GUNN, ADDIS and LEE, 1979; GUNN, HAYASHIDA, and LEE, 1980; HAYASHIDA, KAUFFMANN, and LEE, 1981, 1982). Unlike the Bibliography of Seismology (*International Seismological Center*, 1965-present), CEL database included preprints and was current, not 1 or 2 years behind. Unlike the Bibliography and Index of Geology or Georef (*American Institute of Geology*, 1961-present), we did not index any meeting abstracts. Furthermore, we had on file a copy of every paper which we indexed. Most novel of all was the fact that we only indexed papers that were considered useful by at least one seismologist or geologist. This person could be the auther himself. The reasoning was that, if no one recommended it, and the author himself did not recommend his own work, then why should we bother to index it at all. In practice, some 100 geoscientists collaborated and we also included papers that were recently submitted to journals. Over a 4 1/2-year period, we built up a database of over 10,000 items. For example, let us compare the 1981 results (the latest figure available for ISC is for 1980):

	CEL	ISC	GEOREF
Time Lag	0–6 months	1–2 years	6 months–1 year
Seismological item	~3,500	~1,600	~1,700 (including ~500 abstracts)

As you recall, over 50 percent of citations in my study refer to works published within the last 4 years. I was just past the critical half-way mark when I was told that CEL had to be terminated due to lack of funding. Despite the present setback, I do believe that we must index earthquake literature on computers, and to microfilm them systematically so that the information becomes easily accessible. A computerized earthquake literature database must be a part of an international earthquake data bank.

Let me illustrate the economics and saving of space of microfilmed literature. A few years ago, I persuaded the Seismological Society of America (SSA) to microfilm all its bulletins (BSSA). Now you may purchase the complete set of BSSA on microfiche for about $250 and put them in one large shoe box. A set of regular BSSA costs about $5,000, but you cannot purchase it easily—SSA does not have a complete regular set for sale, and the regular set will take up one regular size bookcase. Basically, you save a factor of about 20 in cost and a factor of about 60 in space. If we managed to put all earthquake literature on microfilm, it might cost about $10,000 to own a set and would take up no more room than a regular bookcase or two. Even if my estimate is off by a factor of 2 or 3, I think most institutions and even some individuals could afford to own and store the complete set of earthquake literature on microfilm. I do believe that by having the existing literature at everyone's fingertips it would greatly improve the quality of research, especially for seismologists in developing countries.

Archiving and Retrieval of Earthquake Data

As I said earlier, we must rely on machines to process the earthquake data. Although modern computers are capable of handling the data, it is still not easy to obtain any particular data set that one wishes. First, there are too many different types of computer hardware and software so that it is not easy for one computer to communicate with another. Second, most data sets are not documented and are not centralized. Third, no uniform standards have been accepted in the seismological community so that earthquake data exist in many different formats. Worse yet, we don't even agree on some of our measurement conventions. For example, the maximum trace amplitude on a seismogram, which is often used to determine the earthquake magnitude, may be measured from peak-to-center or from peak-to-peak.

It is a myth that if we have the computers, then our data processing and analysis problems will go away. Computers can be of great help, but they can also be a great liablity. It is interesting to note that one of the computer pioneers has recently published a book emphasizing a pencil and paper approach. This is what TUKEY (1977, p. 663) said:

"Today the world is going through a process of computerization that is culturally rapid but humanly show. . . . This book focusses on paper and pencil. . . . Some would say that this is a step backward, but there is a simple reason why they cannot be right: Much of

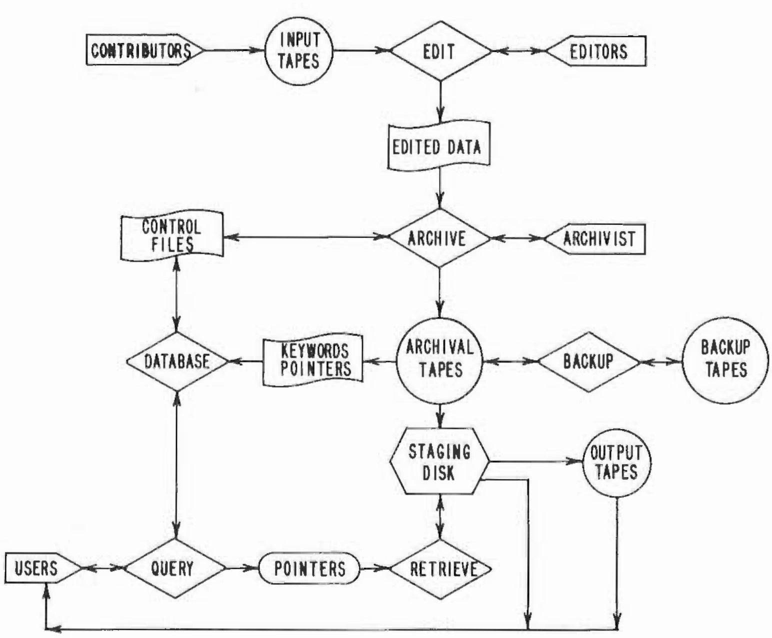

Fig. 4. Overall scheme for organizing earthquake-related data.

what we have learned to do to data can be done by hand—with or without the aid of a hand-held calculator—LONG BEFORE one can find a computing system—to say nothing of getting the data entered. It will be a long time until this fails to be so. . . ."

I think Tukey has pointed out the major difficulty in using computers, namely, how to get the data in and out of computers. With the help of a physicist and a database expert, I have designed a computer-based system to archive and retrieve earthquake data. The overall scheme is illustrated in Figure 4. This system has many distinct features: (1) the system is modular in design, i.e., it is made up of several independent components, (2) the system can create and maintain several independent data libraries, (3) data are transferred in set or sets, and (4) data sets are indexed by keywords, so that users can query and retrieve the full data set(s) from archival tapes. This system has been developed (LEE, SCHARRE, and CRANE, 1983), and is now being tested with actural earthquake data. Like the literature database, a computer-based system for archiving and retrieval of earthquake data must also be an important part of an international earthquake data bank.

