Bulletin of the Geological Survey of Japan, vol. 37(5), p. 207-231, 1986 551.763: 552.3: 553.2(510)

Characteristics of Cretaceous magmatism and related mineralization of the Ningwu Basin, Lower Yangtze area, eastern China

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ISHIHARA, S., LI, W., SASAKI, A., SHIBATA, K., MATSUHISA, Y. and TERASHIMA, S. (1986) Characteristics of Cretaceous magmatism and related mineralization of the Ningwu Basin, Lower Yangtze area, eastern China. *Bull. Geol. Surv. Japan*, vol. 37(5), p. 207-231.

Abstract: There are volcano-plutonic basins in the depressed zone of the Yangtze platform where intense mineralizations including iron and base metal are known to occur. The Ningwu Basin, located between Nanjing and Wuhu in the Lower Yangtze area, is an early-middle Mesozoic sedimentary basin filled up later with late Jurassic-Cretaceous volcanic rocks and intruded by Cretaceous intrusive rocks, both of which belong to the Late Yanshanian cycle.

The volcanic and intrusive rocks are mostly of the magnetite series. They are divided into four as follows: (i) Longwangshan-Dawangshan volcanic-subvolcanic rocks, which belong to calc-alkaline suite and basalt and andesite in composition. Subvolcanic microgabbro and diorite accompany magnetite-hematite ore deposits at the top of individual bodies. (ii) Calc-alkaline granite and granodiorite. (iii) Niangniangshan-Gushan volcanic rocks of alkaline suite in a small amount. Copper veins are associated with the Niangniangshan cauldron activity. The intitial $^{87}Sr/^{86}Sr$ ratios of these Cretaceous igneous rocks increase with the age from 0.7055 to 0.7063. The $\delta^{18}O$ ratios appear to be higher than those of common magnetite-series granitoids. (iv) Alkaline olivine basalt of Paleogene age in very minor amount.

Both rock and ore sulfurs of the Ningwu basin show characteristically high $\delta^{34}S$ ratios: an average around +13‰ for the intrusive rock sulfur and +6‰ for the disseminated ore (pyrite) sulfur. This unique ^{34}S-enriched characteristics are explained by the presence of Triassic evaporite sulfates occurring underneath the Cretaceous volcanic rocks, through which the intrusive magmas ascended. Chlorine and sulfur contents of the magmas may have been increased drastically by this magma-evaporite interaction. Thus the intense mineralizations of the Lower Yangtze area, relative to the Daxing'anling and southeast coastal volcanic areas, are also explained by this model.

Introduction

Mesozoic volcanism and plutonism are widespread in eastern China from the Northeast China to Guangdong Province, and have brought various magmatic hydrothermal ore deposits. The most famous regions are magnetite series (with local ilmenite-series) volcano-plutonic belt along the southeast coast (including Zhejiang, Fujiang and Guangdong Provinces, see Fig. 11) and volcanic terrane of the Daxing'anling Mountains (ISHIHARA, 1984). The Lower Yangtze area concerned here has received less intense and sporadic Mesozoic igneous activity, but the intensity of mineralization per unit area appears to be much more than that of southeast coastal area or Daxing'anling region, because of large ore deposits seen in

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the Lower Yangtze area.

The Lower Yangtze area is a part of the Yangtze platform which develops along the Yangtze River, but has received a mild to strong deformation and locally igneous activities of the Yanshanian cycle; hence called sometimes Yangtze Folded Belt. This magmatism has brought up significant mineralizations of high-grade magnetite and copper ores and subsidiary Pb-Zn ores. The mode of occurrence is unique. Copper deposits, for example, consist of 1) Cu-bearing massive pyrite bed, 2) Cu-bearing skarn with replacement-type Cu vein near the metasomatic zone, 3) disseminated ores in the intrusives known as porphyry copper deposits. These three types of mineralization occur closely associated with each other, although the disseminated type may not be present in every mineralized area, thus the mineralization is called "Three in One" (or Trinity, LI, 1983).

Under the ITIT (Institute for Transfer of Industrial Technology) Project No. 8113 of three-year co-operation research project between the Geological Survey of Japan and the Nanjing Institute of Geology and Mineral Resources, the first year tour was made by the senior author (S.I.) in 1981 autumn to one of the typical mineralized areas of Ningwu basin, southeast of Nanjing, and a part of Jiangxi Province. Field investigation of the tour was already published in ISHIHARA (1982a, b; 1983) and ISHIHARA and SATO (1982). This report describes chiefly the results of microscopic observation, chemical analyses and isotopic studies, which were performed at the Geological Survey of Japan, on the samples obtained through the tour. Laboratory results of the earlier visit in 1979 are also supplemented.

The Yangtze Platform

The Lower Yangtze area where intense magmatic-hydrothermal mineralizations are known, is located in the lower stream area of the Yangtze River (or Chang Jiang) from Wuhan to Shanghai. It occupies the eastern half of the E-W trending Yangtze platform, which is actually paraplatform for folding, faulting and magmatism appeared in Mesozoic time (HUANG, 1959). The platform is well bounded its north by the Tancheng-Lujiang Fault and several WNW-ESE faults along the Qinlin Suture, but poorly defined its south by NE-trending faults passing through Hangzhou-Shaoxing area. The platform is subdivided into the northern depressed zone and the southern uplifted zone (Fig. 1).

The basement is non-metamorphic or metamorphic rocks of Archean and Proterozoic ages. The Platform cover is generally shallow marine clastics and carbonates from the Sinian to Triassic in age. The strata have been upheaved and mildly to locally strongly deformed by the Indosinian movement. The sea regression appeared in middle Triassic in the Lower Yangtze area, as shown by the presence of red sandstones with plant fossils and lagoon carbonates including rock salt and gypsum (NAKAJIMA, 1984). The change in their tectonic setting is also seen in the axes of each sedimentary basin, which are ENE-WSW in the Sinian to lower Paleozoic, NE-SW in the upper Paleozoic, but NNE-SSW in the uppermost Triassic strata, which is parallel to the famed Tancheng-Lujiang Fault (WENG and WANG, 1981).

In the early and middle Jurassic, isolated basins were developed in NNE-SSW direction and filled with both marine and non-marine clastics and carbonates. The platform was exposed to the Yanshanian magmatism from late Jurassic to early Cretaceous, which brought ore deposits of the trinity association in proper areas and typical porphyry copper deposits at Dexing in the southern uplifted zone (Fig. 1). Faulting was most strong during this period, because the sedimentation, magmatism and mineralization are controlled by several lineaments. After the Yanshanian activity, non-marine sediments were depos-

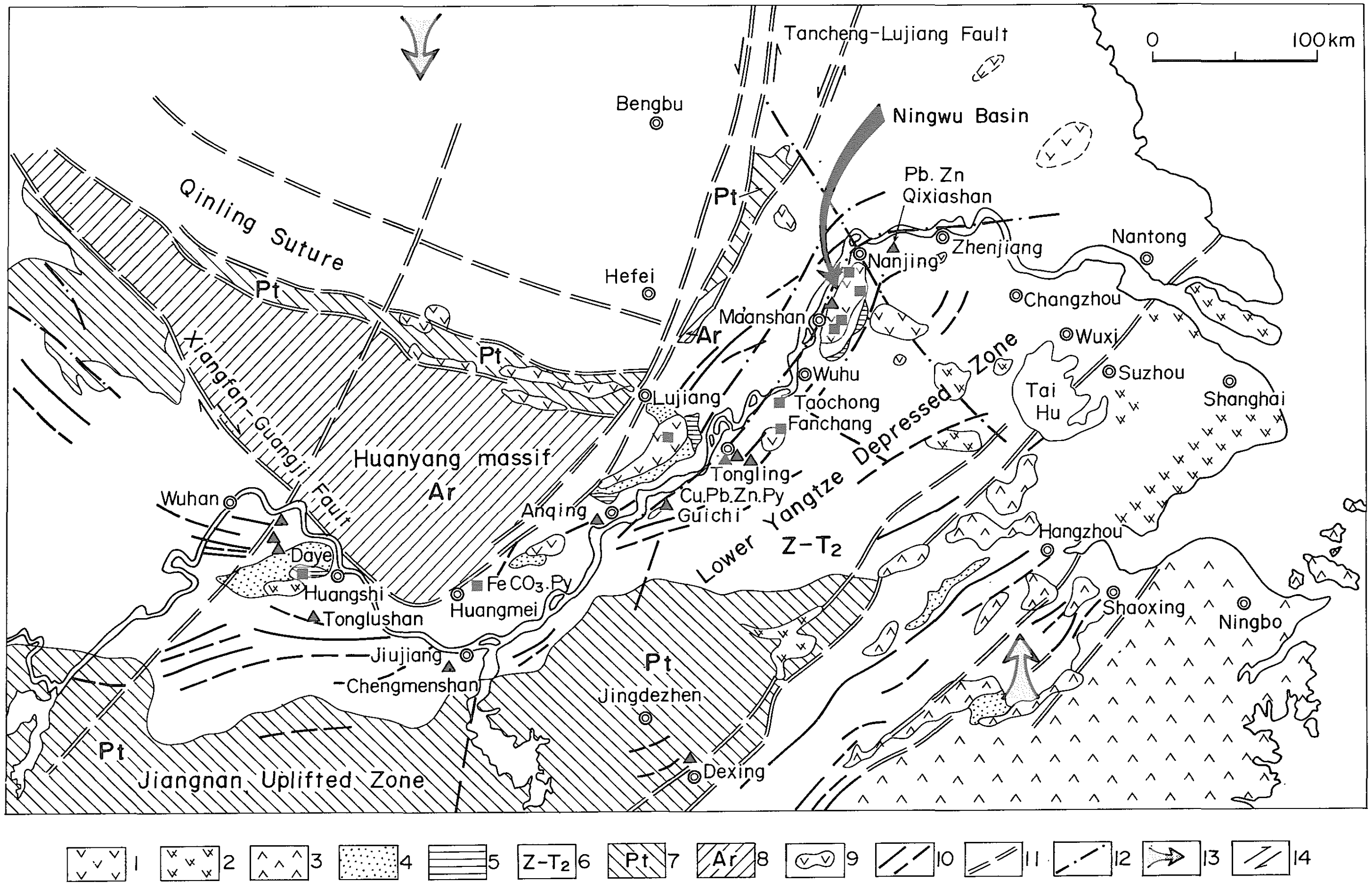

Fig. 1 Index map of the Lower Yangtze area showing important magnetite (■) and copper(-lead-zinc) deposits (▲). 1 Intermediate, 2 Intermediate-felsic, 3 Felsic volcanic rocks. 4 Xiangshan Group and its equivalents (middle Trias.), 5 Huangmaqing Group and its equivalents (upper Trias.). 6 Sinian (Z) to middle Triassic (T) formations. 7–8 Pre-Sinian basement. 9 Mesozoic volcanic basin. 10 Axex of anticline and syncline of middle Triassic formations. 11 Deep fault, 12 Large fault, 13 Movement of massif. 14 Lateral movement along deep faults. $FeCO_3$ and Py at Huangmei implies siderite and pyrite deposits. Copper deposits at Guichi contain workable amount of lead-zinc and pyrite (after Ningwu Research Group, 1978 and Li, 1983).

ited locally, and Paleogene basalts were erupted very sporadically.

The Ningwu Volcanic Basin

The Ningwu volcanic basin, which is named after an old name of Ning for Nanjing and Wu for Wuhu, is located at southwest of Nanjing city having a NNE-SSW trend (Fig. 2). This was developed since early Mesozoic, probably by pushing of Jiangnan massif toward north and breaking up of the Huanyang massif during the Yanshanian movement (Fig. 1).

