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GEOLOGICAL SURVEY OF JAPAN

FRACTURE SYSTEM AND NATURAL GAS OCCURRENCE IN THE JOBAN COAL FIELD

By

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Masatsugu SAITO, Director

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Abstract

Successful natural gas wells in the Joban coal field, Tertiary in age, are found along the NNW trending faults in the southern area, and near the junction of the WNW and NW faults in the northern area. Prominent trends of faults in the coal field area are WNW, NW, NNW, ENE and NNE, while those of joints except that are parallel to the faults are NNE, NE and NNW. They are called here Shirasaka A, Shirasaka B, Idozawa, Karasudate and Yumoto fault sets: and joint set I, II and III.

Among them, field evidences indicate, WNW, NNW and ENE faults are as old as pre-Tertiary. A rhombic pattern consisting of NNW and WNW faults was formed in the earlier fault movements in pre-Tertiary. The later fault movement in Miocene was strongly controlled by this rhombic pattern of the basement rocks, and formed lots of parallel, normal dip-slip faults in the Tertiary rocks. Possibly NW faults and NNW joints are related structurally to the pre-existing NNW faults. NNE faults, NNE joints and NE joints are possibly consequence of the lateral compression perpendicular to WNW and NW faults. Thus, NNW and WNW faults or Idozawa and Shirasaka A fault sets in the basement rocks are considered most important to the occurrence of the natural gas.

I. Introduction

Natural gas in the Joban coal field has been exploited after the last World War and in 1961 the annual production amounted to about 35 million m^3 in 30 or 40 drillings. The large part of the production is used for chemical industry as raw material and the rest for fuel in cities and towns.

The natural gas in this field has been studied by many individuals and groups. Among them are Arakawa (1961), Asano (1960), Eguchi and others (1960), Ishiwada and others (1958), Motojima and Makino (1958), Tohoku University, Geological Survey, Furukawa Coal Mining Co., Joban Coal Mining Co., and Nakoso Gas Exploitation Co.. Geological and technical summarizations on the exploitation of the natural gas was published by Eguchi and others (1958) and, recently, by the Research Committee on the exploitation of the natural gas in the Joban coal field under the sponsorship of the Commerce and Industry Office at Sendai (1962).

It has been acknowledged by all these workers that the occurrence of the natural gas is closely related to the structural features. Usually the productive gas drillings are found along faults or in faulted zones. Most of the previous workers agree that migration and accumulation are likely done through the minor fractures made by faultings.

This work was done in hope of obtaining more knowledge about the fracture system of the Tertiary sedimentary rocks in the Joban coal field, that is, the fracture pattern on a regional scale and the cause of the local concentration of minor fractures. The study of fracture system, or that of the second fractures which is resulted from any primary crustal deformations such as faultings or foldings contains many undissolved problems, and it is true that the fracture studies in most fields have proved too complex for reliable interpretation because of the complicated regional structure. Nevertheless, the fracture study of this field is considered hopeful because of simplicity of the structure, regularity of the fault pattern, detailed geological contributions by many previous workers, and abundant subsurface data provided by coal mining companies and gas exploitation companies.

This work was made as a part of the first year's work in the five-year research program of coal mine gas in the Geological Survey of Japan, and the field survey was done from October 31 to November 24 in 1960, with an additional survey of several days in the next spring.

The author thanks Prof. Fred A Donath, Prof. Motoki Eguchi, Prof. Toshio Kimura, Dr. Arata Sugimura, Prof. Shin Kitamura and Dr. Tokihiko Matsuda for discussion and critical reading of the manuscript. Thanks are also due to Taira Branch of Tokyo International Trade and Industry Bureau, Furukawa Mining Co., Dainihon Coal Mine Co., Nihon Suiso Kogyo and Joban Coal Mine Co. for hospitality in the field.

II. General Geology

Previous Works

The Joban coal field is the Palaeogene coal field along the Pacific Coast of Japan. Topographically it consists of low hills less than 200 m in height and alluvium plains made by the southeasterly rivers. On the west it is bounded by the Abukuma Plateau, a peneplain rising abruptly 500–700 m from the hills.

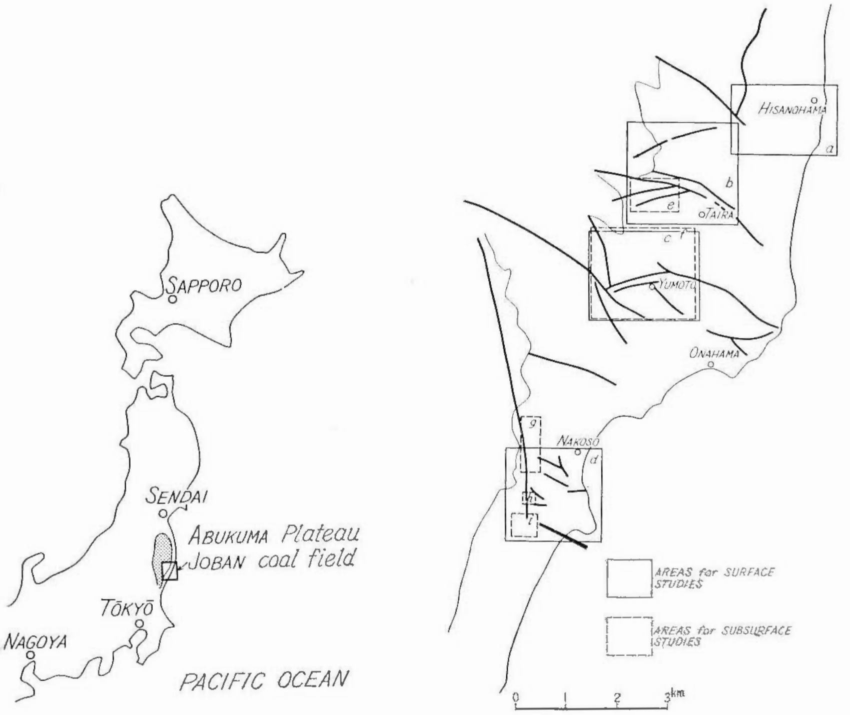
Since this is one of the oldest coal fields in Japan, it has been studied in detail by many geologists. The latest contributions concerning the stratigraphy and the structure are those of Shoji and Kamada (1958); Omori (1954 a, 1954 b); Matsui, and Sato (1951, 1952, 1953); Suzuki (1954); Yoshida and Suyama (1952); and Iwao and Matsui (1961). The geological map in scale of 1/50,000 with the explanatory text of this coal field was published in 1957 by the Geological Survey. As compared with the Tertiary sedimentary rocks in the coal field, the basement rocks in the Abukuma Plateau have been less studied either stratigraphically or structurally.

Watanabe and others (1955) studied the igneous activities of the Plateau with some references on the structural features. Omori and others (1953) studied about the faultings in the Tanakura tectonic belt.

Descriptions in this chapter are based mostly upon these contributions.

Basement Rocks

The Abukuma Plateau constitutes a massive uplifted block of both metamorphic or non-metamorphic pre-Tertiary sedimentary rocks that are so-called "the Older Rocks" and granitic or basic igneous rocks in the core of the Plateau, and Cretaceous sedimentary rocks along the eastern margin. The geology of the core has been little known because of complicated structure among the Older Rocks or the igneous rocks and between the both. Most prominent structural features are three approximately N 150° W trending large faulted belts, which has been named Futaba, Chuo, and Tanakura faulted belts from north to south. Watanabe and others (1955) described that the Older Rocks exhibit apparently a pattern of S shaped structure among these



a)	HISANOHAMA	Fig. 7
b)	TAIRA	Fig. 8
c)	YUMOTO	Fig. 9
d)	NAKOSO	Fig. 10
e)	TAIRA	Fig. 12
f)	YUMOTO	Fig. 13
g)	NAKOSO-1	Fig. 14
h)	NAKOSO-2	Fig. 15
i)	NAKOSO-3	Fig. 16

Fig. 1 Index map of the Joban coal field and the selected areas of fracture study

large faulted belts; they have a constant trend of N 30–40° E in the middle between Futaba and Chuo faulted belts, but toward the north of Chuo faulted belt they vary in trend from north to N 10° W, nearly parallel to Chuo faulted belt, and they trend northeast in the southern part of the Plateau between Chuo and Tanakura faulted belts. Among the three, Tanakura faulted belt has been best studied by some workers. Omori and others (1953) considered that this faulted belt, the structural sheared zones in which Tertiary sedimentary rocks as well as the Older Rocks have been crushed into blocks, was formed in late Miocene just along the places where the antecedent faults had occurred before the sedimentation of the Tertiary sedimentary rocks. This older faulting is characterised by the presence of mylonitic rocks and by the appearance of intense and extensive deformation of the Older Rocks among many parallel faults, and perhaps the faulting in the belt was repeated two or three times during that

Table 1 Stratigraphy

AGE	GROUP	FORMATION	ROCK	THICKNESS (m)	FAULTING
Lat. Miocene	TAGA group		tuff's ss tuff's sh	100—600	Later Faultings
	TAKAKU group		ss, ms	0—240	
Mid. Miocene	SHIRADO group		tuff breccia tuff's ss	70—170	
	YUNAGAYA group	TAIRA formation	tuff breccia ss, ms	400—800	
		KAMENO-O formation	alt.; sh, ss		
		MIZUNOYA formation	sandy ms		
Earl. Miocene		GOYASU formation	ss, cg, (coal), G		
	SHIRAMIZU	SHIRASAKA formation	sh	300—500	
		ASAGAI formation	ss, G		
Oligocene		IWAKI formation	ss, cg, coal, G		
Pre-Tertiary	BASEMENT COMPLEX of the ABUKUMA PLATEAU				Earlier Faultings

G: gas reservoir bearing formations

times, though the latest was dated likely in Cretaceous or Palaeogene. It is probable that the older faulting occurred also in Futaba and Chuo faulted belts.

The latest faulting along Futaba faulted belt has been dated quite recently. Mita (1951) and Sugai and others (1957) observed that along Futaba fault, Yunagaya group moved upwards relatively to so-called Taga group along the fault plane ranging in dip from 24° to 30° westward.

Tertiary Sedimentary Rocks

The Tertiary rocks of the Joban coal field range from Oligocene to late Tertiary in age and the thickness is between 900 and 2,300 meters. Structurally they are divided into two; the older is the strata between Shiramizu and Takaku groups, which has been deformed more or less and as a whole dips approximately 10° eastward and strikes north to south: the later is Taga group, which, having been little deformed, was deposited in several basins unconformably upon the older, and dips nearly horizontally.

The Shiramizu group forms remarkably a cycle in sedimentation from coarse grain of Iwaki formation to fine of Shirasaka formation. The Iwaki formation is made up largely of coarse, loose sandstone, in some beds, become coarser to be pebbly conglomerate, and contains the workable coal seams 150 or 250 m high from the base of the formation. The Asagai formation is made up largely of massive, medium sandstone and includes Asagai fauna (late Oligocene). The Shirasaka formation consists of massive shale and displays extinctly a regular jointing on its exposure.