CONCLUSIONS

I have taken a rather unusual path in helping to organize an international earthquake data bank. To me, such a bank should include every level of earthquake data, from raw observations to finished scientific papers. Although the primary goal is to develop accurate and homogeneous earthquake catalogs, I do believe that it is very important to have all the necessary materials organized first. Implementation of this organizational task is technically feasible and can be accomplished in one to two decades. So far, the Historical Seismogram Filming Project has copied about 400,000 seismograms on microfilm, approximately 20 percent of the intended seismogram library. The bulk of existing seismograph station bulletins (about 300,000 pages), which accounts for about 1/3 of all the earthquake literature, has also been microfilmed. In a related effort, the Current Earthquake Literature database contains over 10,000 papers of the last 5 years, and a computer-based archiving and retrieval system has been developed that is potentially capable of handling all the existing earthquake data, if in digital form. After the critical earthquake data have been organized for easy accessibility, I believe that the progress towards accurate and homogeneous earthquake catalogs can be rapid.

Although we have a good start towards implementing an international earthquake data bank, much remains to be done. I hope with your help that progress will be rapid and that a truly international earthquake data bank will materialize soon. In particular, I would like to urge you to do the following:

(1) Encourage your country to join and support the Historical Seismogram Filming Project and related activities.
(2) Encourage your scientists to contribute data and to work on data standards, and
(3) Support the concept of an international earthquake data bank, and help enlarge the International Seismological Center and/or World Data Centers to operate and maintain an international earthquake data bank.

Acknowledgements

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Excavation Survey of Active Faults for Earthquake Prediction in Japan—with Special Reference to the Ukihashi Central Fault and the Atera Fault

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ABSTRACT

The trench excavation survey plays a very important role for revealing the detailed movement history of active faults in Japan. The Geological Survey of Japan (GSJ) started a new comprehensive study of active faults from 1979 as a part of the Five -Year Program of the Japanese Earthquake Prediction Project and is carrying on the trench survey as one of the main items of the project.

GSJ excavated the Ukihashi central fault in 1980 and the Atera fault in 1981. The Ukihashi central fault is one of the southern portion of the Kita-Izu fault system which caused the Kita-Izu earthquake of 1930 (M. 7.0). It is inferred from the excavation that the recurrence interval of the Ukihashi central fault is 3000–4000 years. The Atera fault is one of the most active faults in central Japan which extends 80 km along the NW-SE strike with left lateral slip with northeastern upheaval component. From the excavation survey the Atera fault is estimated to have repeated the movements with 2000–3000 years recurrence interval since 12,000 B.P. Judging from its long recurrence interval and high long-term slip rate, it is suggested that the Atera fault has a high potential of causing great earthquakes with the lateral displacement of 6–15 m. Through these excavation surveys, we will be able to acquire many basic information for the Earthquake Prediction Project in Japan.

INTRODUCTION

By means of recent intensive geological and geomorphological studies of active faults, we had obtained a large amount of knowledge about distribution and long-term slip rate of active faults of Japan, but further studies are required to predict the approximate time and magnitudes of forecoming earthquakes to be produced by slip on individual faults. Generally speaking, the recurrence interval of active faults in Japan is much longer than our historical time. Accordingly, most active faults have no historical records of seismicity.

Surface deformations like extension fractures, pressure ridges, flexures, deformation of soft sediments and sand blows are often found along surface faults associated with earthquakes. In some conditions, those are well preserved in the Holocene strata as geologic records. Therefore, the investigation of Holocene sediments along active faults provides valuable information on their displacement history. Trench excavation survey across the fault is a direct approach to reveal the events of prehistorical earthquakes.

CLARK *et al.* (1972) obtained many prehistoric evidences of faulting from trenches across the San Jacinto fault which displaced during the 1968 Borrego Mountain earthquake. By excavation across the San Fernando segment of the Sierra Madre fault system which moved during the 1971 San Fernando earthquake, BONILLA (1973) recognized previous events. SIEH excavated several trenches across the San Andreas fault at Pallet Creek and revealed prehistoric earthquakes with a 160 year average recurrence interval (SIEH, 1978).

The first trench excavation survey in Japan was attempted at the Tachikawa fault by the Geographical Survey Institute (GSI) in 1977. The Tachikawa fault has dislocated the Musashino

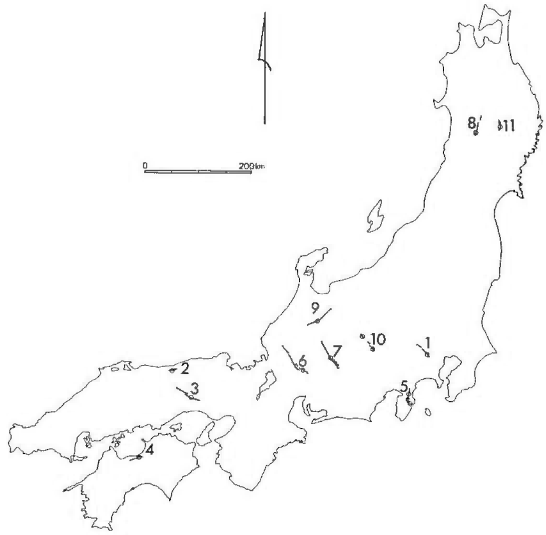

Fig. 1. Excavated active faults and trench sites (open circles) in Japan. 1: Tachikawa fault, 2: Shikano fault, 3: Yamasaki fault, 4: Median Tectonic Line (Hatano fault), 5: Kita-Izu fault system (Tanna fault, Ukihashi central fault, Himenoyu fault), 6: Nobi fault system (Umehara fault), 7: Atera fault, 8: Senya fault, 9: Atotsugawa fault, 10: Itoigawa-Shizuoka Tectonic Line, 11: Urata fault.

upland in the Western suburbs of Tokyo with 20 km in length and 0.3 m/1000 yr. of vertical slip rate (YAMAZAKI, 1978). In 1978, the Shikano fault associated with the Tottori earthquake (M. 7.4) of 1943 was excavated (OKADA *et al.*, 1981). In 1979 they also excavated the Yamasaki fault in Hyogo prefecture (OKADA, *et al.*, 1980), which is the main study field for the earthquake prediction in western Japan where many kinds of geophysical observation have been performed.