The first sedimentary sequence of the basin is lower-middle Triassic limestone of the Qinglong Group (more than 500 m thick) or upper Triassic sandstone and shale of the Huangmaqing Group (500-800 m). These are marine sediments but evoparite beds of similar age are known to occur in the surrounding area, such as in suburban area of Nanjing city and in southern part of Ningwu basin. Middle Triassic sandstone of the Xiangshan Group (1500 m) is well developed, which is marine initially but becomes nonmarine in later facies. The next sequence is upper Jurassic conglomerate, carbonates and sandstone of the Xihuangshan Group (more than 1000 m), which intercalates purple-red sandstone and andesitic tuff. There was no severe tectonic disturbance during the sedimentation period, but all the sequences together were folded and faulted by the succeeding Yanshanian tectono-magmatic activity.

The Ningwu Basin is well covered by terrestrial volcanic rocks and intruded by cogenetic subvolcanic and plutonic rocks (Fig. 2). The volcanic sequence is divided into the four members listed in Table 1.

The Longwangshan member is distributed along the eastern margin of the volcanic basin (Fig. 2). The constituents are lava and pyroclastics of generally hornblende-bearing basaltic andesite to andesite and locally trachyandesite. The lowest unit consists of purple-brown tuff breccia, the middle part is yellow-white to purple-gray lava and locally brecciated lava, and the top unit is alternation of purple sandstone, yellow-brown lava and tuff breccia.

The Dawangshan member is most widely distributed in the basin. This is also composed of basaltic andesite and andesite, which are partly trachytic. They differ from the Longwangshan andesites by the presence of more augite in the mineral constituents. The lowest unit is alternation of tuffaceous sandstone and shale; the middle part is alternation of tuff, lava and volcanic breccia.

The Gushan member crops out locally in the southernmost part (Fig. 2). The lower half is alternated unit of conglomerate, sandstone, shale and tuff breccia, while the upper half is lava and volcanic breccia intercalating thin layers of tuff. The basal conglomerate contains pebbles of magnetite ore and granodiorite. The volcanic rocks are andesitic to dacitic in composition.

The Niangniangshan member occurs also locally around Mt. Niangniang filling a cauldron of NE-SW 6 km and NW-SE 3.5 km in dimension. The lower part is composed of leucite-bearing phonolitic lava and porphyry (Fig. 3), breccia and tuff, while the upper part is characterized by welded tuff. The volcanic rocks are of alkaline suite containing

Table 1 Volcanic sequence of the Ningwu basin. After Ningwu Research Group (1978).

Member	Geological age	K-Ar age(Ma) (number of analyses)	Thickness (meter)
Niangniangshan	Middle Cretaceous	91-104(n=3)	880
Gushan	Early Cretaceous	110-116(n=5)	290
Dawangshan	Early Cretaceous- Upper Jurassic	120-121(n=2)	950
Longwangshan		125-127(n=2)	500

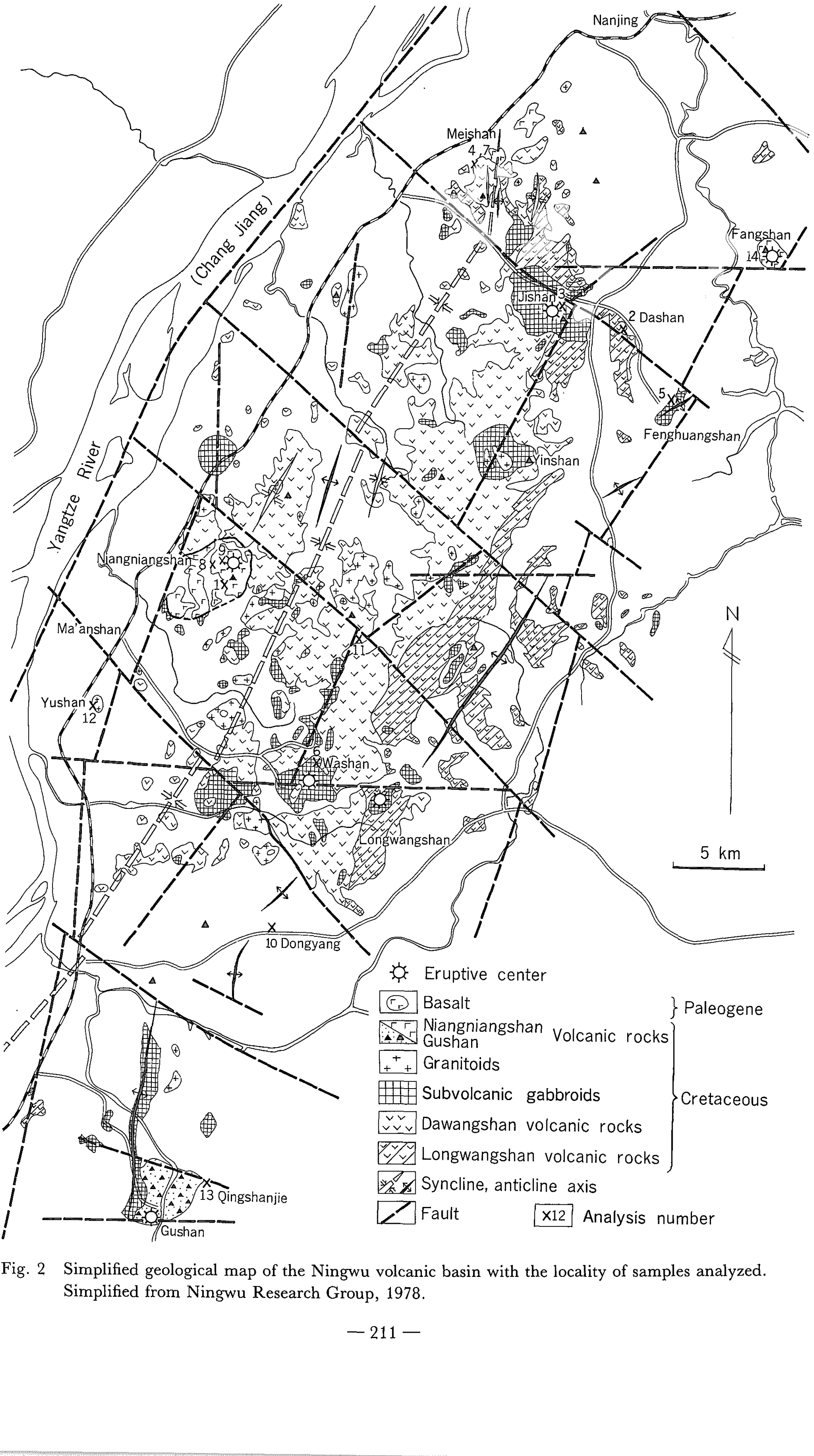

Fig. 2 Simplified geological map of the Ningwu volcanic basin with the locality of samples analyzed. Simplified from Ningwu Research Group, 1978.

Fig. 3 Leucite porphyry of the lower member occurring in the southwestern part of the Niangniangshan volcanics.

feldspathoids and aegirine.

Magnetic susceptibility of the volcanic rocks measured by a portable device (ISHIHARA, 1979) in the northern part of the Meishan-Fenghuangshan mine's area and the southern part of the Niangniangshan-Washan mine area is as follows:

Dawangshan volcanics (8 localities):
20, 20, 70, 700, 760, 1300, 1440, 1560 $\times 10^{-6}$ emu/g.
Niangniangshan volcanics (6 localities):
20, 20, 20, 20, 25, 690.

Although the number of measurement is small, most of the Dawangshan volcanics are highly magnetic as 700-1600 $\times 10^{-6}$ emu/g. Three low values, which are within the range of ilmenite series (less than 100 $\times 10^{-6}$ emu/g), are possibly due to hematitization over magnetite by hydrothermal alterations, which prevail in the volcanic rocks of the Ningwu basin. However, general low values on the Niangniangshan volcanics indicate possibility of some magnetite-free rocks involved in this unit.

Intrusive rocks are divided into subvolcanic rocks and plutonic rocks. The subvolcanic rocks occur as small stocks, less than 5 km in diameter, more or less following tectonically weak zones (Fig. 2). Their shape is irregular three-dimensionally, being mashroom, lens, tongue or layer, yet these are connected at depth each other as observed by drilling in the Ma'anshan area.

The subvolcanic rocks are present associated with each volcanic cycle but most commonly with the Dawangshan cycle. They have a sharp contact with sedimentary wall rocks, giving a thermal metamorphism in the latters. However, the boundary with the volcanic rocks, especially with those of the Dawangshan cycle, is unclear and the transition is often gradual. This field relationship and fragments of magnetite ore in the Gushan Group mentioned before indicate these rocks of very high level intrusions.

Most of the subvolcanic rocks of the Dawangshan cycle are very fine-grained, having the grain size of the constituents less than 1.5 mm. Distinct porphyritic texture is not well developed. The composition varies from gabbroic diorite to diorite, which is similar to that of Dawangshan volcanics. Thus, they can be called microgabbro or microdiorite but have been traditionally named as porphyrite in Chinese literature referring porphyritic variety of intermediate to mafic rocks with plagioclase (usually labradorite) phenocryst. The rocks accompany many magnetite deposits in and around the top of the bodies. About the examined points in the magnetite-mineralized areas, "fresh" rocks are highly magnetic as 1600-1800 $\times 10^{-6}$ emu/g, which is often reduced one or two order of magnitude by alteration.

Plutonic bodies are much smaller in size, less than 3 km in diameter. The rocks are fine-grained but granitic in texture. The composition varies from place to place, but generally more felsic than the subvolcanic group. An earlier intrusion of granodiorite(-quartz diorite) is probably related to the Dawangshan cycle, while the later biotite granite and granophyric rocks may be close to the Niangniangshan cycle. The observed magnetic susceptibility consists of two groups: one around 15 (n=3) while the other about 700-750 $\times 10^{-6}$ emu/g.

Late Cretaceous red beds were deposited

locally after the Yanshanian magmatism. Paleogene basalt was erupted at a few places.

Chemical Composition of the Igneous Rocks

Volcanic and plutonic rocks of the Ningwu basin are not well exposed, besides they in general have been severely altered hydrothermally. Among the samples collected (see appendix of GSJ ed., 1985), six volcanic rocks, three subvolcanic rocks and three granitic rocks were analyzed by conventional wet method for the major chemistry and by atomic absorption and other methods for the minor elements. The results are listed in Table 2 and illustrated in Fig. 4. The analyzed samples have the following microscopic characteristics:

Longwangshan-Dawangshan Volcanic Rocks

1) 81102811: Strongly altered olivine-augite andesite. Fragment contained in agglomerate in the center of the Niangniangshan cauldron (Longwangshan cycle?).

Phenocryst: Plagioclase, less than 2 by 3 mm, partly altered to carbonates; augite partly altered to carbonates and chlorite; olivine altered mainly to carbonates; magnetite only partly hematitized; and apatite.

Groundmass: Originally composed of plagioclase, pyroxene, magnetite and phlogopitic mica, but now hardly seen due to strong carbonatization.

2) 81103003: Altered olivine-orthopyroxene-augite andesite at Dashan (Dawangshan cycle).

Phenocryst: Plagiocalse less than 1 by 2 mm, augite partly altered to carbonates and chlorite, magnetite, actinolite pseudomorph after orthopyroxene, and carbonates and chlorite pseudomorph after olivine.

Groundmass: Probably the same as the phenocryst but strongly altered to carbonates, epidote, etc.

3) 81102705: Altered pyroxene porphyrite at Jishan open pit mine (Dawangshan cycle).

Phenocryst: Plagioclase less than 3 by 4 mm, often zoned and altered to sericite, pyroxene strongly altered to carbonates and chlorite, biotite, and magnetite less than 0.3 mm and hematitized moderately.