Yunagaya group rests unconformably upon the Shiramizu group. The thickness range between 400 and 800 meters. Between Gayasu and Kameno-o formation, this group is similar to the Yunagawa group in cyclic sedimentation, but differs from the

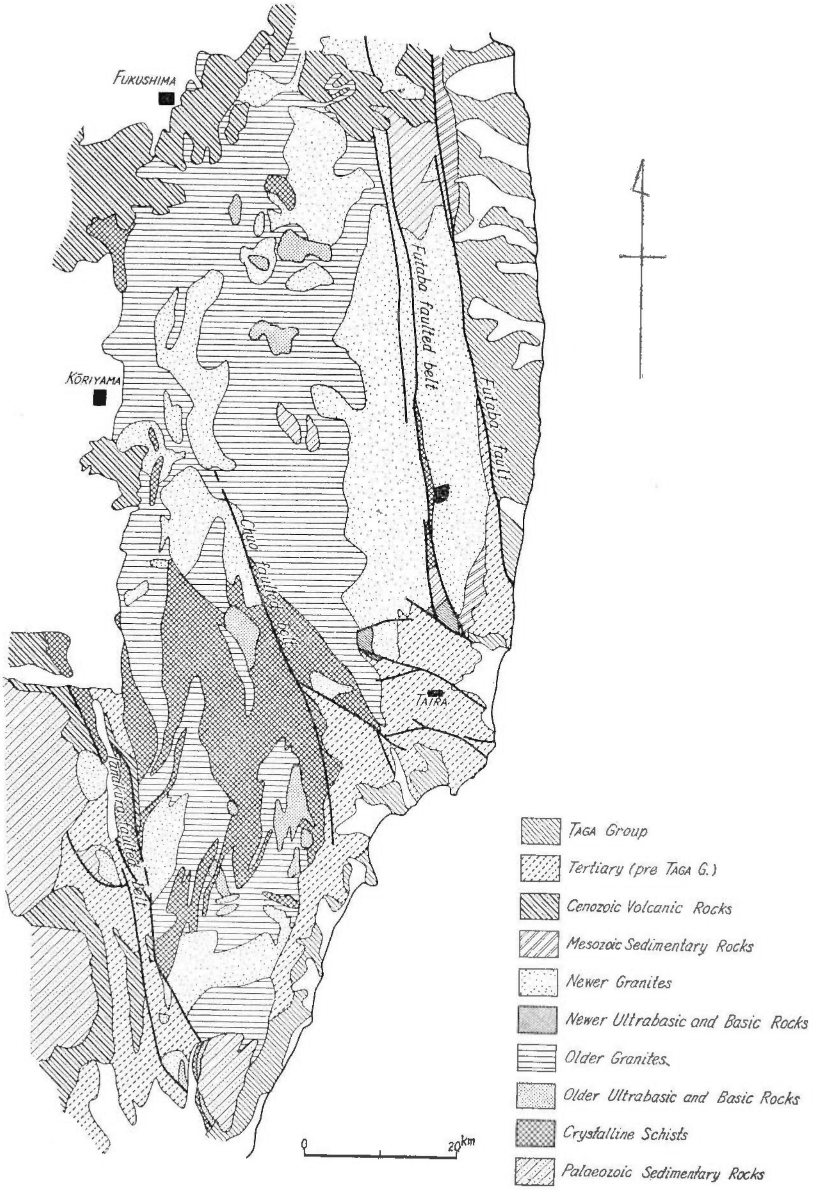


Fig. 2 Geological map of the Abukuma plateau

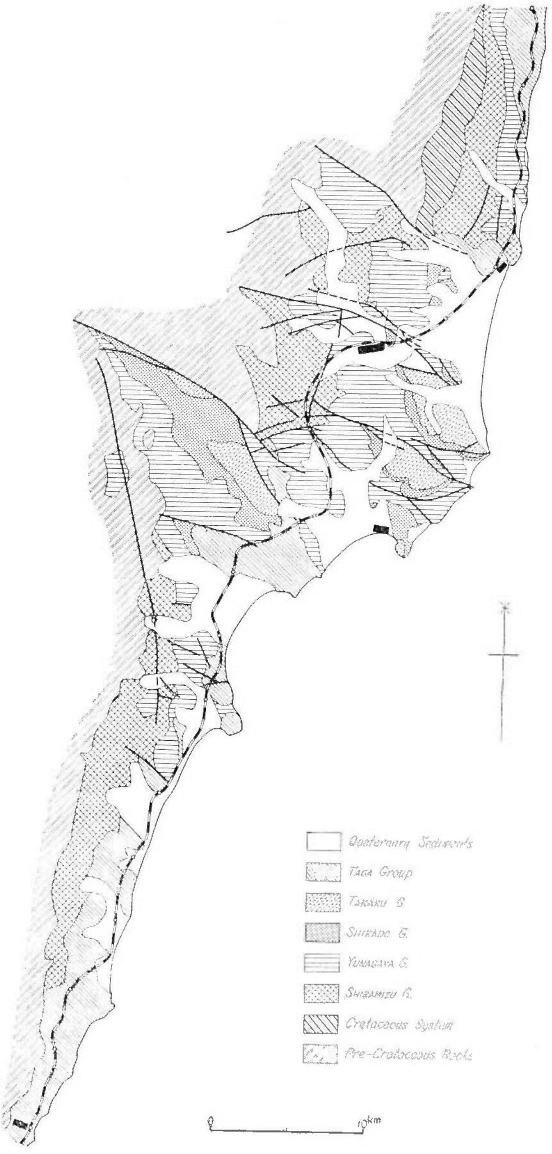


Fig. 3 Geological map of the Joban coal field

Yunagaya in the presence of interbedded tuffaceous matter. The Taira formation, the upperest one of the group consists of 70 to 170 meters of massive pyroclastic rocks, such as tuff breccia and andesitic tuff interbedded with sandstone and sandy mudstone.

The Shirado group rests upon the Yunagaya group unconformably in some places. This group is also a series of pyroclastic rocks that include tuff, tuffaceous sandstone, and shale, and the thickness is variable in places. Shoji and Kamada (1958) described Yunagaya and Shirado groups to range from early to late Miocene in age.

Sugai, Matsui, and Sato (1957) distinguished, in so-called Taga group, a series of the sedimentary rocks which have folded as much as the strata between Yunagaya and Shirado groups from that which have little folded and been called the former Takaku group. Some workers including Shoji and Kamada (1958) disagreed with this consideration.

The sedimentary rocks older than Taga group have been clearly faulted by Futatsuya, Yunotake, and other faults in the Joban coal field. Yoshida and Suyama (1952), moreover, noticed that the Iwaki formation must have deposited differentiately in several basins isolated each other by uplifted pre-Tertiary rocks because the coal seams and other marked beds could not be correlated among these basins. This differentiation decreases as it comes to the upper formation of Shiramizu group. However, in Goyasu formation of Yunagaya group the sedimentation was again differentiated slightly. They interpreted the uplifting of pre-Tertiary rocks as resulted from the earlier movements of WNW or NW trending large faults including Futatsuya and Yunotake.

Therefore the earlier movement must have occurred before the sedimentation of Shiramizu group and again, but less intensely, before that of Yunagaya group.

Besides, the structural features of the Tertiary rocks clearly indicate that the later movement of these faults might have been made after the Takaku groups and before Taga group. It is further indicated that all other larger faults were formed at that time and, then, the latest structure of the Joban coal field was completed.

Taga group, consisting of 100 to 600 meters of coarse tuffaceous sandstone and interbedded with shale, was deposited unconformably upon these later faults in several places. Shoji and Kamada (1958) considered that Taga group was formed in late Miocene or between late Miocene and early Pliocene.

As compared with the geology of the Abukuma Plateau, both the earlier and the later faultings in the Joban coal field are likely to belong to the same geologic age as those along the N 15° W large faulted belts in the Plateau. The earlier faulting is dated before the sedimentation of the Tertiary rocks, or older than Oligocene, while the later faultings dated perhaps in late Miocene. The thrusting along the southern part of Futaba fault that occurred undoubtedly after so-called Taga group may be considered to follow to this later faultings in late Miocene, but more probably it may be attributed to be another faulting, different in nature and later in age.

III. Natural Gas Accumulations

The natural gas in the Joban coal field is classified as the so-called coal mine gas merely because it has been collected from the drillings in the coal field and because the reservoir beds are not far from the coal seems.

The productive reservoir is coarse sandstone between middle Iwaki and lower Asagai formations. This coarse sandstone has been considered to be capable of gas

Nakajio Area
1. Nakajio 2
2. Nakajio 5

Hashirikuma Area
3. JI 24
4. Nissui-Hashirikuma 5
5. Nissui-Hashirikuma 1

Sumiyoshi Area
6. JI 56-2
7. Iwasaki Pit. Joban Coal Mine Co.

Izumi-Shimofunao Area
8. Tsurumaki
9. Kakinotaira
10. Izumida
11. Hosoda
12. Tanabe
13. Usuzaku
14. Tanakajima
15. Ohgida
16. Takijiri
17. Yokoyama
18. Oyama
19. Torikaenouchi
20. Shimokawa

Successful Drillings

◎ surface productive wells; daily production, more than 1,000 m^3

○ surface productive wells; daily production, less than 1,000 m^3

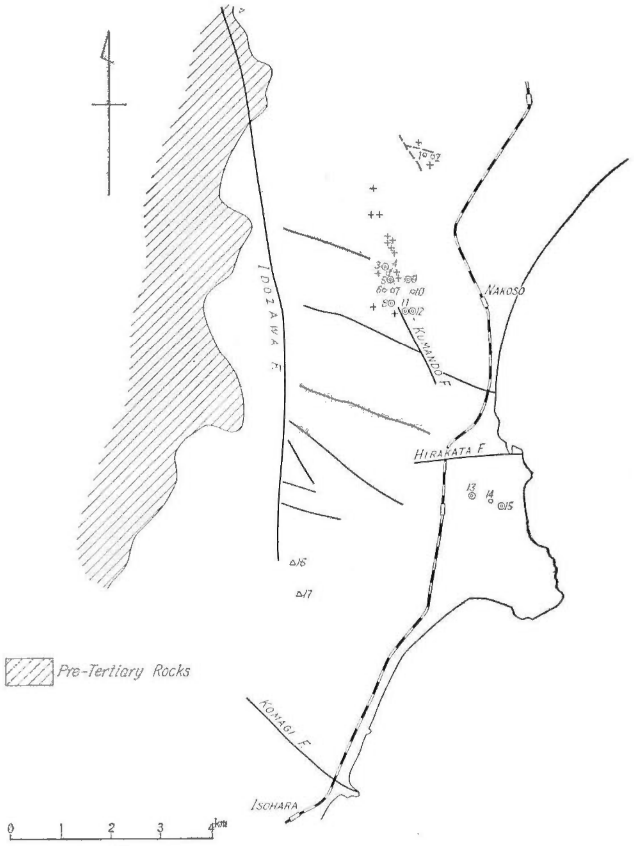
▣ underground productive drillings

△ surface non-productive wells

\+ unsuccessful drillings*

Fig. 4a Location of natural gas drillings in the Joban coal field:—
(A) Northern part

*) including only that, of which information was obtainable.