Since the excavation survey was adopted as an item of the 4th Five-Year Program of Japanese Earthquake Prediction Project in 1979, the Geological Survey of Japan (GSJ), Kyoto University and Earthquake Research Institute of Tokyo University conducted the trench survey every year. During this project, the Tanna fault (MATSUDA *et al.*, 1982), the Nobi fault system (OKADA *et al.*, 1981), the Senya fault (MATSUDA *et al.*, 1983) and the Atosugawa fault (The Research Group of the Atotsugawa Fault, 1983) were excavated. Figure 1 shows 11 excavated active faults in Japan. The Senya fault, the Itoigawa-Shizuoka Tectonic Line and the Urata fault are vertical slip type faults and others are strike slip type faults. GSJ excavated the Ukihashi central fault of the Kita-Izu fault system in 1980 and the Atera fault in 1981. These two cases are reported in this paper.

TRENCH EXCAVATION SURVEY OF ACTIVE FAULTS

Surface phenomena caused by major fault movement, like minor fault scarplets, undulation, open cracks, deformation in soft sediments and sand blows are sometimes well preserved in the sedimentary record. Therefore, in a trench exposure, termination of secondary faults at distinct levels within the stratigraphic section, remnants of open cracks, and deformation and unnatural thickness change of sediments are good indicators of past events.

The result of excavation survey depends on site conditions. Favourable sites for excavation are as follows,

(1) Where Holocene deposits with accumulation of peat, wood remains and wide spread

air fall ash layers exist for the chronological study of the fault movements.

(2) Where detailed information of the fault trace already exsists. We must find the fault trace within the zone of 30 m for trenching.

(3) Where sufficient open space to conduct the trench open work can be utilized.

Because of high rate of depositional process due to the climatic condition in Japan, the deformed strata and tectonic landforms caused by earthquakes are rapidly covered by the overlying deposits and are preserved in the depositional region. The natural conditions in Japan are advantageous for detailed studies of faulting from the deformed sediments compared with arid regions where it is difficult to find a radiocarbon dating sample.

The Ukihashi Central Fault

This fault is one of the southern segment of the Kita-Izu fault system which caused the Kita-Izu earthquake of 1930 (M. 7.0). Along this segment, surface faults are observed with 1 to 2 m left lateral displacement and slight vertical displacement. The Kita-Izu fault system traverses the northern half of Izu-Peninsula in N-S direction (Fig. 2) and shows left lateral movement with long-term slip rate of 2 m/1000 years since about 500,000 years ago. Trench site is located at the western margin of the small Ukihashi basin. The trench was excavated in T-shape to observe the three dimensional pattern of the fault trace (Fig. 4). A Power shovel

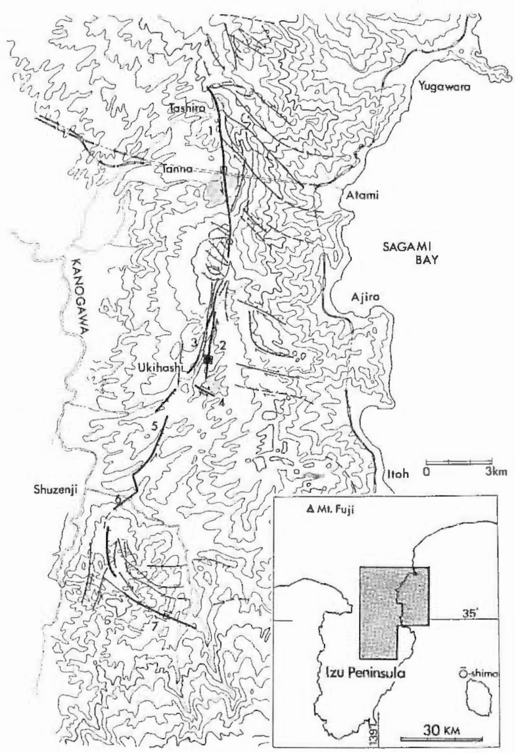

Fig. 2. Index map of the Kita-Izu fault system and location of trench sits. Thick lines indicate the earthquake fault of 1930 (Matsuda, 1972) and thin lines show active faults which did not move at the earthquake. ▣: Trench site of Ukihashi central fault. □: Trench site of Tanna fault by Earthquake Research Institute. ○: Other trench sites at Osawa-ike and Himenoyu by GSJ. 1; Tanna fault (sinistral) 2; Ukihashi central fault (sinistral) 3; Ukihashi-west fault (sinistral) 4; Tawarano fault (dextral) 5; Ono fault (sinistral) 6; Kadono fault (sinistral) 7; Himenoyu fault (dextral).

Fig. 3. Trench opening work at Ukihashi.

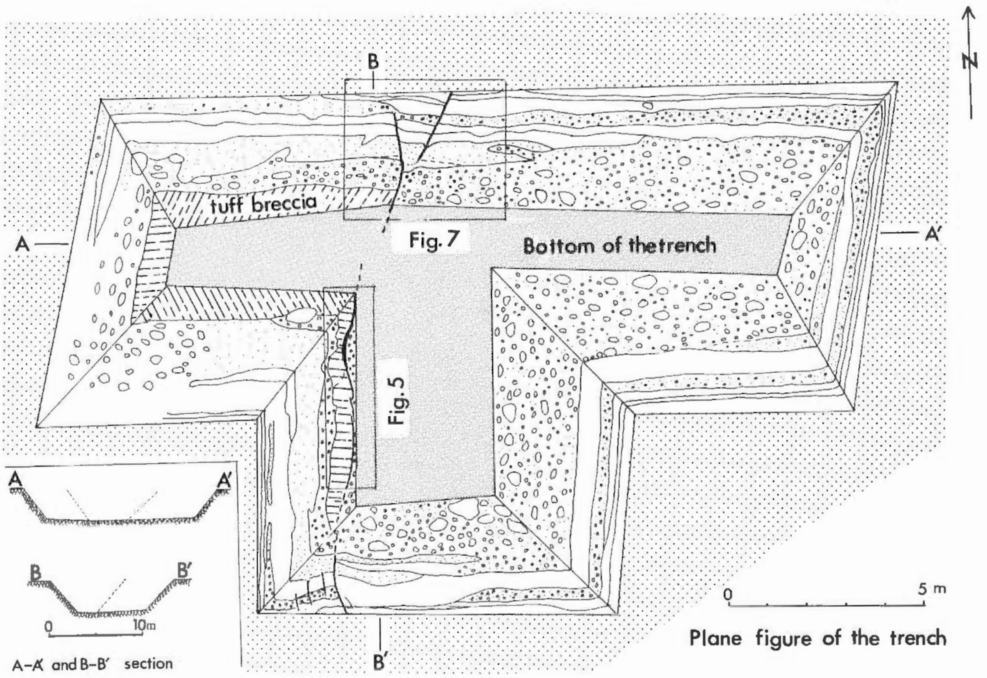

Fig. 4. Shape and size of the trench at Ukihashi.