Groundmass: The same as the phenocryst minerals but with strong alteration. Lots of pyrite disseminated in silicate minerals or replacing magnetite.

4) 81102608: Altered hornblende-biotite andesite at Meishan (Dawangshan cycle).

Phenocryst: Plagioclase less than 1.5 by 2 mm, opacite, hornblende and/or biotite filled with carbonates and clays, apatite, and magnetite. Some plagioclases may be xenocryst. Phenocrystic quartz surrounded by clays and carbonates is originally pyroxene but formed by silicification.

Groundmass: Plagioclase, pyroxene, magnetite partly hematitized, micrographic intergrowth of quartz and alkali feldspar. Strong carbonatization and silicification.

Dawangshan Subvolcanic Rocks

5) 81102702: Altered microdiorite at Fenghuangshan mine. Microholocrystalline (not porphyritic) in texture, all grains less than 0.5 mm. Euhedral plagioclase replaced by carbonates. Opacite after amphiboles. Euhedral-subhedral magnetite, strongly hematitized along the margin and cracks. Some ilmenites, two grains of chalcopyrite and one grain of pyrite in magnetite.

6) 81102901: Orthopyroxene microdiorite at Washan open pit mine. Microcrystalline and porphyritic, coarser than 81102702.

Phenocryst: Plagioclase less than 2 by 3 mm, generally zoned, orthopyroxene, clinopyroxene(?) altered to actinolite, polygonal to rounded magnetite less than 0.5 mm in diameter, often accompanied with small crystals of ilmenite having 20–40% hematite areally.

Groundmass: The same as the phenocrysts. Irregular form, secondary biotite replacing pyroxenes. Some pyrite scattered.

7) 81103015: Altered porphyrite at Meishan (Dawangshan cycle).

Table 2 Major and minor compositions and their normative constituents of the Ningwu igneous rocks.

	Volcanic Rocks				Subvolcanic Rocks		
Analysis No.	1	2	3	4	5	6	7
Sample No.	81102811	81103003	81102705	81102608	81102702	81102901	81103015
SiO_2 (%)	51.22	54.94	56.90	60.17	52.99	55.36	56.96
TiO_2	0.97	0.81	0.65	0.48	0.71	0.82	0.59
Al_2O_3	18.31	18.55	16.74	16.53	17.96	17.41	15.40
Fe_2O_3	4.34	5.07	4.19	2.27	4.28	4.59	3.24
FeO	2.26	2.44	2.69	2.41	2.84	3.34	2.69
MnO	0.20	0.14	0.13	0.10	0.08	0.13	0.14
MgO	2.55	1.72	2.89	2.03	1.34	3.75	3.63
CaO	6.25	6.31	4.99	5.30	8.63	6.92	4.79
Na_2O	4.00	4.11	3.45	3.84	4.04	4.53	2.59
K_2O	5.45	3.25	3.29	1.86	1.01	2.32	3.79
P_2O_5	0.58	0.54	0.28	0.27	0.42	0.31	0.31
H_2O^+	0.28	0.70	1.16	1.51	1.67	0.28	2.10
H_2O^-	0.18	0.26	0.32	0.56	0.48	0.12	0.62
Total	96.59	98.84	97.68	97.33	96.45	99.88	96.85
T.C (ppm)	8,400	3,040	3,760	7,200	10,000	120	6,700
S	120	30	9,600	50	180	310	7,200
Cu	38	3	76	66	47	6	30
Zn	139	36	81	66	101	30	55
Pb	33	13	14	10	20	11	20
Li	35	20	18	21	22	9	37
Rb	131	75	98	40	20	75	126
Sr	2,300	756	528	720	718	601	549
Be	5.6	2.1	1.5	1.0	1.5	1.4	1.8
Sn	1.9	0.9	1.0	0.6	0.5	1.0	0.6
Kai	1,250	1,560	1,300	700	1,630	1,750	530
Q (%)	—	5.16	10.27	16.68	8.65	2.62	12.43
C	—	—	—	—	—	—	—
or	32.21	19.21	19.44	10.99	5.97	13.71	22.40
ab	22.19	34.78	29.19	32.49	34.19	38.33	21.92
an	15.91	22.57	20.47	22.37	27.89	20.32	19.20
ne	6.31	—	—	—	—	—	—
wo	—	—	—	—	0.65	—	—
wo-di	4.72	2.17	1.02	0.90	4.44	5.00	1.06
en-di	4.08	1.88	0.83	0.60	3.34	3.93	0.81
fs-di	—	—	0.07	0.23	0.66	0.52	0.14
en-hy	—	2.40	6.37	4.45	—	5.41	8.23
fs-hy	—	—	0.57	1.71	—	0.71	1.41
fo-ol	1.59	—	—	—	—	—	—
fa-ol	—	—	—	—	—	—	—
mt	5.12	5.97	6.07	3.29	6.20	6.65	4.70
hm	0.81	0.95	—	—	—	—	—
il	1.84	1.54	1.23	0.91	1.35	1.56	1.12
ap	1.34	1.25	0.65	0.63	0.97	0.72	0.72
Q+ab+or	60.71	59.14	58.90	60.16	48.81	54.66	56.75

1 (81102811) Altered olivine-augite andesite (Longwangshan cycle? 竜王山旋回). Fragment contained in agglomerate in the center of Niangniangshan (娘々山) cauldron. 2 (81103003) Altered olivine-orthopyroxene-augite andesite (Dawangshan cycle), Dashan (大山), ZK-02, −135 m. 3 (81102705) Altered pyroxene porphyrite. Jishan (吉山) open pit magnetite mine, +43 mL, Section III. 4 (81102608) Altered hornblende-biotite andesite. Meishan (梅山) mine site, quarry near the main shaft. 5 (81102702) Altered microdiorite, Fenghuangshan (鳳凰山) underground mine, 3rd L (−150 m), main drift to southwest. 6 (81102901) Orthopyroxene microdiorite. Washan (凹山) open pit mine, +45 mL, south edge of the pit. 7 (81103015) Altered porphyrite. Meishan underground mine, −200 mL. Footwall 303. In Tables 1 and 3, T.C is total carbon; Kai is magnetic susceptibility in emu/g, $\times 10^{-6}$.

Table 2 Continued

Niangniangshan Volcanics		Granitic Rocks			Alkaline Basalt	
8	9	10	11	12	13	14
81102806	81102808	81103008	81103007	81103006	81103001	81103011
59.94	60.52	63.41	65.55	65.71	44.32	47.80
0.41	0.48	0.65	0.51	0.65	2.22	2.36
19.52	19.47	15.97	15.15	17.02	14.62	15.77
2.15	1.83	2.32	2.15	1.31	3.22	5.98
0.86	0.86	2.91	1.76	0.72	6.86	4.92
0.16	0.16	0.11	0.04	0.04	0.23	0.18
0.64	0.59	2.39	1.73	1.93	9.71	5.56
2.13	1.96	4.19	3.16	4.88	9.58	8.32
5.85	6.31	3.33	3.73	5.75	4.58	4.22
6.81	7.03	3.92	3.73	0.59	1.68	2.33
0.14	0.12	0.07	0.18	0.24	0.98	0.71
0.75	0.02	0.45	0.64	0.69	1.63	1.26
0.26	0.20	0.02	0.06	0.28	0.16	0.42
99.62	99.55	99.74	98.39	99.81	99.79	99.83
140	60	550	2,950	2,220	130	540
1,010	2,000	60	80	20	360	70
5	4	25	3	6	49	47
81	75	37	11	8	96	109
25	24	16	5	10	17	13
51	32	21	10	7	8	10
154	148	134	109	10	37	51
641	442	451	352	634	918	803
6.4	6.5	1.9	1.8	2.6	2.4	2.4
1.4	1.5	1.6	2.2	0.8	1.7	1.9
25	690	750	700	20	650	350
—	—	16.24	20.62	18.16	—	—
—	—	—	—	—	—	—
40.24	41.54	23.17	22.04	3.49	9.93	13.77
39.69	38.62	28.18	31.56	48.65	11.73	27.73
6.89	4.04	17.05	13.58	18.89	14.37	17.21
5.32	8.00	—	—	—	14.64	4.32
—	0.35	—	—	—	—	—
1.15	1.70	1.37	0.38	1.57	11.17	8.11
1.00	1.47	0.89	0.30	1.35	7.97	6.81
—	—	0.38	0.05	—	2.21	0.26
—	—	5.06	4.01	3.45	—	—
—	—	2.17	0.64	—	—	—
0.42	—	—	—	—	11.36	4.93
—	—	—	—	—	3.47	0.21
2.10	1.90	3.36	3.12	0.57	4.67	8.67
0.70	0.52	—	—	0.92	—	—
0.78	0.91	1.23	0.97	1.23	4.22	4.48
0.32	0.28	0.16	0.42	0.56	2.27	1.65
85.25	88.17	67.58	74.23	70.30	36.30	45.82

8 (81102806) Nosean phonolite welded tuff (Niangniangshan cycle). Quarry at south of Yaoshan (窰山). 9 (81102808) *ditto*, Tong'aoshanzui (銅坳山咀). 10 (81103008) (Pyroxene-)hornblende-biotite granodiorite. Dongyang (洞陽), T103, ZK-2, −300 m. 11 (81103007) Altered hornblende-biotite granodiorite. Putang (濮塘) at east of Ma'anshan (馬鞍山), ZK-LI, −508 m. 12 (81103006) Altered (epidote) granodiorite. Yushan (雨山), TO76-2. 13 (81103001) Augite-olivine basalt (Paleogene). Qingshanjie (青山街), Fushan (釜山). 14 (81103011) *Ditto* (60 Ma), Fangshan (方山), Suburb of Nanjing city.

Phenocryst: Plagioclase less than 1.5 by 3 mm, euhedral and zoned, strongly altered to carbonates (areally 50%). All mafic silicates altered to opacite, carbonates (+chlorite). Magnetite less than 0.6 mm replaced by hematite bands along 111 cleavage or irregularly.

Groundmass: Very fine aggregates of plagioclase, actinolite and pyroxene. Lots of pyrite disseminated.

Niangniangshan Alkaline Rocks

8) 81102806: The same as bellow, but much less magnetite.

9) 81102808: Nosean phonolite welded tuff, recrystallized.