Eguri Area
1. Eguri 1
2. Eguri 2

Kubota Area
3. R. 12
4. R. 3
5. R. 4
6. HKR 8
7. HKR 3

Takai Area
13. Takai 5
14. Takai 11
15. Takai 1

8. HKR 1
9. R. 13
10. HKR 9
11. HKR 2
12. HKR 4

Sekimoto Area
16. No. 13
17. No. 19

Fig. 4b Location of natural gas drillings: —(B) Southern part pool if fractured so intensely that the natural gas can accumulate and migrate through the numerous minor fractures. The granular porosity of the coarse sandstone range from 16% to 30% and the granular permeability for gas in dry medium sandstone is betweeen 1 and 90 md. These figures have been considered to be too small to explain the abundant, constant production from a natural gas well during a long period, unless minor fractures have been formed rather extensively and in considerable numbers in the coarse sandstone (Eguchi and others, 1960; Arakawa, 1959, Lit. 21, Motojima and Makino, 1959). The overlying thick and massive shale of Shirasaka formation, being less porous and more ductile has been regarded as cap rock. The less productive formations are in Goyasu and Kameno-o of Yunagaya group, and in Taga group.

The natural gas is collected with the wells which were drilled at the surface, except only one in Yumoto where gas is collected with the bore holes in the galleries.

Gas pressure in the wells is extremely low. The induced pressure is about 1.0 kg/cm^2 at most wells, being 2.0 kg/cm^2 at the most, while the confining pressure is less than 10.0 kg/cm^2 at most areas except the wells in Takai, which attains about 20 kg/cm^2.

In Figures 4a and 4b are shown the locations of the gas wells in this coal field. Here the terms are used in the following meanings. *Successful well* are these that can collect whatever amount of gas for commercial use, and *productive wells* are the successful ones of which the gas is being used.

In Fig. 4a, along Hirakubo fault there are two productive wells. Nakajio well 2 and 5, in which natural gas is collected at the depth of 300–350 m at the upper Iwaki and lower Asagai formation. They are structurally located at the shoulder of Hirakubo fault or at varying point of the fault from N70°W to N50°W in strike. Mutual interference of gas production between both wells indicates that the both belong to the same gas pool. Accumulative production since the beginning of collection at both wells amounted to six million m^3 by October 1961.

Along Shirasaka faults, there are three productive wells, Nissui-Hashirikuma well 1 and 5, and JI (Joban Coal Mine Co.) well 24. In well 5 and well 24, gas is collected at about 300 m deep at Goyasu formation. These two wells were not drilled deeper than Goyasu formation.

However, Arakawa considered that the gas in the both wells would perhaps have been reserved in fissures that was kept opened between Goyasu and Iwaki-Asagai formations because of the prompt decrease of gas production in the first several days. The gas of well 1 is poor in production, if it is compared with the above two, but it is collected directly at Asagai-Iwaki formations.

The productive wells along the Shirasaka faults are found also at the shoulder of the faults.

Along the extension of Aikawa fault, there is Sumiyoshi JI well 56–2, in which gas is collected mostly about 800 m deep Iwaki formation and partly about 370 m in depth at Goyasu formation. This well is found at the place, where N45°W trending Aikawa fault ends and an alternate fault begins to extend in a direction of N70°W, and therefore the structural relation between faults and gas wells is similar to those in the former two areas. In Izumi-Shimofunao area along Tabasaka faults and their possible southern extension, there are the most numerous productive drillings in the Joban coal field. The surface wells of them contain those in Tsurumaki, Kakinotaira,

Table 2 Natural Gas in Productive Wells

AREA	WELL	Main Reservoir Beds		Confining Pressure (kg/cm^2)	Daily Production (M^3)	*1) Water Level (m)
		Depth (m)	Equivalent formation	beginning to present*3)	beginning to present*3)	
NAKAJIO	Nakajio 2	355	As°	1.75→0.28	32,000→2,700	
	Nakajio 5	304	As	1.40→0.28	29,000→8,000	
HASHIRI-KUMA	J 24	395	Go°°	4.0	50,000→1,000	300
	Nissui 5	312	Go	0.4 →0.4	7,000→2,200	
	Nissui 1	500	As	5.7 →5.6	250	
SUMIYOSHI	Sumiyoshi	805	Iw°°°		4,000→ 320	
IZUMI | SHIMOFUNAO	Tsurumaki	252	Iw	0.41	800→ 410	308
	Kakinodaira	447	Iw	1.42	800→1,300	241
	Izumidai	546	Iw	2.62	400→ 500	170
	Hosoda	358	Iw	3.25	10,000→8,340	
	Tanabe	360	Iw	5.8	10,000→4,000	300
	Oyama	561	Iw	9.3	6,500→3,750	
	Tanakajima	603	Iw	3.8	150→ 170	403
	Yokoyama	434	Iw	4.4	1,150→ 400	250
	Ohgida	551	Iw	6.8	600→ 510	
	Torikaenouchi	407	As	11.5	31,000→8,100	310
	Takijiri	187	Go	10.2	100,000→*2)	30
	Shimokawa	559	Iw	8.4	700→ 930	400
	Usuzuku	508	Iw	2.9	900→ 780	390
EGURI	Eguri 1	93	As		1,500→ 600	
	Eguri 2	100	As		660→ 600	
KUBOTA	R 3	70	As		4,500→ 500	
	R 4	73, 116	As, Iw		3,000→1,000	
	R 12	70	Iw		1,200	
	R 13	185	Iw		2,000	
	HKR 1	128～132	Iw		8,800→5,700	
	HKR 2	120, 137～150	Iw	2.2→1.6	1,700→1,300	130
	HKR 3	134	Iw	2.6→1.8	850→ 600	125
	HKR 4	127	As, Iw	2.7→1.4	2,600→1,700	150
	HKR 8	91, 115, 119 124, 133	As, Iw	2.3→0.8	200→ 100	100
	HKR 9	134	As		750→ 700	
TAKAI	Takai 1	380	As		3,700→2,000	194
	Takai 5	410, 420	As	16.7→16.0	150,000→5,000	250
	Takai 11	411	As	15.5	1,000	

° Asagai formation °° Goyasu formation °°° Iwaki formation

*1) "Water Level" is the depth of water surface in the bore hole when pump is not in operation.

*2) This well was drilled recently and is in preparation for production.

*3) "present" means spring, 1962, when the first manuscript was completed.

Izumida, Hosoda, Tanabe, Oyama, Torikaenouchi, Shimokawa, Usuzaku, Yokoyama, Ohgida, and Tanakajima; and the subsurface drillings are those in the gallery of Joban coal mine. All these drillings are in a N25°–30°W trending faulted zone of about two km in width which is composed of Tabasaka and the eastern smaller parallel faults east of Tabasaka, and some wells such as Yokoyama, and Oyama are considered to be related also to N70°W trending so-called Watanabe fault that crosses this faulted zone. The reservoir beds in this area are considered also to be found in coarse sandstone between middle Iwaki and lower Asagai which ranges in depth approximately from 200 to 600 m.

Most of these wells keep a consistency in daily production and the accumulative production amounted to 32 million m^3 by October 1961. The concentration of numerical drillings in this area is due to a condition geologically good for migration and accumulation of natural gas; the Iwaki and Asagai formations are made up largely of coarse sandstone, and abundant minor fractures were formed extensively by many small faults.

In the southern part of the field, gas wells are concentrated in four areas; Eguri, Kubota, Takai, and Sekimoto.

In Eguri area, Fig. 4b there are two productive wells, ER 1 and ER 2, in which reservoir beds are about 100 m in depth and at upper Asagai formation. Shirasaka formation was eroded out in this area, and so the fine sandstone of Goyasu formation and mudstone of Mizunoya formation are considered as cap rock. N65°–80°W trending and N25°W trending faults are presumed to run closely north and west of the wells.

In Kubota area, there are ten productive wells; R 3, 4, 12, and 13; and HKR 1, 2, 3, 4, 8, and 9. Natural gas is collected at about 70 to 190 m in depth and between middle Iwaki and lower Asagai formation. Although this area is underlain by Alluvium deposits, Kumando fault is considered to run in a direction of N20°W accompanying abundant minor fractures. Some wells are considered to be related to west-north western smaller faults as well as to the Kumando fault. Many fissures were found to be filled with calcite vein in drilling cores. Accumulative production in the ten wells probably amounted to about 30 million m^3 by December 1961.

In Takai area, there are two productive wells, Nissui Takai well 1 and 5. Recently well 11 was reported to be successful. Reservoir beds are in upper Iwaki and lower Asagai formation. Well 5 producted daily 15,000 m^3 at the beginning, the greatest daily production in this coal field. Accumulative production amounted to about 8 million m^3 by October 1961. The geographical distribution of these three wells is closely related to N80°W trending Takai fault, however it is very interesting that this area is situated on a southern elongation of the Kumando fault. The wells in this area differ from those in other area in higher confining pressure, 20 kg/cm^2 at the largest of well 5. Eguchi (1960) stated that the study of granular porosity and permeability indicated that the natural gas in this area was accumulated in fissures as well as intergranular spaces and that migration might be done through the fissures.

In Sekimoto area, there are two successful wells, well 13 and 19, in which reservoir beds are in upper Iwaki and lower Asagai formation. Structurally they are closely located along the southern end of Idozawa fault in the east and of the fault.

In summary, the disposition of successful gas drillings in the Joban coal field is related closely to the fault pattern. In the northern three areas, along Hirakubo, Shirasaka, and the extension of Aikawa faults, they are found at the place where the fault vary in strike from N50°W to N70°W. In the area such as Izumi-Shimofunao, Eguri, Kubota, and Sekimoto they are related to N15°-25°W trending faults and to N70°-80°W small faults. In Takai area they are along N70°-80°W Takai fault.

IV. Method of Fracture Study

The regional relation of the fractures with respect to each other and also with respect to other structural features are expressed primarily in term of fracture pattern. For the study of the regional fracture pattern of this field, fractures were classified according to the magnitude of fracturing into three groups; joints, minor faults, and major faults, and then the relationships among them were studied.

Major faults are used here to denote such faults that they can be expressed individually in the geological map of 1/50,000 in scale. In the study of the major fault pattern, the 1/50,000 geological map by the Geological Survey (1957) was used as a base map and it was corrected by using subsurface data available from coal mining and gas exploitation companies. Major faults in Figures 3, 7, 8, 9, 10, 12, and 13 were drawn in this way.

Joints are used in the ordinary meaning that they are the fractures that are not accompanied by any discernible displacement of one face of the fracture relative to the other. Usually joints occur in sets and each set is composed of joints being parallel to one another, although mean interval between the neighbouring two joint planes is considerably variable in different rock materials. If the rock is exposed in the atmosphere later, *weathering joints* would be formed between the antecedent *systematic joints*. The weathering joints are roughly normal to the systematic joints, but show random curvilinear pattern and hardly cross the systematic joints. An example of the systematic joints and the weathering ones is shown in Photo 2. This study was made exclusively of the weathering joints.

Fifty-three localities were selected for the study of joints, and the mean planes of prominent joint sets at each locality were studied, with statistical method at 43 localities, and with field observation at 10 localities. The statistical method was done in the following order; at each locality the strikes and dips of 25 or 100 joint planes were measured, and a distribution diagram was made by plotting the poles perpendicular to the joint planes on the lower hemisphere of the Schmidt equal-area net, and then by drawing the contour lines in the net. The Schmidt distribution diagram of 41 localities are shown in Figures 5. In the diagram, a concentrated-area of contours represents a joint set. The other 10 localities were of supplementary studies, where the parallelism of individual joint set is so clear that the mean plane of a joint set can easily be determined by field observation.