and a bulldozer were used for the excavation (Fig. 3). Length and depth of the trench were 20 m and 3 m.

The western side of the fault consists of tuff breccia of the Taga volcano (middle Pleistocene) and thin fluvial deposits and the eastern side of the fault consists of thick fluvial deposits including many boulders.

Figure 5 shows the horizontal fracture pattern near the bottom of the trench. En-échelon arrangement of minor faults indicates a left-lateral slip motion. The width of the fault gouge changes from a few mm to 20 cm. The grain size of materials in the gouge is the finest on the tuff breccia side and becomes larger to the gravel side (Fig. 6). This grain size distribution indicates that the fault gouge is created *in situ* according to the experimental studies (ENGELDER *et al.*, 1975; LOGAN and SHIMAMOTO, 1976) and the fault had moved repeatedly

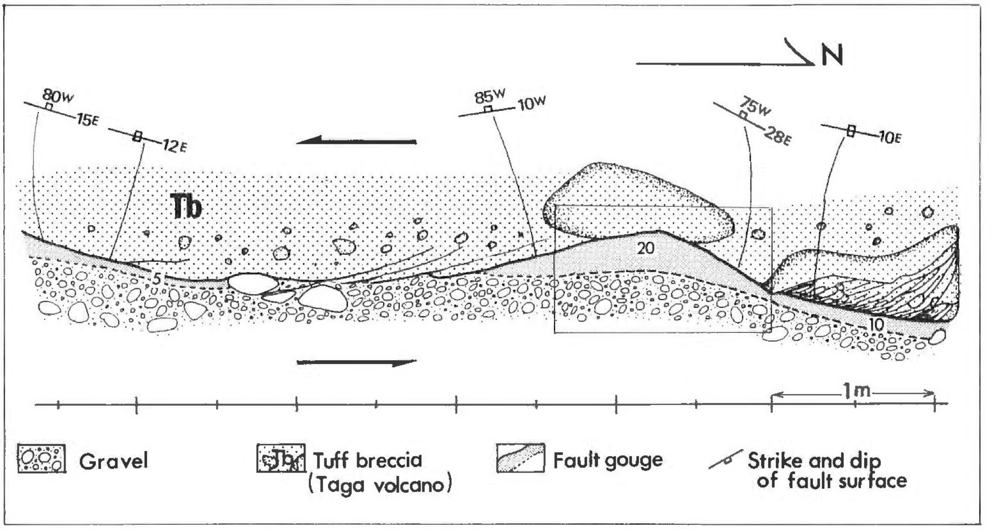

Fig. 5. Shear zone between tuff breccia and fluvial gravels at the bottom of the trench. Location of this figure is indicated in Figure 4.

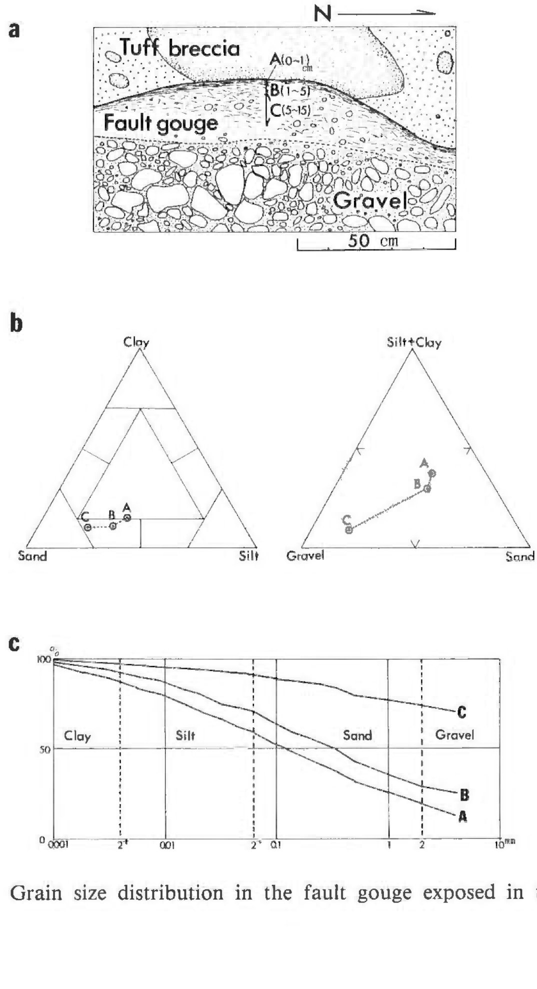

Fig. 6. Grain size distribution in the fault gouge exposed in the trench.

to create the 20 cm fault gouge. A slickenside with low-angle striation is observed on the surface of tuff breccia-fault gouge interface.

The detailed observation of the north wall is shown in Figure 7. A thick shear zone of the lower part of the wall and overlying faulted layers were observed. The shear zone has a N20°E strike and 80°W dip. The main fault in the lower part of the trench splits into two breaks in the upper part. The western break offsets the fine sand (C), charcoal rich layer (D), tuffaceous sand (E) and pebble layer (F), but this break does not displace the overlying layers (G, H, I, J). Layer (G) and (H) are air fall sediments and are believed to have burried and flattened the fault scarp which developed after the movement of western fault. The layer (H) is contained the pumice fall which is called Kawagodaira pumice erupted from the Amagi volcano in 2.900 B.P., and the charcoal rich sediments (D) is dated as 4.670 B.P. by radiocarbon dating. Therefore, it is estimated that the western break occurred in the period between 4.600 and 2.900 B.P.