Phenocryst: K-feldspar (2V≑50°) less than 2 by 4 mm, nosean with rare apatite inclusion, aegirineaugite, alkali amphibole,

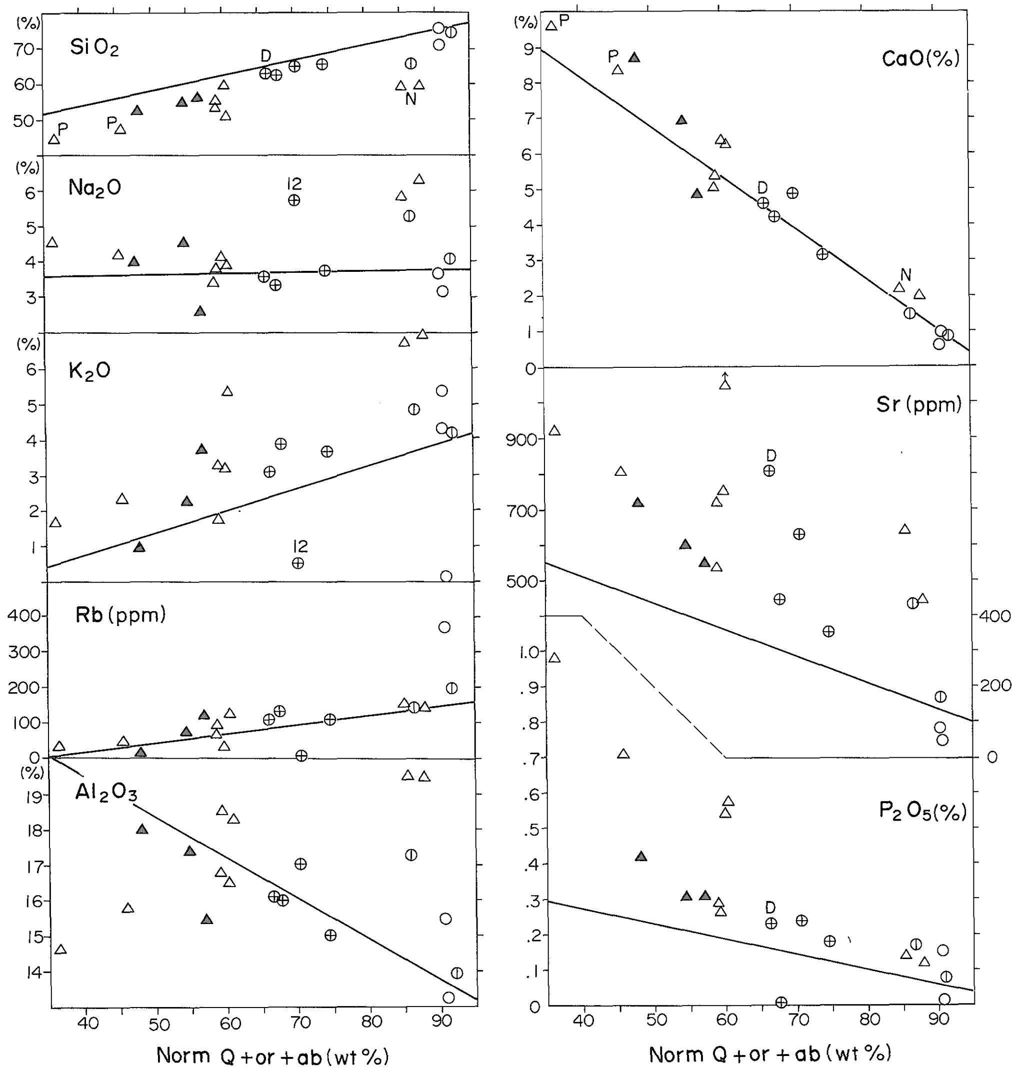

Fig. 4 Chemical composition plotted against normative Q+or+ab: △ volcanic rocks (N, Niangniangshan; P, Paleogene basalt), ▲ Subvolcanic rocks, ⊕ Granitoids (D, Dexing), ⦶ Magnetite-series granitoids of northern China, ○ Ilmenite-series granitoids of southern China. Straight line is the trend of the average composition of late Cretaceous-Paleogene magnetite-series granitoids of Southwest Japan (ISHIHARA *et al.*, unpublished data).

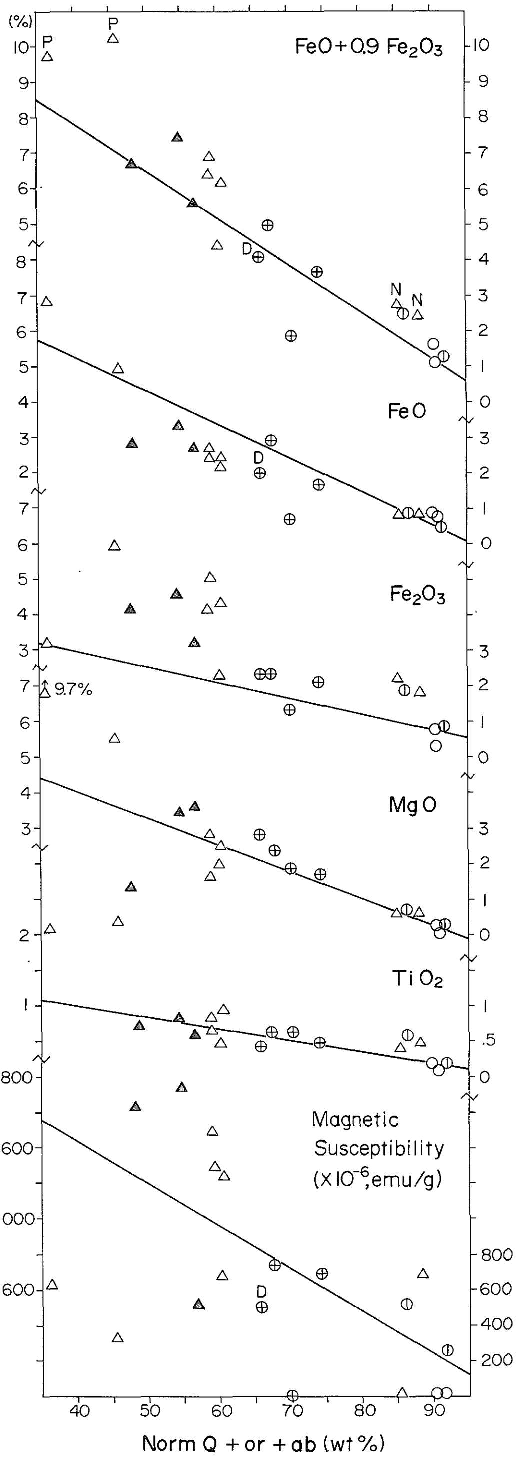

Fig. 4 Continued

sphene, biotite, magnetite (0.4 mm) and rare plagioclase.

Groundmass: Completely recrystallized.

Dawangshan Granitoids

10) 81103008: Pyroxene-bearing hornblende-biotite granodiorite at Dongyang. Euhedral plagioclase less than 2 by 5 mm, generally unzoned, some sericite specks contained. Euhedral and interstitial quartz, some showing graphic intergrowth. Subhedral orthoclase, reddish brown biotite and actinolitic amphibole. Euhedral-polygonal magnetite up to 0.5 mm in diameter, occurring generally with mafic silicates. No hematitization. Little subhedral ilmenite containing some (up to 10%) hematite molecule. Some secondary sphene.

11) 81103007: Altered hornblende-biotite granodiorite at Putang. Euhedral plagioclase altered to carbonates and sericite. Brown biotite mostly altered to chlorite, actinolitic amphibole strongly replaced by carbonates. Granular quartz. Polygonal, cubic or rounded magnetite occurring with mafic silicates and no hematitization. Only little stubby ilmenite containing an equal amount of hematite. Large crystal of secondary sphene.

12) 81103006: Altered (epidote) granodiorite at Yushan. Euhedral plagioclase, generally unzoned and cut by albite microveinlet-network and epidote. Subhedral K-feldspar. No fresh mafic silicates but originally amphibole. Lot of secondary sphene and epidote. No magnetite but some ilmenite with hematite lamellae.

Paleogene Basalt

13) 81103001: Augite-olivine basalt at Fushan.

Phenocryst: Olivine, large augite (4 mm in length) with sieve texture including olivine, phlogopitic mica and felsic minerals.

Groundmass: Plagioclase, clinopyroxene, magnetite much more than ilmenite, olivine, phlogopitic mica and apatite.

14) 81103011: *ditto* (alkalic), Fangshan, Nanjing.

Phenocryst: Olivine converted to iddingsite completely or along the margin, titaniferous augite. Xenocryst of quartz rimmed by clinopyroxene grains.

Groundmass: Plagioclase, clinopyroxene (titaniferous?), magnetite, olivine (iddingsite), unidentified colorless mineral in the interstitial. Some carbonates.

Chemical Characteristics

The rocks obtained from the Ningwu basin are severely altered as described in the previous paragraphs. Total carbon for example, which is probably all carbonate carbon, reaches 3.7 wt.% (81102702), so that an exact evaluation of the analytical data cannot be possible. However, unique characteristics of different rock types are still exhibited in common variation diagrams of Fig. 4, in which the rocks are compared with typical magnetite-series granitoids of the Inner Zone of Southwest Japan.

Normative Q+or+ab: This amount in average varies as follows:

Paleogene basalt (n=2)	41.1 wt.%
Niangniangshan welded tuff (n=2)	86.7
Dawangshan granitoids (n=3)	70.7
Dawangshan subvolcanic rocks (n=3)	53.4
Dawangshan volcanic rocks (n=3)	59.4

Dawangshan volcanic and subvolcanic rocks are similar, thus the rocks may be grouped into four.

SiO_2, Na_2O, K_2O and Rb: Rocks of the Ningwu basin have lower silica but higher potassium contents than the Japanese granitoids. Among the Ningwu rocks, Paleogene basalt and Niangniangshan welded tuff are most depleted in SiO_2 and enriched in Na_2O and K_2O, indicating strongly alkaline characteristics of these rocks. Yet rubidium is as low as the Japanese granitoids (Fig. 4, left). Extremely high content of Na_2O and low content of K_2O of the sample 81103006 are due to albitization over plagioclase and some K-feldspars.

Al_2O_3, CaO, P_2O_5 and Sr: Alumina is extremely high in the Niangniangshan rocks but very low in the Paleogene basalt (Fig. 4, middle). Calcium shows no distinct tendency but strontium and phosphorus are very rich in the Ningwu rocks (Fig. 4, middle). Altered andesite of 81102811 contains 2300 ppm Sr. Paleogene basalt and two altered andesites (81102811 and 81103003) have especially high contents of P_2O_5.

FeO, Fe_2O_3, MgO, TiO_2 and magnetic susceptibility (Fig. 4, right): Total iron content of the Ningwu rocks is similar to that of the Japanese granitoids, except for the Paleogene basalt which is somewhat enriched in iron. But Fe_2O_3/FeO ratio is generally higher than that of the typical magnetite-series granitoids. Dawangshan volcanic and subvolcanic rocks in particular, are highly oxidized; the characteristics shown by high magnetic susceptibility values of these rocks. Magnesium and titanium are more or less the same as those of the Japanese granitoids, except for the Paleogene basalt, which is enriched in these elements.

Other minor elements: Among the other minor elements, content of sulfur and copper varies greatly. Even that of zinc, which is positively correlated with the amount of ferromagnesian components in general, has a remarkable variation. A main reason for the variation may be sought in the severe alteration on these rocks. Content of lithofile elements such as Li, Be and Sn is constantly low, but the Niangniangshan welded tuff is enriched in Li and Be.

Summary: Chemically and mineralogically, the Ningwu rocks are largely grouped into two, alkaline and non-alkaline suite. The former is composed of the Niangniangshan volcanic and Paleogene basalt, both of which are very rich in Na_2O+K_2O (Fig. 5). The Niangniangshan rocks, however, are different from the basalt, being enriched in Al_2O_3, S, Li and Be, but depleted in MgO, TiO_2 and P_2O_5. Thus, they may be independent magma types.

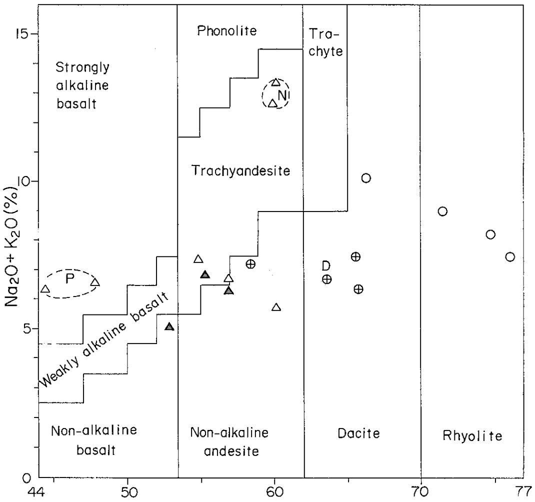

Fig. 5 Alkali-silica diagram for rocks of the Ningwu basin (81102811 is excluded). The classification is taken from MIYASHIRO and KUSHIRO (1975). Symbols are the same as those of Fig. 4.