The joints in the shale of Shirasaka and Kameno-o formations are so prominent that individual set are distinguishable from each other and so numerous that required number of joint planes can be measured at a smaller exposure better than in any other rocks. For this reason, the localities were selected mostly out of these two formations; Among 53 localities, 38 are in Shirasaka and Kameno-o formations.

Minor faults are used here to denote the fractures which are too small to be drawn on the 1/50,000 geological map. The minor faults were studied in subsurface data of Iwaki formation in coal mining areas, and the studies contain the both procedures which were used in the study of the major faults and the joints, either by checking the previous data or by using the Schmidt net. The results are shown in Figures 12, 13, 14, 15, and 16. In figure 13, for instance, the minor fault pattern was completed from data of coal mine companies and the Schmidt diagrams were done by plotting 100 or 125 minor faults measured at gallery walls on the lower hemisphere of the Schmidt net. Minor faults were proved very useful for the study of the relation between the faults and the joints.

The fracture study was made in four areas; Hisanohama, Taira, Yumoto, and Nakoso. The latter three were studied because these areas contain many natural gas drillings, while the former one was selected for the reason that structurally this area is very simple and has many kinds of sedimentary rock, from coarse to fine or from Iwaki to Shirasaka formation, so that the fracture pattern can be observed in relation to rock materials, and the other structural features.

The results of fracture study in these four areas are shown in fracture maps between Figures 7 and 16.

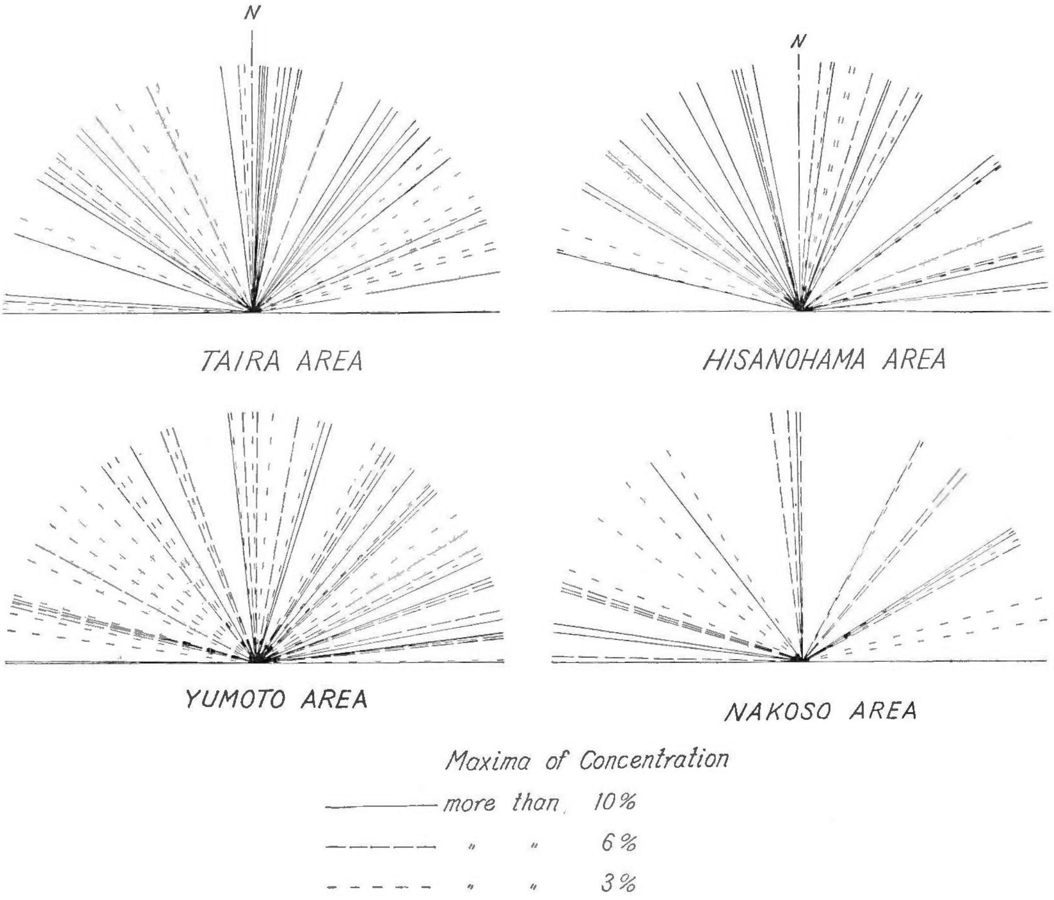


Fig. 6 Frequency diagram of prominent directions of joints at studied localities

V. Fracture Pattern in Selected Areas

Hisanohama Area

Faults: Futatsuya fault is the most remarkable structural feature in this area. This fault strikes northwest, dips southward at 55–65° being the south side downward relatively. Being underlain by Taga group in the east and by the fault-scarp sediments in the west this fault can be observed only at a few places but has been considered as composed of some parallel faults at most parts. The vertical separation is estimated about 600 m in the west, but decreases eastward. The older are the rocks at either side of the Futatsuya fault, or, in other words, as the rocks vary from the basement rocks to Yunagaya group, and further to Taga group, the more intensely they have been undergone deformation along the fault plane. Therefore Iwao and Matsui (1961) stated that Futatsuya fault has repeated movement perhaps two times. There are three less prominent faults in the north of Futatsuya faults; Shiroiwa, Yotsukura, and Hisanohama; the former two trend about north-south and the third is parallel to Futatsuya faults. Apparently they are normal faults.

Joints: Joints in this area have been formed in a good accordance with the faults. The most prominent are N15° or 40°W in strike and nearly parallel to the western part of Futatsuya faults. They are shown at localities 4, 6, 7, 8, and 10 in Figure 7. Those at localities 6 and 7 must have been genetically related to Hisanohama fault. In the north, apart from Futatsuya faults these N15°–40°W trending joints become less prominent and the other joint sets dominate numerically. N20°–25°E trending joints are prominent at localities 2 and 3, and N70°E or N80°W trending ones prominent at locality 1. These three prominent trends of joints are found on most Schmidt diagrams throughout Hisanohama area, although each of them would show various degrees of prominence in different localities. It is noted that Shiroiwa fault varies in strike to about N40°–45°E directly north of Futatsuya faults and the parallel joints also occur at locality 7.

The joints were studied in more detail along a stream that flows westerly through locality 6 in shale of Shirasaka formation (Fig. 11). Along the stream, 10 or 20 joints were measured at several places but as a whole prominent trends are similar to those described above.

In summary, fracture pattern of this area is idealized in Figure 17.

Taira Area

Major faults: Hirakubo and Akai faults, large WNW–ESE trending faults, are most prominent as Futatsuya are in Hisanohama area. The 1/50,000 geological map of the Geological Survey (Sugai and others, 1957) described Omuro fault to be between Hirakubo and Akai faults in trend of N35°W. But the latest information by a coal mining company indicates this fault not to be present. The dip of Hirakubo and Akai faults ranges between 50° and 60° southward and the south side of the faults is down relatively. Vertical separation of them is estimated 200 or 300 m at the largest for each of them and about 500 m in the total of both, while normal horizontal separation in the total of both is estimated about 5 or 6 km of an apparent displacement of Shiramizu group. The Hirakubo fault is composed of two parts in strike, one N70°W in the west and the other N50°W in the east. A similar composition is also found at Akai fault, although it varies in strike more gradually from one to the other.