The eastern break displaces all layers including layers (H) and (I), but not layer (J) which is the present paddy field soil. Because we cannot find any other breaks cutting layers (H) and (I) in this trench and it is without doubt from the record that surface break of 1930 appeared in this trench site, it is inferred that the eastern break indicates the tectonic event of 1930. The layer (I) is assumed to be the old soil of paddy field before the earthquake of 1930.

We distinguish two events of earthquakes caused by this fault, that is, the event of 1930, and between 4600 and 2900 B.P. These data imply that the recurrence interval of the Ukihashi Central fault is roughly 3000 or 4000 years.

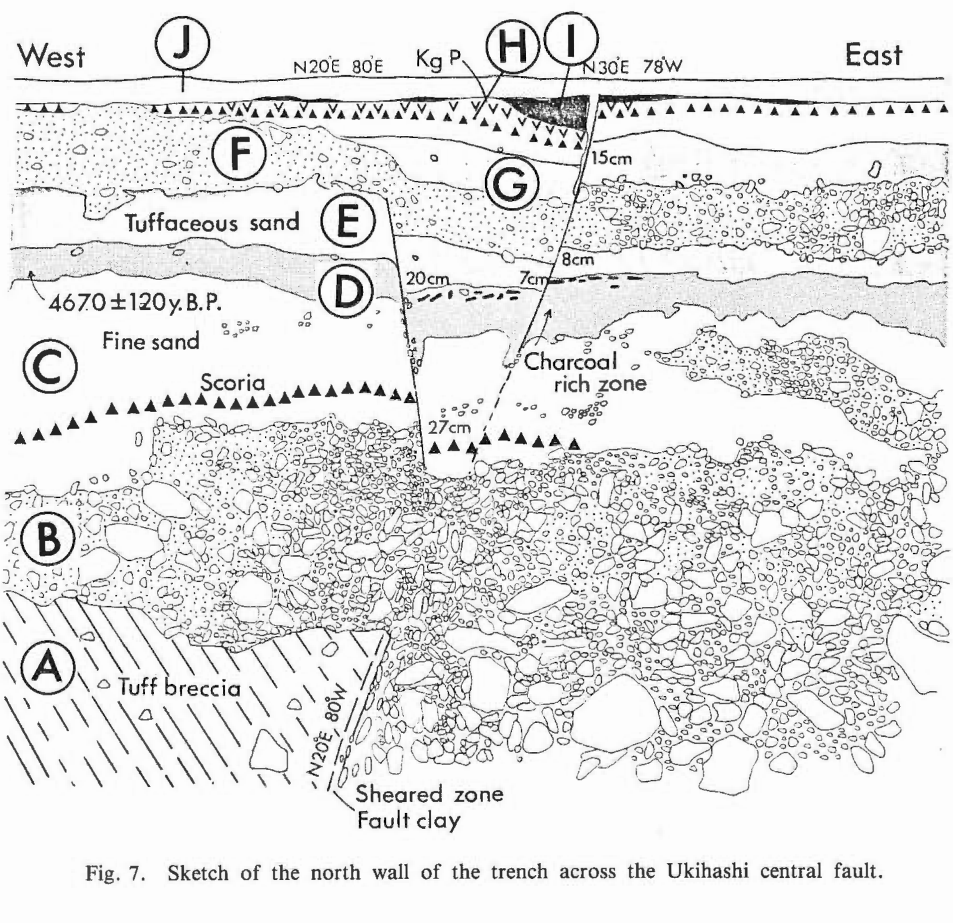

Fig. 7. Sketch of the north wall of the trench across the Ukihashi central fault.

Besides this trenching, the Kita-Izu fault system were excavated in the Tanna basin in 1980 and 1982 by the Earthquake Research Institute. From the evidences obtained from this work, the recurrence interval of earthquake along the fault is estimated to be 700–1000 years during the past 7000 years (MATSUDA *et al.*, 1982; The Tanna Fault Trenching Research Group, 1983). The difference of the recurrence time between these two faults in the same fault system may be due to that of mechanical implication of those faults in the system. That is, the Tanna fault is the central main fault and the Ukihashi fault is a branch with much lower fault activity. According to TCHALENCO (1970), Tanna fault is a principal displacement shear and Ukihashi central fault is a Readel shear. In another words, roughly speaking, it can be said that while central main fault ruptures three times in about 3000 years, this branch fault does only once. In the eastern part of the Kita-Izu fault system, there are many right-lateral slip faults with NW-SE strike which are conjugate Readel shears (Fig. 3). They did not move at the time of the earthquake except for the Tawarano fault to the south of Ukihashi central fault and the Himenoyu fault in the southern end of the fault system. Although a long-term behavior of these dextral faults is not sure up to now, it could be said mechanically that they also have lower activity than a principal displacement shear. More trench studies will be necessary to picture the whole Kita-Izu fault system.

The Atera Fault

The excavation of the Atera fault was conducted in 1981 (TSUKUDA and YAMAZAKI, 1982). The Atera fault, which dissects central Japan with a NW-SE strike and is 80 km long (Fig.