Dawangshan volcanic and subvolcanic rocks are plotted around the boundary between non-alkaline andesite and trachyandesite in the alkali-silica diagram (Fig. 5). They can be considered to be cogenetic in origin. Dawangshan granitoids, on the other hand, are different from the volcanic and subvolcanic rocks by higher content of silica or normative Q+or+ab. Thus, the granitoids appear to have different genesis.

Mineralization in the Ningwu Basin

Mineralization of the Ningwu Basin is characterized by socalled porphyrite iron orebodies whose size reaches 500 million tons. Subordinate amount of pyrite and sulfate deposits are known to occur related to the iron mineralization. Gold-copper veins were once operated at Tongnan in the Niangniangshan cauldron.

The iron deposits occur in and around the upper part of microgabbro-diorite bodies at many places in the basin. The best mineralization is seen as massive orebodies around the subvolcanic cusp (Meishan type), which changes downward to brecciated orebodies with vein type roots (Washan type) and further downward to disseminated mineralization (Taocun type, Fig. 6). Pyrite halo occurs generally above the magnetite orebodies (Xiangshan-type pyrite deposit).

Secondly important are those occurring in sedimentary wall rocks in contact with the subvolcanic rocks (Fenghuangshan-Gushan type, Fig. 6, 7). Minor stratabound orebodies (Longqishan type) occur in the intruded andesitic rocks and some specularite and/or magnetite veins are present in the volcanic rocks near the intrusives (Longhushan type).

The typical Meishan deposits occur as mostly lenses and partly veins in the Dawangshan andesite and microdiorite. The host rocks are strongly altered to garnet, diopside and apatite. The other alteration minerals are scapolite, albite, epidote, actinolite, chlorite, carbonates, kaolinite and quartz. Microscopic study on selected samples indicates that magnetite is generally hematitized (20–80% in area) and that colloform to granular pyrite is quite common occurring as veinlet or surrounding hematitized magnetite and filling its cavities. Thus the pyrite is later than the iron oxides. Apatite in the Washan deposits is very large as 20–30 centimeters in diameter.

Copper vein deposits in the Niangniangshan area occur within the cauldron cutting all the volcanics (Fig. 8). They extend in NNW-SSE direction for about 3 km in the depth of 300 m in general (max. 500 m). The veins are 2–3 m in width as a whole but have a composite feature consisting of the following five stages' materials:

i) Gold-bearing chalcopyrite-quartz vein
ii) Siderite vein parallel to the main vein
iii) Barite vein
iv) Chalcedony vein
v) Later carbonate vein

Sulfur Isotopic Studies

Sulfur isotopic ratio was determined on two least altered rocks, five sulfide-bearing ores,

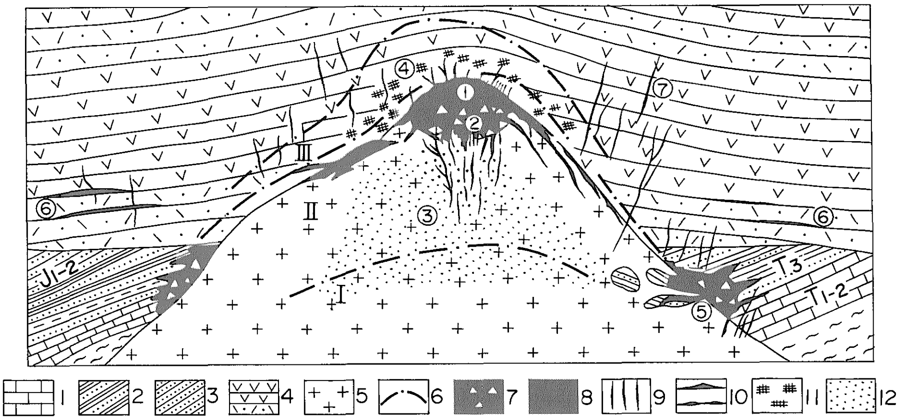

Fig. 6 Idealized profile of "porphyrite iron ore" deposits.
1 Qinglong Group limestone (T_{1-2}), 2 Huangmaqing Group (T_3), 3 Xiangshan Group (J_{1-2}), 4 Longwangshan-Dawangshan volcanic rocks (J_3/K_1), 5 Gabbro-diorite-porphyrite, 6 Boundary of alteration zones: I Lower light-colored zone (alkali feldspar), II Middle dark-colored zone (garnet, pyroxene, scapolite), III Upper light-colored zone (pyrite, sulfate, quartz, kaolinite), 7 Brecciated ore, 8. Massive ore, 9 Specularite-magnetite vein, 10 Stratabound ore, 11 Pyritized zone, 12 Disseminated magnetite ore. ① Meishan type, ② Washan type, ③ Taocun type, ④ Xiangshan type, ⑤ Fenghuangshan-Gushan type, ⑥ Longqishan type, ⑦ Longhushan type (after Ningwu Research Group, 1978).

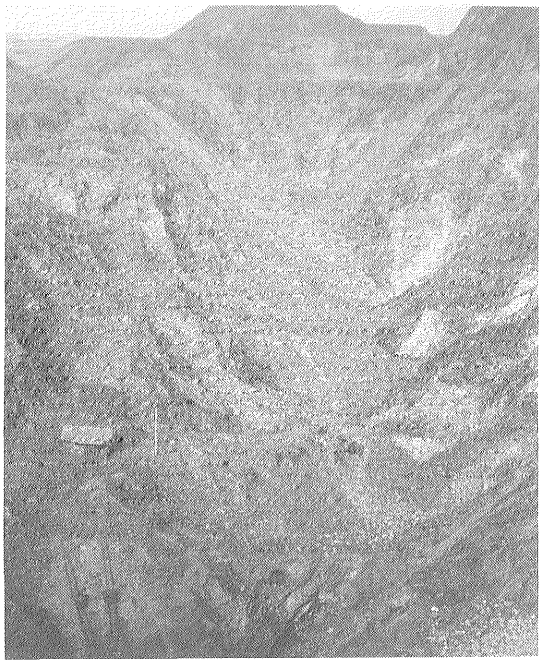

Fig. 7 Open pit part of the Fenghuagshan iron deposits. The left half is the sedimentary wall rocks including the orebody dipping about 45° to the left, and the right half is the intrusive subvolcanic rocks.

two ore sulfates and two evaporite sulfates by the methods described in SASAKI *et al.* (1984). The results are listed in Table 3.

Rock Sulfur

Microdiorite from the Washan open pit (81102901) may be the least altered among the subvolcanic rocks studied. Although it has suffered actinolitization, hydrothermal alteration products are nil in this specimen; its CO_2 content is 0.04 wt.% and the rock-forming magnetite is not hematitized. Sulfur content is somewhat higher than common magnetite-series granitoids as 310 ppm, which occurs mostly as disseminated pyrite grains of subhedral to rounded forms. Some pyrite replaces mafic silicates as irregular grains. Very fine grains of chalcopyrite fill the interstices of the groundmass constituents. This rock gives $\delta^{34}S$ (CDT) of +13.6‰.

Granodiorite from drilling core at Dongyang (81103008) contains also little alteration products, such as sericite and carbonates (0.2 wt.% CO_2). Magnetite is again fresh. Its sulfur content is very low as 60 ppm as normal magnetite-series granitoids (ISHIHARA

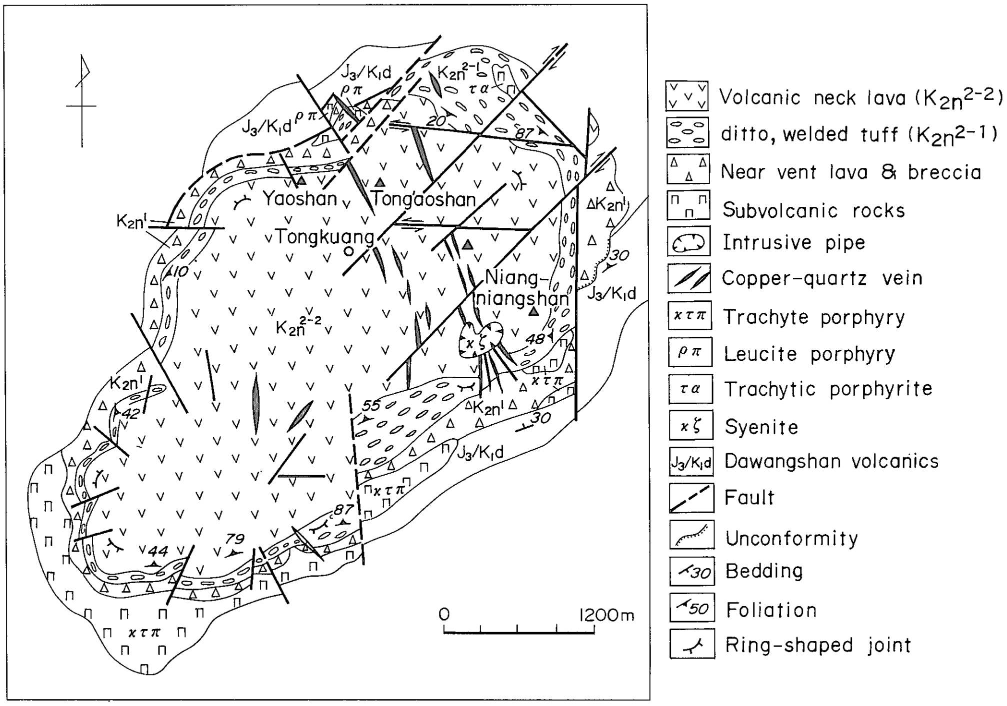

Fig. 8 Geological map of the Niangniangshan cauldron showing the distribution of copper veins (after TAO *et al.*, 1978).

Table 3 Sulfur isotope ratio ($\delta^{34}S_{CDT}$, ‰) from the Ningwu Basin

Sample No.	Locality	Rocks and Mode of Occurrence	$\delta^{34}S$ (‰)
Rock sulfur			
81102901	Washan pit, +45 mL, South edge	Orthopyroxene microdiorite, faintly altered	+13.6
81103008	Dongyang, T103, ZK-2, −300 m	Hornblende-biotite granodiorite	+11.3
Ore sulfide			
81103015	Meishan, −200 mL, Footwall 303	Footwall porphyrite, altered	+ 5.0
81103019	Meishan, mill concentrates Oct. 26, 1981	Pyrite disseminated in magnetite orebody	+ 6.8
81102903	Washan pit +59 mL, center	Pyrite-rich band in altered microdiorite	+ 1.3
81103010	Xiangshan, mill concentrates	Massive pyrite orebody in andesitic tuff	+ 4.1
81102813	Tongnan, mill concentrates	Chalcopyrite veins in the center of the Niangniangshan volcanic cauldron	+ 2.8
		(Average	+ 4.0)
Ore sulfate			
81103005	Xiangshan, ZK1406, −545 m	Anhydrite bed in andesitic tuff	+19.6
81102815	Tongnan, 3rd stage vein	Barite vein in the Niangniangshan cauldron	+14.4
Evaporite sulfate			
81103016	Nanjing, ZK-112, −963 m	Anhydrite-dolomite bed	+30.3
81103017	Nanjing, ZK-104, −1080 m	Anhydrite bed (middle Triassic)	+30.0

et al., 1983). Two grains of minute chalcopyrite filling cavity of mafic silicates are seen in this specimen. This rock gives δ^{34}S of +11.3‰.