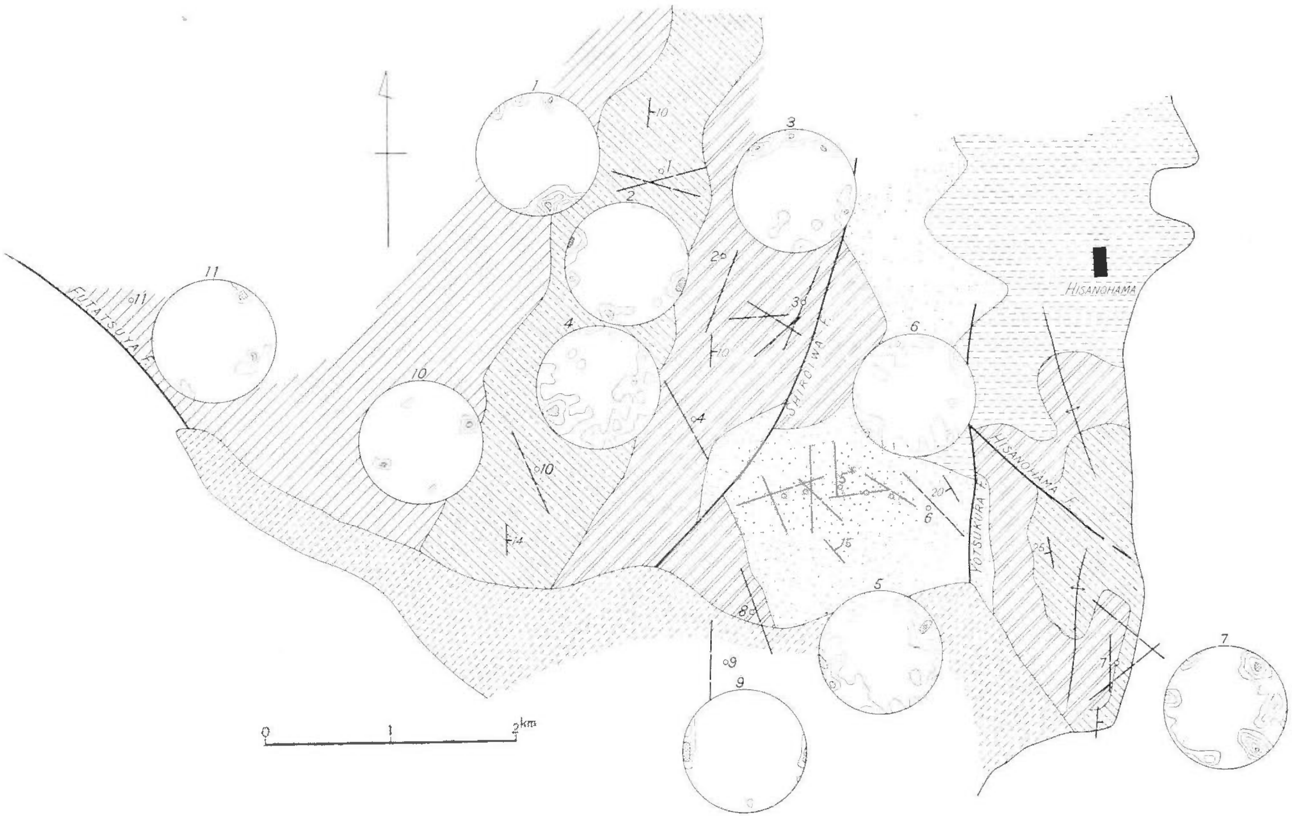


Fig. 7 Fractures map-1 Area (a) at the surface, Hisanohama area

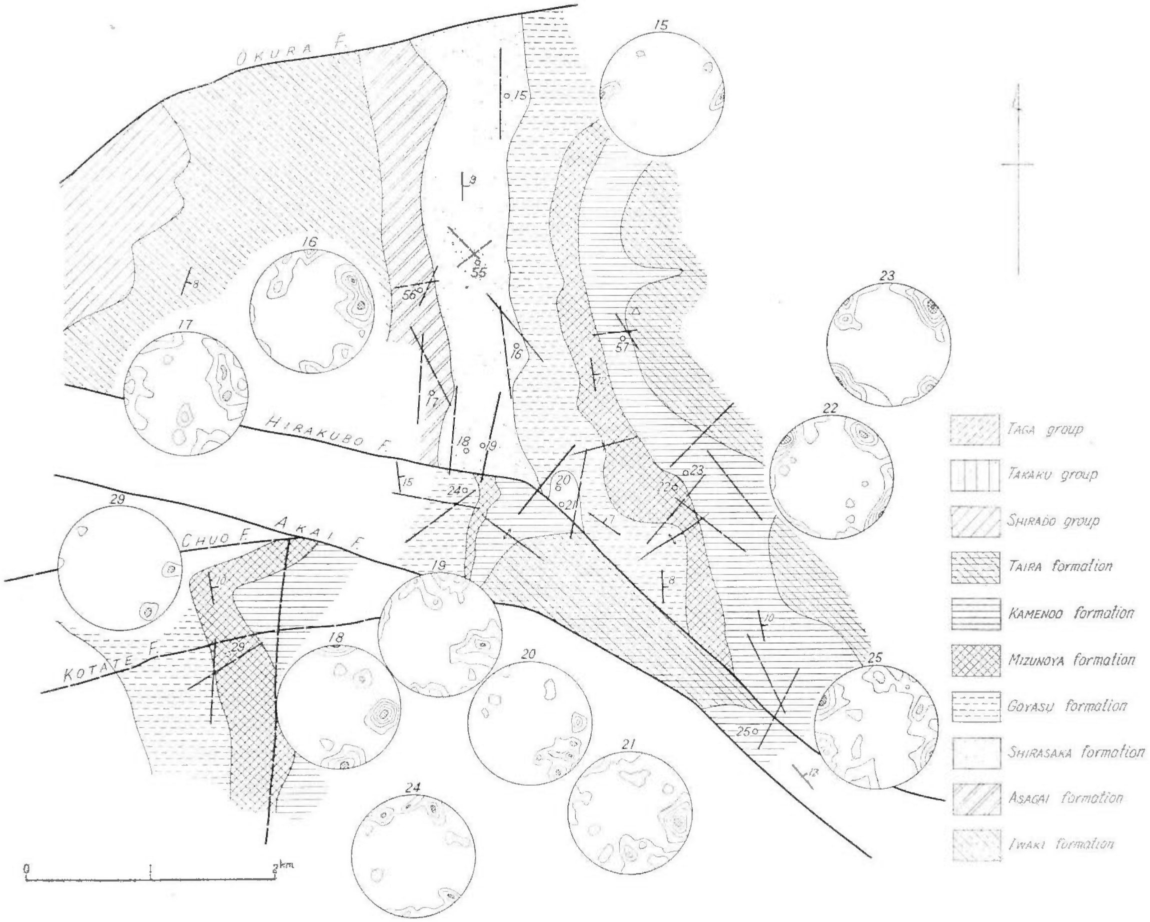


Fig. 8 Fractures map-2 Area (b) at the surface, Taira area

The less prominent faults are WSW-ENE in strike and contain Okura, Chuo, and Kotate faults. Okura fault changes in strike from SW to NE, if going to the west in the basement rocks. Chuo and Kotate faults are hardly recognizable at the surface, but they are traceable as shown in Figure 12 in the underground coal mining area in Iwaki formation. Kotate fault exhibits a broadly curved trace, convex to the north; the strike in the west are parallel to Okura fault and that in the east parallel to Akai fault. Chuo and Kotate faults are apparently normal fault; the angle of dip is about 70°, vertical separation about 40 m, and horizontal separation about 200 m. In Figure 12, semi-spotted line shows the unconformity line between Tertiary sedimentary rocks and pre-Tertiary basement rocks, or, in other word, the area inside the semi-spotted line is that which was remained not to be covered by Tertiary rocks in the beginning of sedimentation of the Tertiary rocks. This limited area has been called "buried hills" by a field name. Since, the topographical feature of buried hills is interpreted to have been formed before the sedimentation of the Tertiary rocks, parallelism between the buried hills and Chuo and Kotate faults indicates there were early fault movement parallel to these faults in pre-Tertiary.

A third group of faults is NNE-SSW in trend and contains Yumoto fault, which is traced northward from Yumoto area and is formed more prominently in that area.

Minor faults: Minor faults were studied in the underground area shown in Figure 12. They have three prominent trends, each of which is parallel to three prominent trends of the major faults described above. This parallelism is also found in Schmidt diagrams of localities 26, 27, and 28.

Joints: One prominent trend is N30°-40°W and nearly parallel to the eastern part of Akai or Hirakubo fault though lying at about 10° north of the faults similar as N15°-40°W joints in Hisanohama area. It is present at localities 16, 17, 23, 25, 55, and 57. The second prominent are N5°-10°E and N35°-40°E, each of which is nearly at right angle to the western or the eastern part of Akai and Hirakubo fault; the former become prominent at localities 15, 16, 17, 18, 19, and 29 in the western part of this area, the latter at localities 20, 22, 23, and 25 in the eastern part.

B of Figure 17 is an idealized map of fracture pattern in this area.

Yumoto Area

Major faults: The fault pattern exhibits considerable complexity, but the regular disposition of various trends of faults and a comparative occurrence between major faults and minor faults here would be useful for the study of the genetical relationship between them. Prominent trends of the faults are NW-SE or WNW-ESE, ENE-WSW, NNE-SSW and NNW-SSE.

The NW-SE or WNW-ESE faults contain Shirasaka, Aikawa, and Fujiwara faults, the dip of which is average 50° though ranging between 40° and 80° southwestward and the vertical separation of which ranges from 200 to 450 m. These faults are apparently normal fault. Shirasaka fault in Figure 9 is N65°-70°W in strike but it varies to N48°-40°W east of this area as Hirakubo fault in Taira area. Aikawa fault strikes N45°-50°W and Fujiwara fault varies in strike from N40°-45°W in the north to N80°W in the south (Fig. 13). The second prominent ENE-WSW faults dominate numerically between Aikawa and Fujiwara faults and the largest one of them is named Karasudate fault. The smaller fault north of and parallel to the Karasudate fault is called Iwaki fault in this paper. The dip of these two faults ranges from 50° to 60° southward. The vertical separation of Karasudate fault varies con-

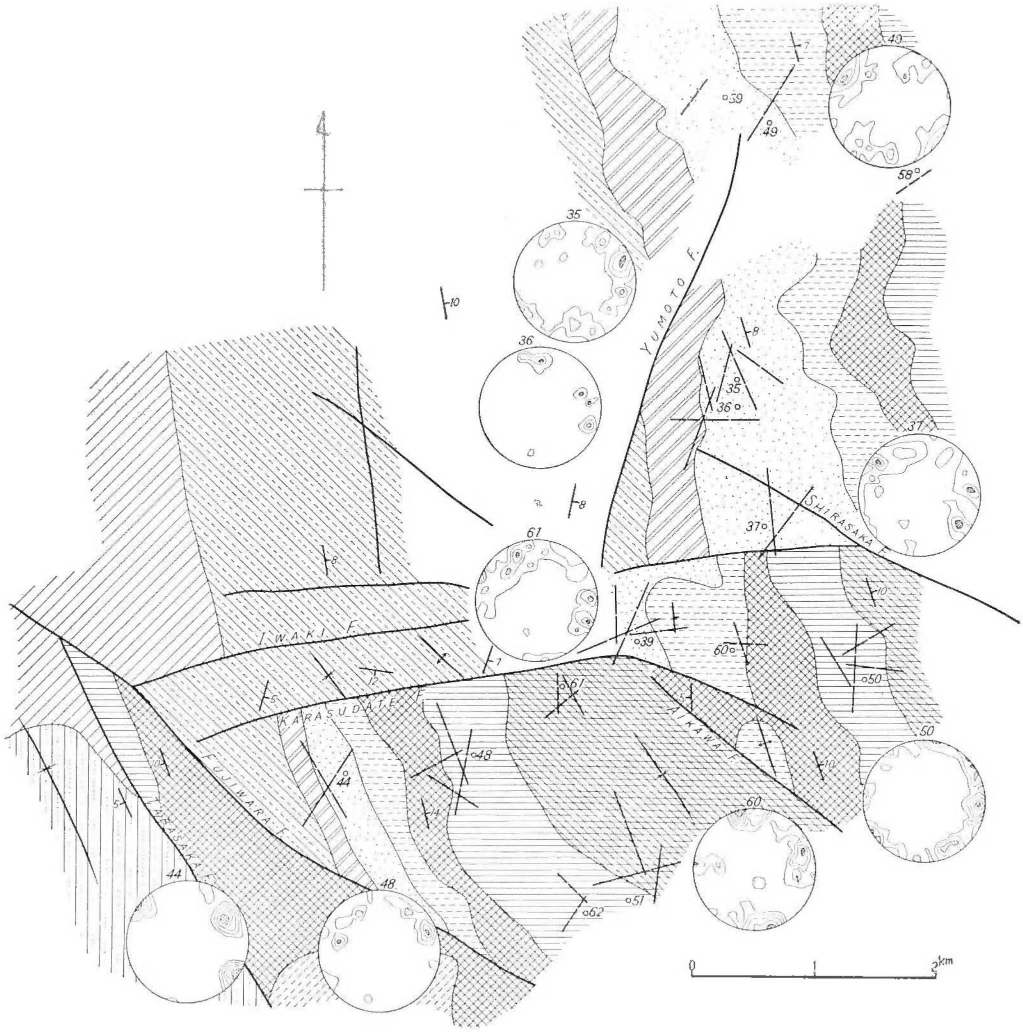


Fig. 9 Fractures map-3 Area (c) at the surface, Yumoto area

siderably; it is about 350 m east of Fujiwara fault but decreases to nearly zero to the east. There are many parallel faults further in the south of these faults. These parallel faults are as much as the above two faults in dip and they range in the vertical separation from 40 to 70 m.

These WSW-ENE faults are apparently normal fault. A relationship between the NW or WNW and the WSW faults is shown in Figure 13, in which the latter seems to be exhibited an offshoot fault of or to be branched from the former.

The third prominent contains Yumoto fault, which is NNE-SSW in strike in Yumoto area. Yumoto fault dips nearly perpendicular and is likely of fissure type. The fourth is represented by the NNW-SSE trending Tabazaka fault. This fault is structurally so important as the NW or WNW faults, since not only it has been formed parallel to large faulted belts in the Abukuma Plateau such as Tanakura and

Futaba, but it has influenced upon either the folding of Tertiary sedimentary rocks before Taga group or the sedimentation of Taga group. This fault dips a little steeper than NW or WNW or WSW faults and the angle of the dip ranges from 60° to 85° southwestward. The vertical separation is about 250 m.

Minor faults: In Figure 13 is shown the minor faults in the coal mining area of Iwaki formation in Yumoto area. The ENE-WSW trending minor faults not only dominate numerically between Fujiwara and Aikawa faults as the ENE trending major faults do, but also has occurred extensively along Yumoto fault. The strike of these ENE minor faults varies from N60°E to N80°W averaging N75°E and the dip is between 60° and 70° and the vertical separation one or five m of most faults. All these ENE minor faults are apparently normal fault. The contour lines of a coal seam in Figure 13 indicate that Iwaki formation between Fujiwara and Aikawa faults exhibit a step-by-step-faulted structure by dip slip movements of the ENE minor faults, in which the north side of the faults moved relatively down of most faults.