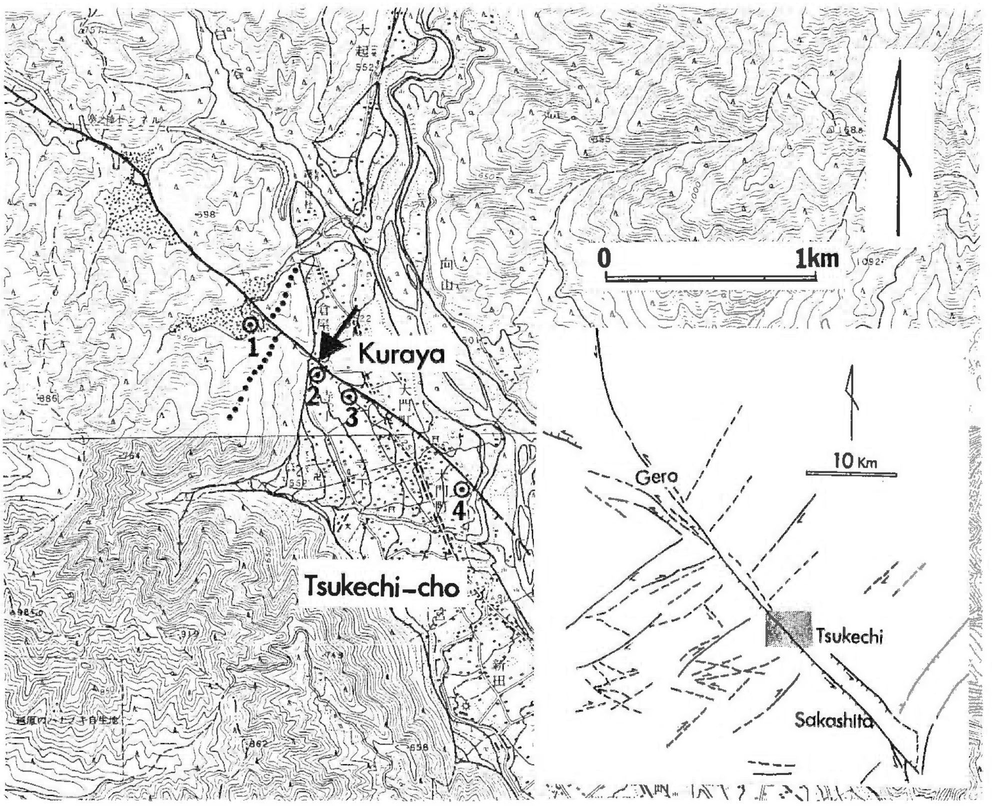

Fig. 8. Index map of the Atera fault. Arrow shows the trench site and dotted circles show sites of boring.

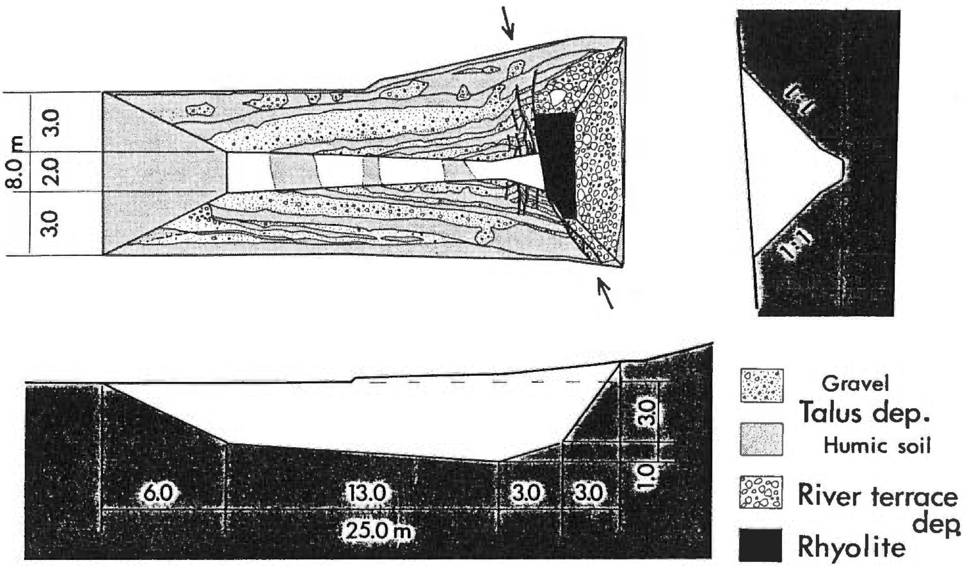

Fig. 9. Shape and size of the exploratory trench across the Atera fault at Kuraya, Tsukechi-cho. Arrows indicate the principal break of the Atera fault.

Fig. 10. Trench exposure at Kuraya.

8), is one of the most active faults in Japan. The fault shows left lateral slip with northeastern upheaval component. The long-term slip rate of left lateral and vertical components are estimated to be 3 or 5 meters and 0.6 or 1 m in a thousand years respectively from the displacement of the Kino river terraces (SUGIMURA and MATSUDA, 1965; HIRANO and NAKATA, 1981). In spite of this extraordinary high slip rate, there are no records of historical great earthquakes from this fault.

We can recognize the obvious fault scarplet on the river terrace at Tsukechi-cho, Gifu prefecture, which is the central part of the fault. Our trench site is located on the northern end of this scarplet. We found a suitable flat place for trench survey, where the fault scarplet is covered and flattened by talus deposits.

The trench is 25 m long and 8 m wide (Fig. 9). The height of the wall reaches 8 m in the deepest part. The principal break zone is exposed at the northeastern part of the trench. Completely different geologic units are exposed on both sides of the fault (Fig. 10). Sediments on the northeastern side of the fault consist of boulder layer of the river terrace and basement rhyolite. On the other hand, the talus deposits of the layered coarse and sandy humic soil

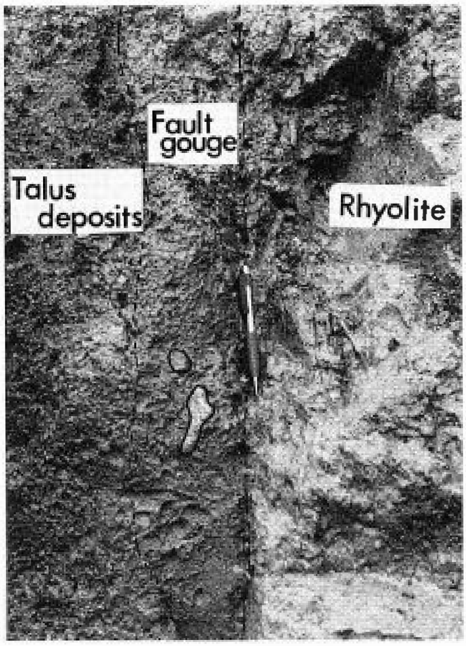

Fig. 11. Shear zone of the Atera fault in the trench.

are exposed on the southwestern side of the fault.