Recently, magnetite-series granitoids of common orogenic belts are found to have +5.0‰ in Japan (SASAKI and ISHIHARA, 1979) and Chile (SASAKI *et al.*, 1984). The observed values of the Ningwu basin is about 8‰ higher than the island arc granitoids. Thus, the isotopic ratio of the rock sulfur designates one of the unique characteristics of the Ningwu rocks.

Ore Sulfur

From the porphyrite iron ore deposits, disseminated pyrite and vein-like pyritized zone were chosen for the analysis. Altered porphyrite (81103015) of the Meishan mine contains abundantly pyrite disseminated. The pyrite is irregular-anhedral in form replacing magnetite or being scattered in the groundmass with or without associated alteration minerals. Magnetite ores of the Meishan mine contain fairly abundant pyrite and this pyrite was concentrated by flotation (81103019). The sample is composed of i) Pyrite fragments of large subhedral crystals, ii) Pyrite surrounding hematitized magnetite or cutting magnetite as veinlet, and iii) Pyrite coexisting with hematitized magnetite. The pyrites and the hematitized magnetite, thus, probably the same stage products, or the former may have been slightly later crystallized. These pyrites give δ^{34}S of +5.0 and +6.8‰, which are about 6‰ lower than those of the rock sulfur; the relationship observed everywhere in orogenic belts (SASAKI *et al.*, 1984).

Vein-type pyrite which occurs along irregularly fracured zone in the Washan open pit may be much later than the pyrites above mentioned. This pyrite zone is composed of aggregates of beautiful cubes or subhedral crystals filled with hematite. The mineralization is considered lower in temperature and more oxidized in chemical condition than the main pyrite-bearing magnetite mineralizations. The pyrite gives δ^{34}S of +1.3‰, which is about 6‰ lower than those of the main stage pyrite, and the lowering is considered due to the different depositional condition.

Stratabound massive pyrite orebody occurs in andesitic tuffs at Xiangshan. Mill concentrates of the orebody consists of nearly 100% of fragmental pyrite and a few percent of colloform ones contained in silicate minerals. The other ore minerals are hematitized magnetite and hematite, and a few grains of chalcopyrite. This pyrite gives δ^{34}S of +4.1‰. There occurs also anhydrite bed separately in andesitic tuffs at Xiangshan. This sulfate gives δ^{34}S of +19.6‰.

Copper concentrates were selected for copper vein deposits in the Niangniangshan cauldron. The sample is composed of *ca.* 80% of pyrite, 10% of chalcopyrite and 5% of bornite and gangue minerals. These sulfides give +2.8‰, while the third stage vein of barite yields +14.4‰. These values are somewhat depleted in ^{34}S as compared with pyrite and anhydrite related to mineralization of the Dawangshan cycle.

Sedimentary Sulfur

Middle Triassic sulfate beds are distributed in the Lower Yangtze area, and may be present locally even underneath the Ningwu volcanic basin. Anhydrite obtained in deep drill hole in the suburban area of Nanjing city gives δ^{34}S of about +30‰. CHEN *et al.* (1981) analyzed gypsum(-anhydrite) from similar Triassic sulfate beds of the Yangtze platform in Sichuan Province and reported *ca.* +17‰ for the upper Triassic and *ca.* +28‰ for the lower Triassic formations. Thus our result is the highest among the Triassic evaporite sulfate values.

Oxygen and Strontium Isotopic Studies and Comparison with Other Areas

The Yanshanian igneous rocks in the Lower Yangtze area are only small portion of the Yanshanian magmatic products which spread over the whole eastern China. Available samples from other areas were analyzed and are compared with the Ningwu rocks in this chapter. The analytical results are listed in Tables 4 and 5.

At the southern margin of the Lower Yangtze area, there occur the Dexing porphyry copper deposits in the Jiangnan uplifted zone (Fig. 1). The ore deposits are related to the Yanshanian intrusive activity (168–172 Ma) of granodiorite porphyry (ZHU *et al.*, 1983), but the intrusive environment is different from that of the Ningwu basin, because the intrusion occurred not in depressed zone of volcano-sedimentary rocks but in uplifted zone of Precambrian metamorphic rocks.

Least altered, hornblende-biotite granodiorite in the barren core of granodiorite porphyry plug at the main orebody of Tongchang is found to contain 5800 ppm magnetite and 1400 ppm sphene (YAN and HU, 1980), thus belonging to magnetite series. Its major and minor element chemistry is similar to that of the Ningwu granitoids (Fig. 4). However, ore sulfides are reported to have an average of +0.12‰ $\delta^{34}S$ (ZHU *et al.*, 1983), which is about 4‰ lower than the average of all the ore sulfides in the Ningwu basin (Table 3).

Two granitoids from northern China, hornblende-bearing biotite granodiorite at Wanlichangcheng to the northwest of Beijing and biotite granite at the Yangjiazhangzi molybdenum-skarn mine (Fig. 11), both belong to magnetite series, because they contain fairly abundant magnetite, sphene and ilmenite. Their chemistry is also similar to that of the Ningwu granitoids, although the Wanlichangcheng rock is richer in Na_2O+K_2O (Table 4). Hence all the magnetite-series granitoids occurring in different tectonic settings appear to have common characteristics.

Ilmenite-series granitoids, on the other hand, tend to occur widely in the Caledonian folded belt of southern China (ISHIHARA and SATO, 1982). Coarse-grained biotite granite with microcline megacryst at Shatian, southern Jiangxi Province, contains muscovite but no magnetite, and is of typical ilmenite-series granite. Medium-grained biotite granite from the underground tunnel of the famed wolframite-quartz vein deposits at Xihuashan also contain no magnetite, thus belonging to ilmenite series. As compared with the magnetite-series granitoids, the ilmenite-series granites are quite different in not only Fe_2O_3/FeO ratio but also inminor element chemistry, being rich in Li, Rb, Pb, Sn and Be, and poor in Sr, which are characteristics everywhere observed on both series of granitoids (ISHIHARA, 1981).

O- and Sr-Isotopic Results

Oxygen isotopic ratios ($^{18}O/^{16}O$) were determined for eight least altered igneous rocks from the three areas mentioned above, and shown by δ-notation relative to SMOW. Strontium isotopic ratios ($^{87}Sr/^{86}Sr$) were determined for eight least altered samples from mostly the Ningwu basin. The ratios were normalized to the initial values by applying geological and K–Ar ages of the rocks. The results are listed in Table 5.

The $\delta^{18}O$ results on the rocks from other area than the Ningwu basin are clearly separated into two groups: the magnetite-series granitoids have the values lower than +8‰ as +6.1 to +7.6‰, whereas the ilmenite-series granitoids are higher in the values as +10.6 and +11.2%. On $\delta^{18}O$–SiO_2 diagram (Fig. 9), the magnetite-series rocks are plotted in the middle of the Japanese magnetite-series granitoids area and the ilmenite-series rocks are also in the Japanese ilmenite-series granitoids area. The studied granitoids appear to have the same genetic history as the Japanese magnetite-series and ilmenite-series granitoids (see MATSUHISA *et al.*, 1982). However, the Ningwu rocks have a variety of the ratios, which may have to be considered together with alteration observed on these rocks. Microdiorite at Washan gives a low value of +5.3‰, which may have been lowered during high temperature alteration of

Table 4 Major and minor compositions and their normative constituents of some granitoids from China

Locality	Dexing	Northern China		Southern Jiangxi	
Sample No.	79061901	79061301	79060901	79062301	79062201
SiO_2 (%)	63.45	66.21	74.63	71.42	75.96
TiO_2	0.44	0.57	0.21	0.17	0.09
Al_2O_3	16.07	17.27	13.94	15.47	13.18
Fe_2O_3	2.35	1.88	0.88	0.84	0.36
FeO	1.98	0.83	0.50	0.86	0.83
MnO	0.05	0.06	0.06	0.06	0.07
MgO	2.83	0.75	0.31	0.27	0.12
CaO	4.53	1.43	0.84	0.66	0.90
Na_2O	3.55	5.18	4.01	3.58	3.13
K_2O	3.14	4.90	4.21	5.38	4.34
P_2O_5	0.23	0.17	0.07	0.15	0.03
H_2O^+	0.75	0.04	0.04	0.45	0.46
H_2O^-	0.08	0.02	0.04	0.06	0.08
Total	99.45	99.31	99.74	99.37	99.55
T.C (ppm)	1,760	20	140	10	40
S	1,000	50	20	10	10
Cu	7	4	5	3	3
Zn	19	48	17	38	31
Pb	7	21	10	30	66
Li	22	51	23	109	171
Rb	112	142	198	371	512
Sr	810	435	169	81	48
Sn	1.0	1.7	1.0	8.5	12.3
Be	1.3	4.3	3.9	5.8	10.2
Kai	500	530	265	15	10
Q	17.53	13.62	33.13	28.29	38.57
C	—	1.25	1.43	2.92	1.77
or	18.56	28.96	24.88	31.79	25.65
ab	30.04	43.83	33.93	30.29	26.48
an	18.64	5.98	3.71	2.29	4.27
wo-di	0.97	—	—	—	—
en-di	0.75	—	—	—	—
fs-di	0.11	—	—	—	—
en-hy	6.29	1.87	0.77	0.67	0.30
fs-hy	0.95	—	—	0.72	1.21
mt	3.41	1.22	1.20	1.22	0.52
hm	—	1.04	0.05	—	—
il	0.84	1.08	0.40	0.32	0.17
ap	0.53	0.39	0.16	0.35	0.07
Q+ab+or	66.12	86.41	91.94	90.37	90.70

79061901: Hornblende-biotite granodiorite, drill core at the center of Tongchang orebody, ZK-305, −300 m, Dexing, northern Jiangxi.
79061301: Hornblende-bearing biotite granodiorite, a few km southeast of Wanlichangcheng sight-seeing site, Hebei.
79060901: Biotite granite, Beishan quarry, Siqian, Yangjiazhangzi mine, Liaoning.
79062301: Porphyritic biotite granite, south of Shatian, southern Jiangxi.
79062201: Biotite granite ("B"), 431 mL, Xihuashan mine, southern Jiangxi.

Table 5 Oxygen and strontium isotopic ratios of selected rocks in China.

Sample No.	Locality	Rock Type	SiO_2 (%)	$\delta^{18}O$ (‰)	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	Age (Ma)	R_0
Lower Yantgze area (magnetite series)										
81103003	Dashan, Ningwu	Altered andesite	54.9	+ 7.8	75	756	0.287	0.70603	120	0.70554
81102901	Washan mine, *do.*	Microdiorite	55.4	+ 5.3	75	601	0.361	0.70622	120	0.70560
81103008	Dongyang, *do.*	Granodiorite	63.4	+ 8.5	134	451	0.860	0.70777	120	0.70630
81102806	Yaoshan, *do.*	Phonolite welded tuff	59.9	n.d.	154	641	0.696	0.70723	105	0.70619
81103001	Fushan, *do.*	Paleogene basalt	44.3	n.d.	37	918	0.117	0.70467	60	0.70457
79061901	Dexing, Jiangxi	Hornblende-biotite granodiorite	63.5	+ 6.4	112	810	0.400	0.70524	170	0.70427
Northern China (magnetite series)										
79061301	Wanlichangcheng, Hebei	Hornblende-bearing biotite granodiorite	66.2	+ 6.1	142	435	0.945	0.70718	185	0.70469
79060901	Yangjiazhangzi, Liaoning	Biotite granite	74.6	+ 7.6	198	169	3.39	0.71309	185	0.70417
Southern Jiangxi (ilmenite series)										
79062301	Shatian, Jiangxi	Muscovite-bearing biotite granite	71.4	+11.2	371	81	n.d.	n.d.	—	—
79062201	Xihuashan, *do.*	Biotite granite	76.0	+10.6	512	48	n.d.	n.d.	—	—

Age data are taken and estimated from Ningwu Research Group (1978) and ISHIHARA and SHIBATA (1980).