The second prominent are the N25°-40°E trending minor faults, which may be traced from Fujiwara to the north of Shirasaka faults in the right side of Figure 13. Those faults, north of the Shirasaka, more limited in strike ranging from N25°-30°E, are possibly genetically related to Yumoto fault because the strike became in parallel to that of the Yumoto fault as it comes closer to the fault.

In eight Schmidt diagrams, Fig. 13, measured of minor faults of Iwaki formation at the wall of coal mining galleries, are also indicated two prominent concentrations of strikes, ENE-WSW or E-W, and NNE-SSW or NE-SW. The dip of these minor faults is between 60° and 80° and the dipside is to both sides of the faults.

Joints: Joint pattern with respect to the fault in this area is considered to be same as that in Hisanohama and Taira areas, although the study of the joint pattern itself is not so easy in this area because of insufficiency of localities of good condition for study and presence of various trends of faults and joints in a limited area. Prominent trends of joints are N-N20°E, N30°-50°E, N25°-35°W, and N65°E-N80°W.

The N-N20°E trending joints dominate numerically along the Yumoto fault and in the southern elongation of the fault, while the N30°-50°E joints are related to Shirasaka, Aikawa, and Fujiwara faults as N25°-40°E trending minor faults. The N25°-35°W trending joints run apparently parallel to Idozawa fault and it may be interpreted also to be related to Fujiwara or Aikawa faults as the N30°-40° joints in Hisanohama and Taira are related to Futatsuya or Hirakubo faults.

The N65°E-N80°W trending joints are closely parallel to the same trending faults and therefore a genetical relation between the joints and the faults of these trends is probably indicated.

The idealized fracture pattern is shown in Figure 17.

Nakoso Area

Major faults: Major faults in Nakoso area have been formed less numerously and less extensively than those in the above three areas, but in detail study this fault pattern is considerably similar to that of those areas. The faults in this area have not so much displacements and always are apparently normal faults.

Most prominent are NNW-SSE trending faults which contains Idozawa, Hattan, and Kumando faults. Idozawa fault is the largest in length in this coal field but the vertical separation is about 200 m at the most, rather small compared with that of any

Fig. 10 Fractures map-4 Area (d) at the surface, Nokoso area

other large NW and WNW trending faults such as Shirasaka and Hirakubo faults. The dip of this fault ranges from 60° to 85°. It has a constant strike of N20°W in the basement rocks, north of Nakoso area, while in the Tertiary rocks in Nakoso area it seems in 1/50,000 geological map to vary in strike to north. However the minor fault pattern in Figures 14, 15, and 16 indicates that Idozawa fault also in this area might have the similar strike ranging from N10°W to N20°W. In these figures all the minor faults along Idozawa fault range in strike from N10°W to N20°W. It is probable that Idozawa fault, not consisting of one fault line from the beginning to the end, but of many fault lines more limited in length and apparently moved west to east by the WNW-ESE trending faults, exhibits apparently in Nakoso area to be a long northward trending fault as drawn in the surface map of Figure 10. Kumando fault was presumed from information of many drillings for the prospection of coal or natural gas in Kubota, Nakoso to be N20°W in strike, too. The Kumando fault or the other parallel fault on the southern end of the Kumando fault was proved to be traceable further southward with the seismic study by the Geological Survey.

The second prominent are WNW-ESE trending faults, which contain Nakoso, Sekimoto, Nakasaku, and Yuizumi faults. They ranges in strike from N60°W to N80°W. Though Nakoso fault ranges from 55°W to 60°W in Figure 10 in other words, in the surface, it is considered to be connected with the N75° or 80°W trending minor faults in the bottom of Figure 14 or in the subsurface. Most of these WNW faults, moreover, may be traced to minor faults of Iwaki formation in the underground coal mining areas such as Nakoso fault. These minor faults indicate that each of the WNW faults consists of two or three small faults which range from one to five meter in vertical separation. The NW-SE trending faults are less prominent and contain Ohsaku fault only, which has been considered in the surface (Fig. 10) as trending N45°W but indicated in the underground (Fig. 15) to be N30°W in strike, if it comes closer to Idozawa fault.

The third are ENE-WSE trending faults, and Hirakata fault belongs to this group. Eguchi and others (1960) described Hirakata fault to be a normal N75°W trending fault ranging from 55° to 60° northward in dip and have vertical separation of about 100 m at the most.

Minor faults: Minor faults in the mining operation areas are shown in Figures 14, 15, and 16. Prominent trends are same as the major faults, that is, N15°-20°W, N60°-85°W, N30°-45°W, and E-N80°E. As shown in Figures 10, 14, 15, and 16, most of the faults that described as major fault are a compound of two or more parallel minor faults. In these figures it is indicated that in Nakoso area, unlike the previous three areas, NW trending faults occur not to be connected with WNW faults but rather connected with NNW trending faults.

All the minor faults are normal and range in vertical separation from one to five meters, and dips at the angle ranging from 60° to nearly vertical.

Joints: Jointing in the Nakoso area has been also related to the faults; they are either parallel to or nearly right angle to the faults.

The N-N 10°W trending joints are prominent along Idozawa fault and most localities east of the fault. The N65°-85°W trending joints having dominated numerically also throughout the area are related to Nakoso or Sekimoto, or to the other parallel faults. The N55°-65°E joints have been formed along Kumando, Ohsaku, Nakasaku and Yuizumi faults, and it seems that they are nearly perpendicular to Kumando, Ohsaku, or Hattan faults. The N20°-30°E trending joints have occurred at localities 67 and 66, along Nakoso or Sekimoto fault.

The idealized fracture pattern in this area is shown in Figure 17.

Regional Feature of Joints

The joints are closely related to the regional fault pattern. In most measurements they have a steep dip ranging from 70° to 90°. Although they exhibit a considerable consistent pattern through the four areas, they are variable in the appearance and the frequency of joint planes among different rock materials: the plane of joints, in shale is quite even, showing remarkably sharp, straight traces on the exposure, and formed very numerously in a short distance, while in sandstone it is curved, irregular, and formed less numerously. Moreover the degree of concentration of the plane in the Schmidt net is better in shale than in sandstone, for the example, Schmidt net diagrams at localities 16 measured in shale and 17 in sandstone in figure 8 show similar pattern but in the latter the interval of contour lines is wider and

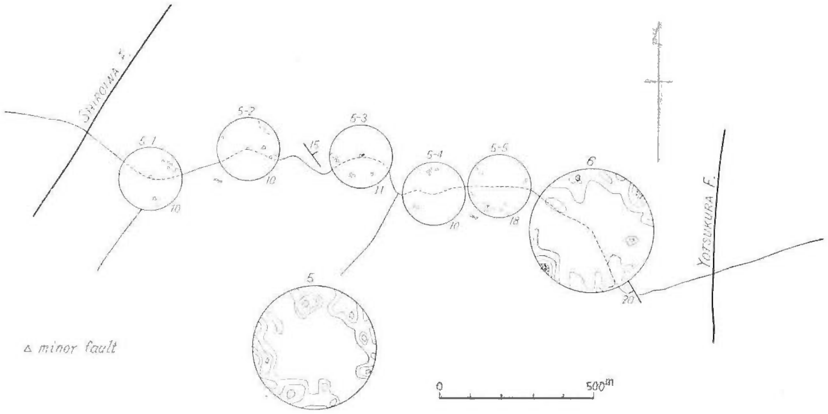


Fig. 11 Fractures map-5 along a stream in Hisanohama area

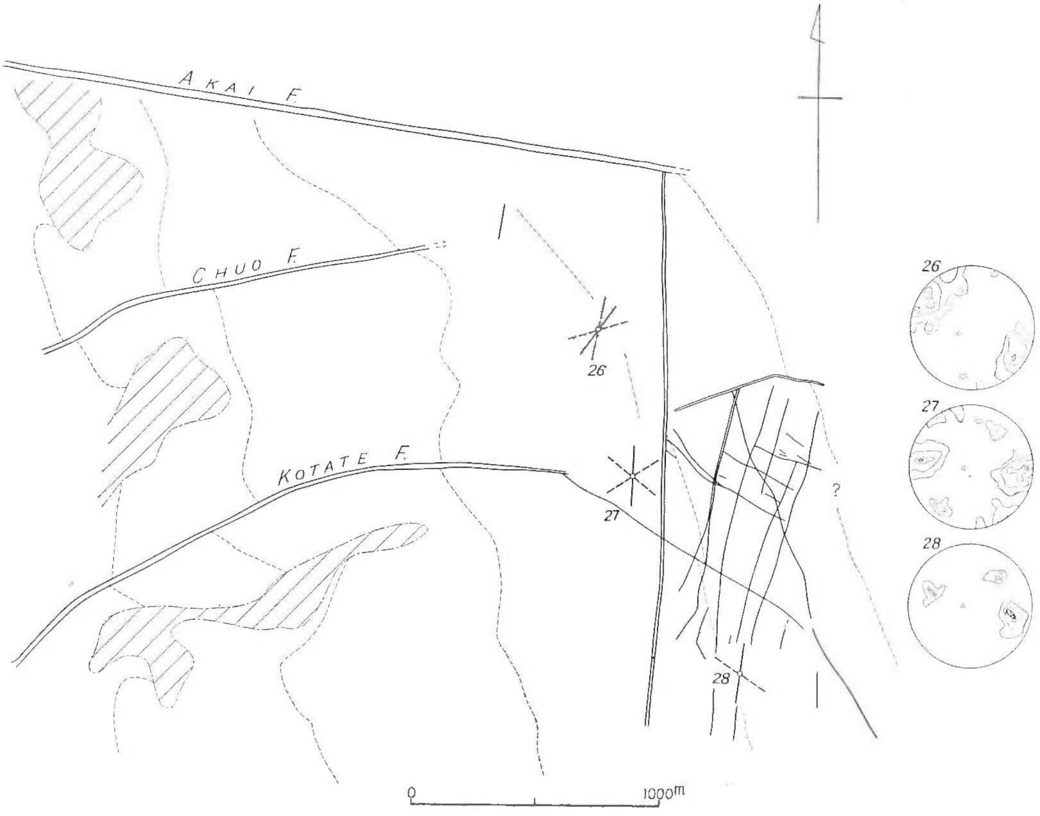


Fig. 12 Fractures map-6 Area (e) in the subsurface Iwaki formation, Taira area

the concentrations in contour lines is more scattered. The variation of some natures of joint planes and the consistency of joint pattern in different rocks is also seen better on Shiramizu group in Hisanohama area which contains a series of representative clastic rocks in the Joban coal field, coarse sandstone of Iwaki formation, medium sandstone of Asagai formation, and shale of Shirasaka formation.

Joints are often filled with calcite veins, width of which is 2 or 3 mm at the most, and the vein seems to be restricted in some beds of Asagai and Iwaki formations. Sand dykes were found in Ohtaka, Nakoso area (photo 4), that intruded into alternate beds of sandstone and shale of Kameno-o formation in width of 1 or 0.1 meters, contact planes N60°E of strike and westerly dip of 85°.