The shear zone of the principal fault strikes N40°W. The fault gouge is about 20 cm wide (Fig. 11). Some boulders derived from the terrace deposits are involved in the shear zone.

Figure 12 shows detailed stratigraphic sequences of the trench walls. Several minor faults occur in the talus deposits. We can see the obvious fault trace and well bedded strata on one side of the fault. Because of the vertical displacement we could not find corresponding sediments on the other side. Accordingly, it is not so easy to estimate directly the age of the major fault movement. But, we could recognize the remnants of open cracks. A distinct level of "open cracks" must be a past ground level during a great tectonic event. These levels are in accord with termination levels of these secondary faults. Figure 13 shows the data of the radiocarbon dating of the layered talus deposits and the termination levels of the minor faults with solid cirlces. The obvious concentration of the solid circles at several levels suggests that the movements of the major fault occurred at these ages. A possible model of fault development is illustrated in Figure 14 which shows that minor faults have developed in front of the major fault below the surface and did not moved repeatedly. This developing pattern of minor faults closely resembles that of the Atotsugawa fault exposure (The Research Group of the Atotsugawa Fault, 1983).

We can distinguish at least 4 events of fault movements, that is, 12,000 B.P., 10,000 B.P., 6,500 B.P. and younger than 5,500 B.P. Because of artificial modification of the ground surface, we could not determine the ages of the events younger than 5,500 B.P. These estimated ages of the events are different from those of Hirano and Nakata (1981), in spite of almost the same recurrence interval. A further survey will be necessary before we come to final decision.

In summary, it is inferred that the Atera fault has moved with the interval of 2,000 or 3,000 years repeatedly since 12,000 B.P.

This long recurrence interval and high long-term lateral slip rate of 3–5 m/1000 y. suggest that the Atera fault has high potential of causing great earthquakes with left lateral displacement of 6 or 15 m at one time.

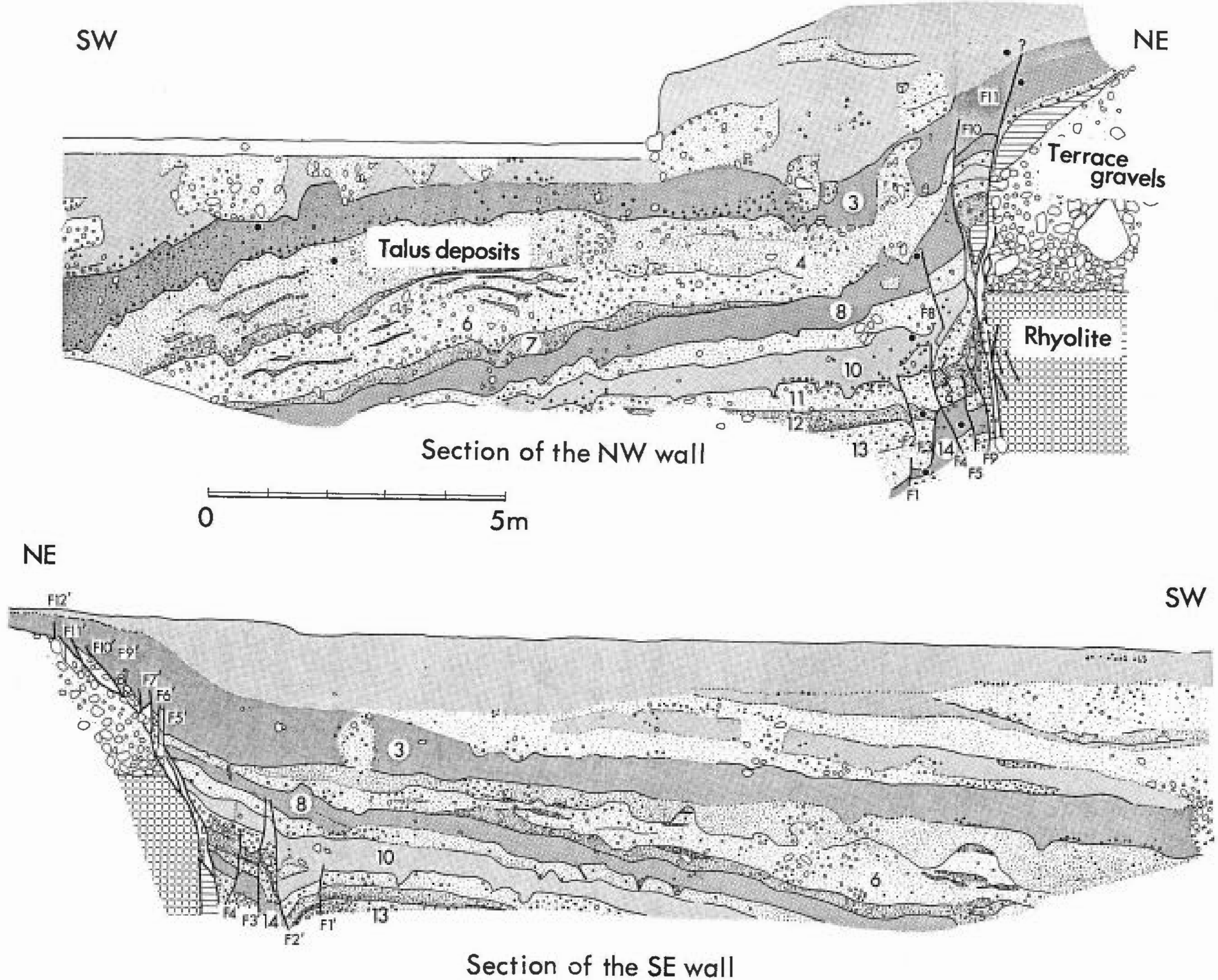

Fig. 12. Logs of the trench across the Atera fault. Solid circles show the point where samples for radiocarbon dating were obtained. Minor faults develop in front of the principal break.