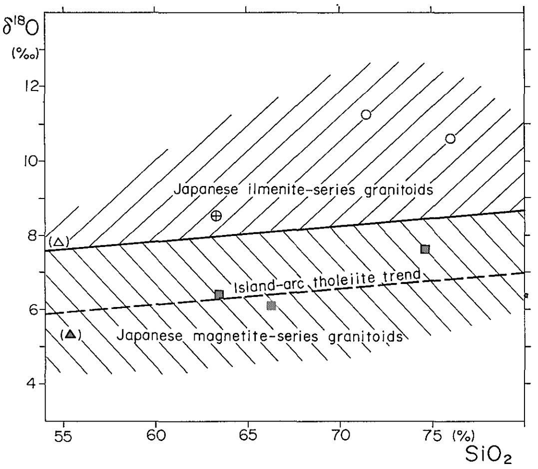

Fig. 9 $\delta^{18}O$ vs. SiO_2 content of the studied rocks. △ Volcanic rock, ▲ Subvolcanic rock, and ⊕ granitoid of the Ningwu basin. ■ Magnetite-series granitoids of Dexing and northern China. ○ Ilmenite-series granitoids of southern Jiangxi. The areas for the Japanese granitoids and island-arc tholeiite are taken from MATSUHISA *et al.* (1982). The symbols in parenthesis indicate isotopic data possibly modified due to alteration.

actinolitization and biotitization. Altered andesite at Dashan has relatively high value as +7.8‰, which may have been ^{18}O-enriched during low temperature alteration of carbonitization and chloritization. Granodiorite at Dongyang is the least altered among the three rocks analyzed and its $\delta^{18}O$ of +8.5‰ is clearly high as being considered it atypical magnetite-series rock. This rock has the highest value of the initial $^{87}Sr/^{86}Sr$ ratio, suggesting a crustal contamination.

The initial $^{87}Sr/^{86}Sr$ ratios also vary clearly among the Ningwu magnetite-series rocks. In following the igneous history, olivine-orthopyroxene-clinopyroxene andesite of Dawangshan cycle and closely related orthopyroxene microdiorite have intermediate values of 0.7055-0.7056. However, pyroxene-bearing hornblende-biotite granodiorite and phonolitic welded tuff are much higher in the ratio as 0.7062-0.7063, indicating that these rocks were generated from Sr-isotopically different materials from those for the Dawangshan volcanic rocks, *i.e.*, much more crustal contribution is expected.

The final volcanism of Paleogene basalt has the lowest ratio of 0.7046 which is different from the other rocks of the Ningwu basin. But this ratio is still higher than that of magmas originated in the fresh upper mantle and, being supported by microscopic observation, a small amount of crustal contribution is assumed. Similar basalts are distributed regionally along the continental margin of eastern China (ZHOU and ARMSTRONG, 1982), and the studied basalt appears to be an independent magmatism unrelated to the Cretaceous Ningwu rocks. It is rather surprising that felsic magnetite-series granitoids of northern China have low initial $^{87}Sr/^{86}Sr$ ratios as 0.7041-0.7047 (Table 5).

Discussion and Conclusions

Igneous rocks of the Ningwu Basin can be divided mineralogically and chemically into four suites within the magnetite-series category.

The first suite is of the early Cretaceous, Longwangshan-Dawangshan volcanic and subvolcanic rocks which are the largest in amount among the Ningwu igneous rocks. The volcanic rocks are basaltic andesite and andesite slightly predominated by K_2O. The subvolcanic rocks are microdiorite and microgabbro, and possibly cogenetic with the volcanic rocks. Although these rocks are mafic in composition, their initial $^{87}Sr/^{86}Sr$ ratios are higher than those of basaltic rocks, which are originated in primitive upper mantle materials, and some degrees of crustal contribution is assumed.

Granitoids may be different in origin from the first suite subvolcanic rocks, because they are more felsic than the subvolcanic rocks and higher in the oxygen and strontium isotopic ratios. Thus, these rocks are considered as independent magma type, having had the involvement of larger amount of crustal materials than the subvolcanic rocks.

The third suite is alkaline rocks of the

Niangniangshan and Gushan cycles. This suite occurred in late Cretaceous time after erosion of iron ores which were formed by the subvolcanic intrusion of the Dawangshan cycle. This suite is quite different from the others by the extremely high alkali content. The initial $^{87}Sr/^{86}Sr$ ratio is higher than the first suite volcanics. Thus, this suite is not the differentiation products of the first suite but an independent magma type.

The fourth one is also an alkaline suite of olivine basalt. This has low initial $^{87}Sr/^{86}Sr$ ratio and is considered to have formed by a small degree of partial melting of the upper mantle materials, due to regional tectonism in the continental margin of eastern China.

Cause for Intensive Mineralization

One of the characteristics of the Ningwu basin is rich mineralizations of unique magmatic-hydrothermal types. This may be coupled with unusually high $\delta^{34}S$ values of rock sulfur in the intrusive rocks (avg. +12.5‰), which is about 8‰ higher than common magnetite-series granitoids in island arc environment like Japan and is the highest one among the rock isotopic ratios obtained from the magnetite-series granitic terranes of the Circum-Pacific region (Fig. 10). The mineralization characteristics are seen in the whole Lower Yangtze area, where large iron and base metal deposits are abundantly seen. The ore reserves and past production figures from this area are much larger than those of the southeast coast and Daxing'anling volcanic terrane where the Yanshanian volcanic and intrusive rocks are distributed in much wider area but only little ore deposits are known to occur (ISHIHARA, 1984).

In China, important evaporite-bearing sedimentary formations are distributed along the Yangtze river (Fig. 11). They are Triassic in age. Calcium sulfate beds are intercalated in marine carbonate rocks. Rock salt is locally present (TAO, 1983). Such anhydrite bed of the Nanjing suburb has extremely high $\delta^{34}S$ value of *ca.* +30‰.

In order to have heavy S-isotopic ratio in intrusive rocks, one of the possible mechanisms is introduction of heavy sedimentary sulfur into the magmas during their ascent through the continental crust. Sulfur appears to be one of the most mobile components among those from the intruded wall rocks (ISHIHARA *et al.*, 1985), so that S-isotopic ratio of given magmas may easily be changed without changing much in other components.

Chlorine present in the evaporite may also be mobile through the magma-wall rock interaction. Among various forms of metal complex to be transported in magmatic fluids, chloride complex model appears to be valid for iron and base metal mineralizations. The Cl-enriched magma may extract these metals from the wall rocks and solidifying magma, and accumulate them into the intrusive cusps. Such a magma would have a large capacity to produce the iron and base metal ore deposits.

This interpretation is supported by isotopic ratios of the related ore sulfur. As mentioned previously, $\delta^{34}S$ value of ore sulfur of the Dexing porphyry copper deposits where granodiorite intrudes directly into the Precambrian basement is nearly 0‰. However, a similar type but iron concentrated, porphyrite iron deposits of the Ningwu depressed volcanic basin where Triassic sulfate beds occur above the Precambrian basement, have $\delta^{34}S$ values

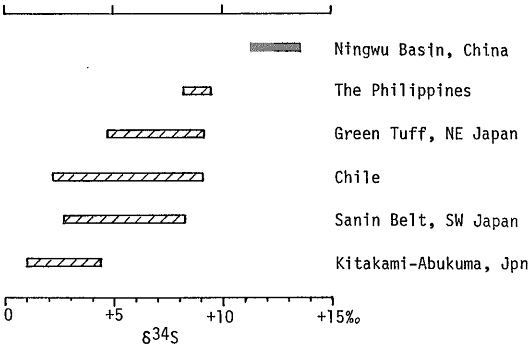

Fig. 10 Sulfur isotopic ratios of rock sulfur extracted from Mesozoic and Cenozoic granitoids of the Circum-Pacific region. The data other than those of the Ningwu Basin are from SASAKI and ISHIHARA (1979) and SASAKI *et al.* (1984).

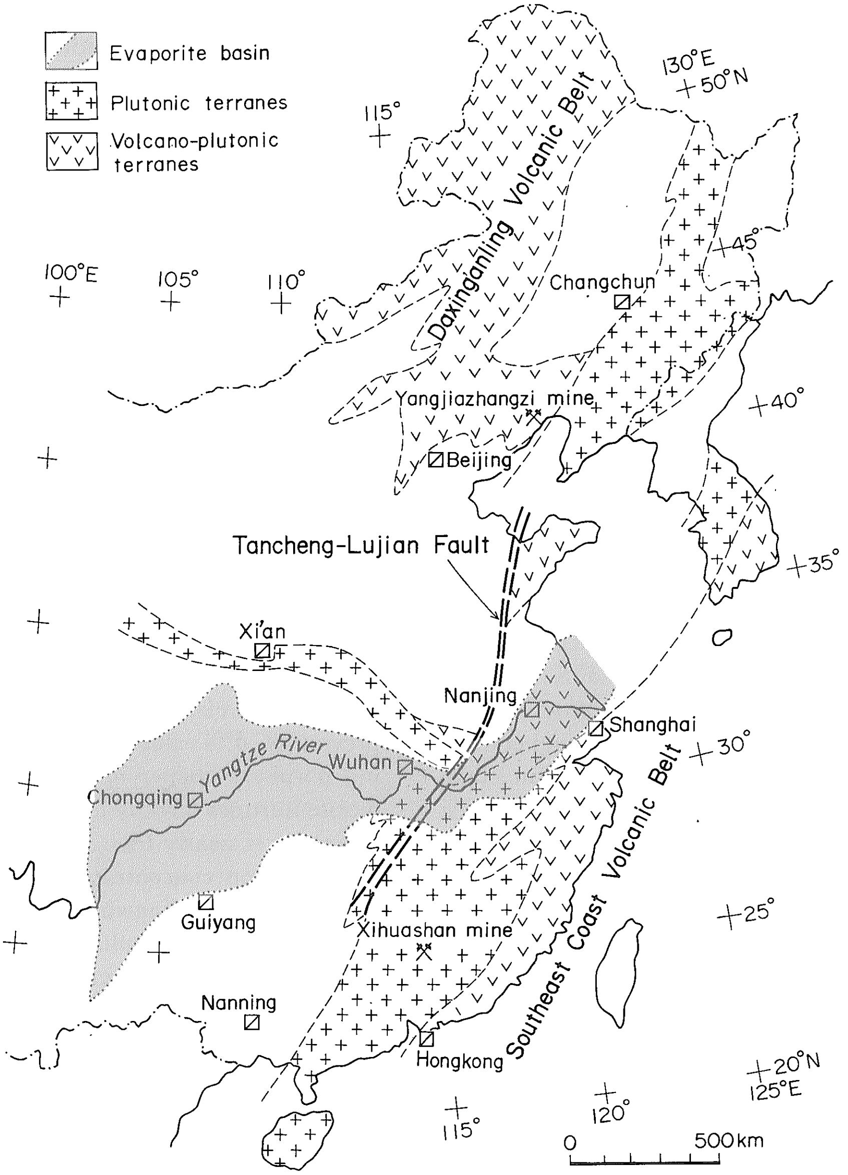

Fig. 11 Distribution of the early Middle Triassic evaporite basin and the Yanshanian volcano-plutonic and plutonic terranes of eastern China. After ISHIHARA (1984) and SHENG *et al.* (1985). Note the evaporite basin intersected by the Yanshanian igneous activities.

around +6‰. The proposed model is schematically illustrated in Fig. 12. The isotopic fractionation between the rock and ore sulfur ratios is about 6‰, which is reasonable value for rocks and ores crystallized under relatively high fO_2 conditions (SASAKI *et al.*, 1984).