Fig. 14 Fractures map–8 Area (g) in the surface Iwaki formation, Nakoso area

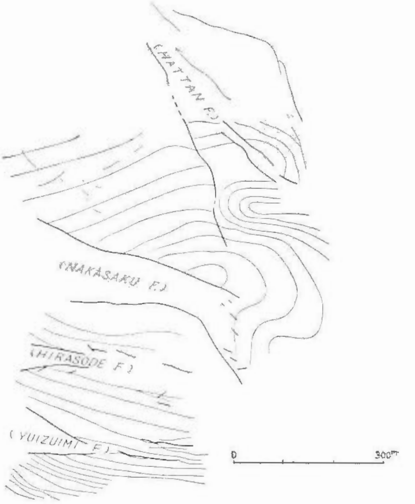


Fig. 15 Fractures map–9 Area (h) in the subsurface Iwaki formation, Nakoso area

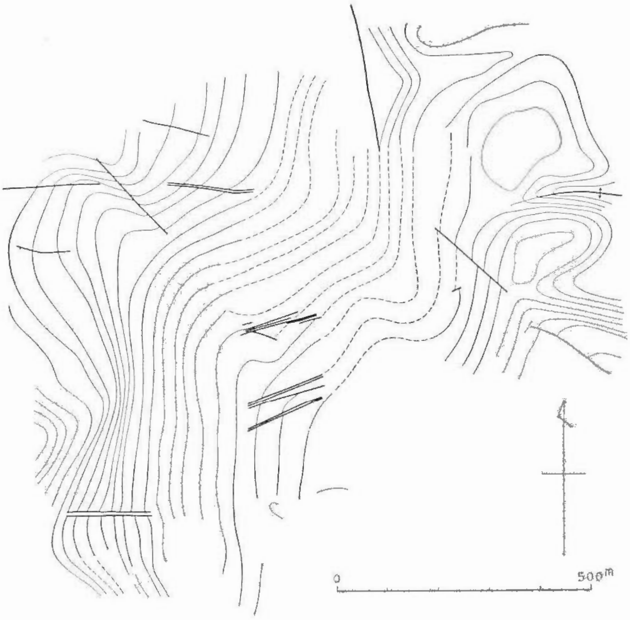


Fig. 16 Fractures map-10 Area (i) in the surface Iwaki formation, Nakoso area

VI. Characteristics of the Fracture Sets

Introductory Statement

The comparative study of regional fracture pattern in the four areas indicates that the fracture pattern exhibits a considerable consistency throughout the field as shown in Figure 17 and that prominent trends of faults and joints are closely related to each other. In conclusion, they are summarized as Figure 18.

The prominent trends of faults are NW-SE and WNW-ESE, NNW-SSE, ENE-WSW, and NNE-SSW. The faults of each trend are called in this paper with conventional name of a fault set, in the same order as above; Shirasaka, Idozawa, Karasudate, and Yumoto fault sets (Figure 18). Shirasaka fault set should be divided into two subsets, WNW trending part A and NW part B. Most prominent trends of joints are those that occurred at right angle to both subsets of the Shirasaka fault set. They are NNE-SSW and NE-SW. The third prominent is NNW-SSE. These joints are called joint set I, II, and III. The other prominent trends of joints that are parallel to and have been formed near the above fault sets may be called with the same names as the fault sets, like Shirasaka A joint set or Karasudate joint set. The minor faults may be called with the name of the most related fault or joint set like Idozawa minor fault set or minor fault set II.

Some trends parallel to joint sets are found also in faults, that is, joint set III is the same as Idozawa fault and joint set I is the same as Yumoto fault set in trend. This will be discussed in the following pages.

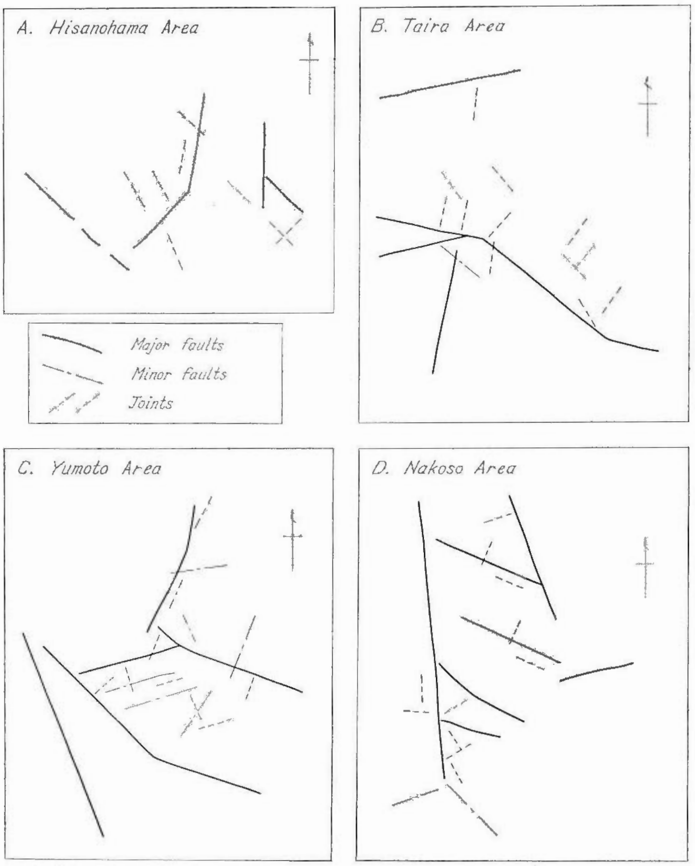


Fig. 17 Idealized fracture pattern in selected areas

Shirasaka Fault Set

The faults of this set are the most prominent structural features in the Tertiary sedimentary rocks of this coal field.

Shirasaka A set, which contains Yunotake, Hirakubo, Akai, Shirasaka, Fujiwara, Nakoso, Sekimoto, Nakasaku, and Yuizumi faults, ranges in strike from N60°W to N80°W at the average N70°W. Shirasaka B set, containing Futatsuya, Hirakubo, Akai, Shirasaka, Aikawa, Fujiwara, and Ohsaku faults, has a consistent strike of average N50°W. The dip of Shirasaka fault set varies considerably ranging between 40° and 80°, but on the average dip A subset is steeper than B subset. This difference was indicated apparently in the Schmidt diagram by Sato (Sugai and others 1957, Fig. 24), in which dip of A subset is about 65° while that of B is about 55°. Shirasaka fault set is apparently normal faults with southwesterly dip, and the southwest side is downward of most major faults.

Most major faults of this fault set in Hisanohama, Taira, and Yumoto areas are composed of a connection of the two subsets, and they exhibit a sharply bending pattern, concaving southwestward or northeastward.

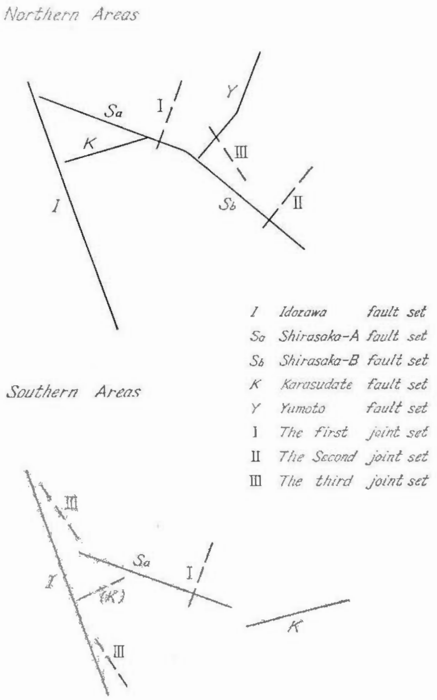


Fig. 18 Model of regional fracture system

Table 3 Characteristics of Individual Fracture Sets

Fracture Sets	STRIKE	DIP	NATURE
I	N5°—30°W Average, 20°W	60°—90°W or E	Normal fault; Apparent vertical separation, being usually small, is 250 m at the largest. (Tabasaka f.).
Sa	N60°—80°W Average, 70°W	50°—80°S Average, 65°S	Normal dip-slip fault; Apparent vertical separation, usually 2—300 m, and 700 m at the largest.
Sb	N45°—50°W	40°—70°SW Average, 55°SW	
K	N75°—80°E	50°—70°S or N	Normal dip-slip fault; Apparent vertical separation is 350 m at the largest (Karasudate); Occurring nearly at right angle to I fault set.
Y	N5°—20°E N40°—50°E	Steep	Small displacement; Occurring at right angle to Sa or Sb fault set.
I	N5°—20°E	70°—90°	being at right angle to Sa fault set.
II	N30°—50°E		being at right angle to Sb fault set.
III	N15°—40°W average, 30°W		being nearly parallel to I fault set.

This bending pattern is recognizable, for instance, of Hirakubo, Akai, and Shirasaka faults; and the pattern is also possible to be traced in Futatsuya, and Yunotake—Fujiwara faults, if further eastward continuation is considered; Aikawa—Noda faults also exhibit the bending pattern. Along the places where fault varies its strike from WNW to NW and further along the parts of NW, most faults are found with local structures. Along the south side of Futatsuya faults, there are seen Okura and the parallel faults, and anticlinal pattern indicated by surface exposure of Shiramizu group in Yunagaya group.

Asano (1960) showed NE or ENE trending minor folds along the part of Shirasaka B set in the northeast side of Hirakubo fault in distance about 1 km NNE from Taira city. And in the opposite side of Akai fault a small syncline is indicated in the geological map of the Geological Survey. Shirasaka faults varies in direction sharply from N70°W to N50°W in distance about 6 km SSE from Taira, where a large syncline is formed in the south side of the fault. Yunotake faults being N60°W in strike is connected with N50°W trending Fujiwara fault at where Karasudate and some parallel faults arose to be traced further east-northeastward. The Fujiwara fault changes it's strike to N80°W in the south.

In Nakoso, most faults of this set belong to Shirasaka A set. Ohsaku fault was classified here to the B subset conventionary but it may be interpreted rather an intermediate one between Idozawa and Shirasaka fault sets.

It is difficult to determine the direction of net slip along the fault planes of this fault set. Measurements of the net slip have been made with direct observation such as slicken side for few minor faults in a fault-belt of this set. The result are; some measurements show strike slip while some do dip slip, and the resultant slip of the fault-belt remains undetermined.

Horizontal separation of Shiramizu group along the fault are estimated from the apparent displacement of the group in Figure 3 as follows; Futsuya faults about 7 km, Hirakubo and Akai faults 4–5 km, and Shirasaka faults 1–2 km. It seems that most faults of Shirasaka A set are dip faults while those of Shirasaka B set is seen to be strike faults, because the Tertiary rocks vary in strike to be parallel with that of fault in the neighbouring area along the NW faults from average strike of N–S.