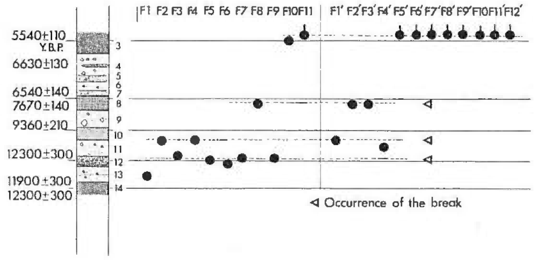

Fig. 13. Radiocarbon datings of the layered talus deposits observed on the trench wall and ages of the slip of each minor fault. Solid circle indicates the horizon of the base of unfaulted layer. Layer number and fault number (3–14, F1-F12) correspond to those in figure 14.

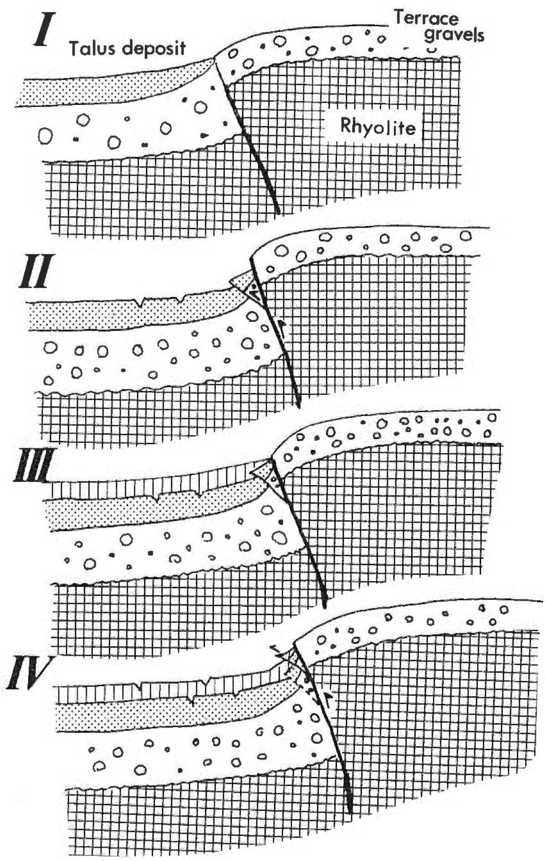

Fig. 14. Progressive displacement of the Atera fault and development of minor faults. I: before the event E, II: event E: minor fault develops near the surface in front of the principal break, III: post event E: deposition of talus sediments during the dormant period, IV: event E+1: new minor fault develops near the surface.

So far, we have mentioned the general status and two examples of trench excavation survey of active faults in Japan. The active fault network of Japan is more complicated than that of the San Andreas region. Therefore, it will be necessary to excavate much more trenches across faults in order to reveal the Holocene behavior of each fault and to estimate the earthquake hazard caused by the fault movement.

There are some problems regarding the trench excavation survey in Japan. Because of thick vegetation and high rate of erosion process, tectonic features accompanied with faults of low activity are easily worn away in the regions where erosional processes prevail. Sometimes it is not so easy to find places with favorable conditions for excavation because such places are usually already developed for other purposes. Another problem is artificial land modification which disturb the valuable data on recent events of faulting. As a matter of fact, at the trench site of the Atera fault, we could not obtain the time of the last event due to the artificial modification of the shallower part of the sediments, Nevertheless, through these trench excavation studies of active faults based on the Quaternary geology, however, we will be able to contribute a long-term earthquake prediction on land in Japan.

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Special Lecture

Geological Structure and Evolution of Continental Margins

by K. HINZ

Geological Survey of Japan Report, No. 263, 1984, p. 365.

Geological Structure and Evolution of Continental Margins

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ABSTRACT

Governments and industry have recently become intensely interested in exploring all available sedimentary basins whose hydrocarbon potential has not yet been assessed. This is primarily due to the rapid growth of world demand for energy caused by the increase in the world population. The most important prospective areas of the future are thought to be the continental margins, located seaward of the shelf areas under 200 m to 400 m of water.

The Federal Institute for Geosciences and Natural Resources has carried out geoscientific reconnaissance surveys on different continental margins with the objective of clarifying the geological structure and geological development of the continental margins and to develop criteria by which the hydrocarbon potential of these areas can be derived. Results of this research effort from convergent margins (Arafura Sea, South China Sea) and from divergent margins (Northwest Africa, Norwegian-Greenland Seas, Labrador Sea, Coral Sea, Weddell Sea/Antarctica) are presented. The most attractive research and exploration goals for the near future are, according to the results of the studies of BGR:

—Mesozoic horst and graben complexes that were formed during the initial opening phase of the oceanic basins;

—Carbonate platform edges and carbonate reef complexes;

—turbidite sand complexes and

—updomings beneath the seaward ages of accretionary wedges.

The phenomenon of buried "wedges of oceanward dipping sub-acoustic basement reflector" observed at a number of passive margins worldwide is also disussed.

Special presentation was made by Professor Hinz at the symposium with the above title. Same presentation was made, however, two months earlier at the Third International Symposium "New Paths to Mineral Exploration" in Germany under the title "Assessment of the Hydrocarbon Potential of the Continental Margins" and the full text is published in its proceedings, Bender, R., ed. (1983) New Paths to Mineral Exploration. E. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart.

地質調査所報告は1報文について報告1冊を原則とし，その分類の便宜のために，次のようにアルファベットによる略号をつける.

A. 地質およびその基礎科学に関するもの
- a. 地　質
- b. 岩石・鉱物
- c. 古生物
- d. 火山・温泉
- e. 地球物理
- f. 地球化学

B. 応用地質に関するもの
- a. 鉱　床
- b. 石　炭
- c. 石油・天然ガス
- d. 地下水
- e. 農林地質・土木地質
- f. 物理探鉱・化学探鉱および試錐

C. そ の 他

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A. Geological & allied sciences
- a. Geology
- b. Petrology and Mineralogy
- c. Paleontology
- d. Volcanology and Hot spring
- e. Geophysics
- f. Geochemistry

B. Applied geology
- a. Ore deposits
- b. Coal
- c. Petroleum and Natural gas
- d. Underground water
- e. Agricultural geology and Engineering geology
- f. Physical prospecting, Chemical prospecting & Boring

C. Miscellaneous

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