In the eastern Hubei Province, CAI (1980) stressed the significance of Triassic evaporite sulfate beds for the iron and copper mineralizations, because 91 percent and more than 70 percent of the iron and copper ore reserves, respectively, are found not in Paleozoic normal marine limestone but in the

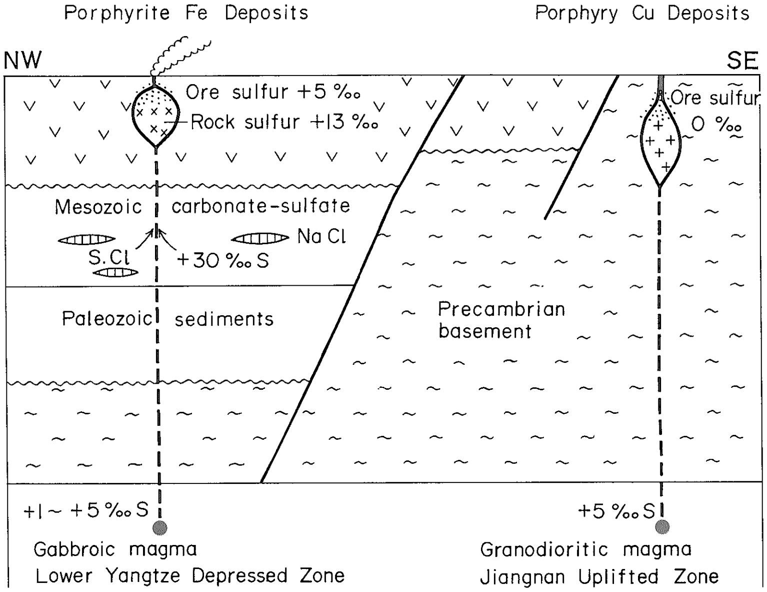

Fig. 12 Genetic model and sulfur isotopic evolution for the ore deposits of the Yangtze platform.

Triassic evaporite-bearing limestone formations. His model considers direct contribution of sulfate and halite to the mineralization, and is in accord with extremely high δ^{34}S values of the ore sulfur for the contact metasomatic iron (+12 ~ +18‰) and iron-copper (+5 ~ +10‰) ore deposits occurring in the volcanic basins of the province (ZHANG, 1980).

Intense mineralizations in the Lower Yangtze area are considered to be resulted from magmatism that occurred in the unique geological environment where a magnetite-series magmatism intersected evaporite basins (Fig. 11). In the Ningwu basin, the hydrous magma was contaminated by the sulfate sulfur and chlorine at a magmatic stage. This external supply of crustal ore constituents may be the main reason for the intense mineralization in the Lower Yangtze area.

Acknowledgement The field work of this study was arranged by the people of the Nanjing Institute of Geology and Mineral Resources, and supported by many resident geologists from the Ministry of Geology and Mineral Resources, and Ministry of Metallurgical Industry, to whom we express sincere gratitude. We also thank to Dr. N. ISSHIKI of GSJ for microscopic observation of alkaline rocks and to the officials of the International Research and Development Cooperation Division of AIST, MITI, and of the Overseas Geology Office of GSJ for their administrative assistance.

References

CAI, B. J. (1980) The relationship of gypsum salt beds with endogenic copper and iron ores in the middle-lower Yangtze Valley. *Geochemistry*, no. 2, p. 193-199 (Japanese translation by F. KISHIMOTO in Open-File Rept. 1985 -2, 23p., Geol. Surv. Japan)

CHEN, J. S. and six others (1981) Sulfur isotopes of marine gypsum deposits. *Sci. Geol. Sinica*, no. 3, p. 273-277.

GSJ (Geological Survey of Japan) edited (1985) *Research on mineral resources associated with volcanic and plutonic rocks*. Rept. ITIT Projects No. 8113, Intern. Res. Develop. Coop. Div., AIST, MITI, Tokyo, 191p.

HUANG, T. K. (1959) New studies on the geotectonic subdivision of eastern China and their characteristics. *Intern. Geol. Review*, vol. 1, no. 11, p. 73-93.

ISHIHARA, S. (1981) Granitoid series and mineralization. *75th. Anniv. Vol. Econ. Geol.*, p. 458-484.

——— (1982a) Mineral resources of China (1) Porphyrite iron ore deposits. *Chishitsu News*, no. 334, p. 20-32.

——— (1982b) *ditto* (2) Porphyry-type Cu and Mo deposits. *Chishitsu News*, no. 335, p. 18-32.

——— (1983) *ditto* (4) Tungsten ore deposits. *Chishitsu News*, no. 346, p. 39-51.

——— (1984) Granitoid series and Mo/W-Sn mineralization in East Asia. *Rept. Geol. Surv. Japan*, no. 263 (Centennial Vol. GSJ), p. 173-208.

——— and SHIBATA, K. (1980) Mineralization age of the Yangjizhangzi molybdenum deposits, China. *Mining Geol.*, vol. 30, p. 27-29.

——— and SATO, T. (1982) Mineral resources of China, (3) Granitoids of southern China. *Chishitsu News*, no. 340, p. 34-45.

——— KANISAWA, S. and TERASHIMA, S. (1983) Sulfur and sulfides in the Cretaceous magnetite-series granitoids of the Kitakami Mountains, Japan. *Jour. Japan. Assoc. Min. Pet. Econ. Geol.*, vol. 78, p. 1-10.

———, MATSUHISA, Y., SASAKI, A. and TERASHIMA, S. (1985) Wall-rock assimilation by magnetite-series granitoid at the Miyako pluton, Kitakami, northeastern Japan. *Jour. Geol. Soc. Japan*, vol. 91, p. 679-690.

LI, W. (1983) Some characteristics of the oxidation zone of sulfide ore deposits in Lower Yangtze area, southeast China. *Mining Geol.*, vol. 33, p. 137-147.

MATSUHIASA, Y., SASAKI, A., SHIBATA, K. and ISHIHARA, S. (1982) Source diversity of the Japanese granitoids: An O, Sr and S isotopic approach. *Abs. 5th Intern. Conf. Geochron. Cosmochron. Isotope Geol.*, Nikko, Japan, p. 239-240.

MIYASHIRO, A. and KUSHIRO, I. (1975) *Petrology II: Classification and nature of rocks*. Kyoritsu Zensho, Tokyo, 171p.

NAKAJIMA, T. (1984) Geology of the Yangtze platform, China. *Chishitsu News*, no. 359, p. 42-56.

Ningwu Research Group (1978) *Ningwu porphyrite iron ores*. Geol. Pub. House, Beijing, 196p.

SASAKI, A. and ISHIHARA, S. (1979) Sulfur isotopic composition of the magnetite-series and ilmenite-series granitoids in Japan. *Contrib. Mineral. Petrol.*, vol. 68, p. 107-115.

———, ULRIKSEN, C. E., SATO, K. and ISHIHARA, S. (1984) Sulfur isotope reconnaissance of porphyry copper and manto-type deposits in Chile and the Philippines. *Bull. Geol. Surv. Japan*, vol. 35, p. 616-622.

SHENG, J. Z., RUI, L. and CHEN, C. Z. (1985) Permian and Triassic sedimentary facies and paleogeography of South China. *The Thethys* (K. NAKAZAWA and J. M. DICKINS edited), Tokai Univ. Press. p. 59-81.

TAO, K. Y., WU, Y., HUANG, G. Z. and CHEN, J. G. (1978) The structural and facies characteristics of Niangniangshan paleocaldra. *Acta Geol. Sinica*, no. 1, p. 40-52.

TAO, W. P. (1983) Triassic marine gypsum deposits of China. *Acta Geol. Sinica*, no. 2, p. 172-183.

WENG, S. J. and WANG, W. G. (1981) Tectonism and magmatism of Lower Yangtze Valley. *Bull. Nanjing Inst. Geol. Miner. Resour.* vol. 2, no. 3, p. 1-74.

YAN, M. Z. and HU, K. (1980) Geological characteristics of the Dexing porphyry copper deposits, Jiangxi, China. In Granitic Magmatism and Related Mineralization (S. ISHIHARA and S. TAKENOUCHI eds.), *Mining Geol. Spec. Issue*, no. 8, p. 197-204.

ZHANG, L. G. (1980) A sulfur isotopic investigations of iron-copper deposits, SE Hubei province. *Bull. Chinese Academy Geol. Sci.*, (Yichang Inst. Geol. Miner. Res. edition), vol. 1, no. 1, p. 113-125.

ZHOU, X. H. and ARMSTRONG, R. L. (1982) Cenozoic volcanic rocks of eastern China—secular and geographic trends in chemistry and strontium isotopic composition. *Earth Planet. Sci. Let.*, vol. 58, p. 301-329.

ZHU, X., HUANG, C. K., RUI, Z. Y., ZHOU, H. Y., ZHU, X. J., HU, C. S. and MEI, Z. K. (1983) *The geology of Dexing porphyry copper ore field*. Geol. Pub. House, Beijing, 336p.

中国東部，揚子江下流域，寧蕪盆地における白亜紀火成活動と関連鉱化作用の特徴

石原舜三・李　文達・佐々木昭・柴田　賢・松久幸敬・寺島　滋

要　　旨

中華人民共和国，揚子江プラットフォームには火山深成岩を伴う沈降帯が知られており，著しい鉄・卑金属鉱化作用を伴う．寧蕪盆地はその一つで，揚子江下流域，南京—蕪湖間に分布する．盆地は中生代初—中期の堆積作用に始まり，ジュラ紀後期—白亜紀の火山作用，白亜紀の貫入活動をうける．これら火成活動は後期燕山期に属するものである．

火山岩と貫入岩類は主として磁鉄鉱系に属し，次の4時期に分けられる．(i)竜王山—大王山期火山岩—亜火山岩類．これはカルクアルカリ岩に属し，玄武岩—安山岩質である．亜火山岩は微粒斑糲岩—閃緑岩で，個々の岩体頂部に磁鉄鉱—赤鉄鉱鉱床を伴う．(ii)カルクアルカリ岩系花崗閃緑岩—花崗岩．(iii)小規模に分布する娘々山—胡山期のアルカリ岩系火山岩類．娘々山カルデラにはその火山活動に関係して銅石英脈がみられる．以上の白亜紀火成岩類のSr初生値は早期(0.7055)から後期(0.7063)へ上昇する傾向を示す．全岩$\delta^{18}O$値は一般の磁鉄鉱系岩石よりやや高い値を示す．(iv)以上と無関係にアルカリ岩系のかんらん石玄武岩が点在する．

S同位体比は，岩石・鉱石ともに高い$\delta^{34}S$値で特徴づけられ，貫入岩の全岩硫黄は平均＋13‰，鉱染状鉱石(主に黄鉄鉱)は平均＋6‰である．この著しく^{34}Sに富む性質はこの火山—深成岩盆地の下位に存在する三畳紀の蒸発性(硬)石膏層に起因するものと解釈された．すなわち，その重い硫酸塩硫黄(＋30‰$\delta^{34}S$)が貫入上昇するマグマに補促され，マグマと鉱液の硫黄同位体比を高めたものである．石膏層には岩塩層が含まれることがあり，したがってマグマ—蒸発岩反応によって，鉱液の生成に最も重要なClとSとがマグマ中に高まることが期待される．同じく磁鉄鉱系火山岩帯である大興安嶺や福建火山帯と比較して，揚子江流域の鉱化作用が著しい点は，上記の生成モデルによって説明される．

（受付：1985年5月16日；受理：1985年6月27日）