There have been two interpretations about faulting of Shirasaka fault set, dip slip or strike slip movement. The former has been accepted by most workers who studied the Tertiary rocks of this field. The latter was adopted by Asano (1960), who studied a part of Hirakubo fault that belongs to the B subset and geology of the adjacent area for the purpose of prospection of natural gas. He interpreted the minor folds along the fault as resulting from strike slip movement of the fault. The result of the fracture survey made by the writer, however, indicated that the movement of Shirasaka fault set in the Tertiary sedimentary rocks, either A or B subset might be dip slip rather than strike slip. The reasons are: 1. the average dip of the faults of Shirasaka set is between 55° and 65°, and this is so low angle to be compared with that of usual strike slip faults; 2. the minor faults and the joints of set I and II are probably due to the compressional force perpendicular to the faults of Shirasaka set, which might have been produced only with the normal dip slip movement of the fault; and 3. the faults of Shirasaka set, at most places, consists of the faulted zone of considerable width which is composed of not only one large fault but many parallel smaller faults. Although Set III is found at right angle to the folding axis, it is hardly considered to have been formed with the same stress which caused the minor folds since joints or minor faults of Set III have been formed in a more extensive area than the minor folds have been made. These local structures should be attributed to differential movement of the rocks which had been made along two fault planes of Shirasaka fault set. It may be possible to consider that the apparent clockwise displacement of NNE trending synclinal axes along Shirasaka faults in the eastern part of this area is due to strike shift of Shirasaka fault set. However, this apparent clockwise displacement does not mean always the strike shift of the faults because these synclines are not symmetrical but the axes incline about 70° eastward, therefore such a displacement may occur by a dip shift too. Further the large synclines elongated south of Yunotake fault or southwest of Fujiwara fault and parallel to each of the both faults are interpreted perhaps resulting from the relative down fall of the hanging wall due to gravitational force and this indicates the dip slip movement of these faultings.

In Nakoso area, subsurface minor fault pattern in Iwaki formation (Figures 14, 15, and 16) indicates that the fault of Shirasaka set in Nakoso area such as Nakasaku, Ohsaku, and Yuizumi faults consists of many apparent normal faults of a small displacement, parallel to one another, and that these small faults are probably dip-slip faults.

Karasudate Fault Set

Karasudate fault set is more limited in length and displacement than Shirasaka set.

Karasudate fault set ranges in strike from N75°E to N85°E and has an average dip of about 60° southward. The faults of this set are probably normal dip slip fault same as those of Shirasaka set. Figures 12 and 13 suggest a detail of the nature of this fault set and a possible relationship with both other fracture sets and the basement rocks. In Figure 12, the iso-depth contour lines of a coal seam of Iwaki formation in scores of meters high from the base of the formation indicate that a ENW-WSW elongated block between Chuo and Kotate faults has moved upward relative to the adjacent hanging walls about 50 m at the most, but in the east this block sinks down relatively and a small parallel fault in an eastern extension of Kotate fault dips northward, while Kotate fault dips southward. Similar faulting of this set is also indicated in Yumoto area by Karasudate and the numerous parallel faults between Aikawa and Fujiwara faults. Studying the contour lines of a coal seam in Figure 13, the structure of this place is considered as a graben composed of Karasudate fault and the minor fault south of the fault, where the Karasudate fault dips southward and the Iwaki formation south of the Karasudate sink down southward step by step. In the surface geological map of Figure 9, the resultant displacement of all these parallel faults is about 350 m at the most. As mentioned in the previous pages, subsurface information indicates that in pre-Tertiary there were some faults in the basement rocks which are parallel to Karasudate set.

In Nakoso area, Hirakata fault ranges in strike from N75°E to N80°E. But some approximately N65°E trending joints among the N55°-65°E joints between Ohsaku and Idozawa faults have been probably formed in a similar relation to the both faults as the relation of Karasudate and other faults in Yumoto area to Shirasaka and Tabasaka faults. The N70°E trending minor faults in Fig. 16 are also in a similar position structurally.

Idozawa Fault Set

Idozawa fault set differs in trend largely from the previous two fault sets. The faults of this set are also apparently normal and dip slip, but have less displacement and steeper dip than the two fault sets. They range in strike from N5°W to N30°W averaging about N20°W and in the angle of dip from 60° to 90° being approximately 70° at most places. The vertical separation is about 250 m at the most of Tabasaka fault.

Although this fault set is less extensive and conspicuous than Shirasaka fault set, it is structurally more important because it is probably closely related both to the N15°W trending large faulted belts in the Abukuma Plateau and to the disposition of successful natural gas wells.

This set contains two prominent faults, Idozawa, and Tabasaka. Idozawa fault has been formed just along the southern extension of Chuo faulted belt in the Abukuma Plateau, if the faulted belt were present as suggested by Watanabe and others (1955). Besides, it is remarkably noticed that most of the unconformity line between the basement rocks and the Tertiary sedimentary rocks trend about N15°W. These N15°W trending lines are seen between Futatsuya and Yunotake faults and south of Yunotake fault. Further it is already described that the disposition of the productive drilling holes of natural gas is due in trend of N15°–20°W at most places in Yumoto and Nakoso areas. Concerning the productive well area along Hirakubo and Shirasaka faults, a remarkable structural feature that is parallel to Idozawa fault set in trend should be mentioned; the parts of Shirasaka B set as well as the position of the two well areas are arranged also in trend of N20°W.

It seems structurally interesting that, in the northern areas, Shirasaka B set of some major faults is arranged in the direction of Idozawa set, while, in Nakoso area, Shirasaka B set itself tends to connect with Idozawa set.

Yumoto Fault Set

Yumoto fault set contains Shiroiwa, Yotsukura, and Yumoto faults. These faults, having nearly vertical dip, little displacement, and broad faulted zone, has been considered rather as of fissure type. Nakamura (1959) described that the high temperature mine-water that is exceptionally abundant in Yumoto area is possibly reserved in fissures along Yumoto fault or about N–S trending faults of the basement rocks.

The strike of this set, varies from north to N50°E being consistently perpendicular to the related faults. Shiroiwa fault changes in strike to N45°–50°E as it comes closer to N45°–50°W trending Futatsuya fault, and Yumoto fault strikes N5°–10°E in Taira area where this fault has been related to the N75°–80°W Akai fault while it strikes N20°–25°E with respect to the N60°–70°W Shirasaka fault.

This, together with that there is no fault of Yumoto set in Nakoso area where the faults of Shirasaka set have been formed less intensively, indicates that there is a close structural relationship between Yumoto and Shirasaka fault sets.

Joint Sets

Joint sets I and II are found at all places to be nearly perpendicular to either A or B subset of the Shirasaka and they are parallel to the faults of Yumoto set at the places where the faults of Yumoto set are present in close distance. This indicates a genetic relation between set I and II and Yumoto set. Set I ranges in strike at most places from N5°–20°E, which is nearly at right angle to the strike of Shirasaka A set, N60°–80°W; while Set II ranges from N30°–50°E, which is nearly right angle to that of Shirasaka B set, N45°–50°W.

The close spatial relationship between Joint sets I and II and Shirasaka fault set is best shown along Hirakubo fault, Taira area. In Yumoto area it is not easy to distinguish Set I from Set II in the fracture maps at a glance, because of mixed disposition of the both sub-sets of Shirasaka, but the greater detail of Figure 9 and 13 shows that the minor faults of Set II lie in strike from N35°–50°E near N40°–45°W trending Fujiwara fault to N25°–30°E near N60°–70°W trending Shirasaka fault and that the joints and the minor faults that trend about N20°E and are present along Yumoto fault and it's southern elongation is related to the N70°–75°W trending parts of Shirasaka and Fujiwara faults. In Hisanohama area the N50°E prominent trend of joint may belong to Set II. In Nakoso area the joints of set I ranging in strike N20°–30°E are found near the N60°–80°W trending Nakoso or Sekimoto faults. But the N55°-60°E trending joints mainly between Idozawa and Ohsaku faults may be considered rather to belong to Karasudate set and it seems probable that in this area the joints of Set II as well as the fault of Shirasaka A set are not present.

Although the joints of Set I and II in shale dip considerably steep or nearly vertical, the joints or the minor faults in sandstone dip on either side at nearly equal angles at many localities such as 17, 42, and 43, and it appears as if it makes a conjugate angle with the axis of vertical plane.

The right angle relation of set I, set II and Yumoto set to Shirasaka set suggests there might be a structural relation between the former three sets and Shirasaka set. Because that Yumoto set is of fissure type, it seems to be extension fracture. So the stress system responsible for fracturing must be that maximum and intermediate principal stresses are parallel to the fracture planes and that minimum principal stress is perpendicular to the planes. In other words, maximum principal stress is perpendicular to Shirasaka set. On the other hand, when Shirasaka fault set was formed, since it is normal dip-slip fault, maximum principal stress was vertical, minimum principal stress is horizontal and perpendicular to the faults, and intermediate principal stress is parallel to the faults. So it is impossible that these three sets are formed by the movement of Shirasaka fault set. The author likes such an assumption that gravitational dip slip movement along the normal faults can produce lateral compression perpendicular to the faults, and therefore can be responsible for extension fracture perpendicular to the faults.

Joint set III, ranging in strike from N15° to 40°W is found nearly parallel to Idozawa fault set.

In Taira and Hisanohama areas the joints of this set striking between N15°–40°W became prominent along Hisakubo fault or the possible elongation of Futatsuya fault. In Yumoto area this set occurs to be parallel to N25°–30°W trending Tabasaka fault as well as it crosses the Shirasaka B set similarly as the set III in Taira and Hisanohama areas. In Yumoto area, however, minor faults of this set seem not to be present. In Nakoso area, there are few joints of set III, and the N30°–45°W trending faults occur in relation to the N20°W Idozawa fault.

Close parallelism between Idozawa and set III indicates a genetical relationship between both. Steep dip, dip slip movement and small displacement of Idozawa fault set would indicate that it is an extension fracture and this interpretation would be possible also of the joints of set III. It is very interesting that set III is formed as if it was accompanied by Shirasaka B set in Hisanohama, Taira and Yumoto areas.

VII. Characteristics of Minor Fractures

Development of Regional Fracture System

It was already discussed that major fault movement in the Abukuma Plateau, either in the mountain area of the Plateau or in the Joban coal field area were dated two times at least, one before the sedimentation of Tertiary rocks and the other in Miocene. These are called here conventionally *the earlier faultings* and *the later faultings*.

In the later faultings, all fracture sets mentioned in the previous pages are included. Characteristics of the individual fracture set and the relation among them are reviewed as follows (Tab. 3).

1. The faults of Shirasaka set are normal, dip-slip; the vertical separation in the large faults is between 200 and 700 m; and the average dips are 55° to 65°. Yumoto fault set, joint set I and set II are genetically same and possibly formed by lateral compression perpendicular to Shirasaka fault set.
2. The faults of Idozawa fault set is normal, dip about 70°, and have small displacements. Joint set III is genetically related to this fault set.
3. The faults of Karasudate set is also normal, dip-slip, range in dip from 50° to 70°, and have small displacements.

The fault movement was normal, dip-slip, of all faults. Joints are vertical in average and possibly extension fractures.

Some fault sets can be traced in the earlier faultings. Shirasaka and Karasudate sets are probably as old as the earlier faultings (refer. Chapter II). The N15°W trending faulted belts like Futaba and Tanakura (Fig. 2) were active at that time and would genetically related to Idozawa fault set. This N15°W faulted belt is of strike slip rather than dip slip, though Idozawa set is of normal, dip-slip. There is no information available as to the nature of movement of Shirasaka and Karasudate sets in the earlier faultings. It might be dip slip or might be strike slip. Since Karasudate fault set is found more local than Shirasaka, the important fault sets in the earlier faultings are N15°W trending faulted belts and Shirasaka set. Was there any genetical relation between both ?

If the former case that the two are related genetically to each other were taken into consideration, the left lateral movement of N15°W trending large faults might be responsible for normal dip slip faulting of Shirasaka set. The second fractures caused by such strike slip faulting was treated by some workers. Cloos (1955) showed experimentally that when the wet clay is subjected to a rotational stress like lateral faulting tensile fractures will open at about 45° to the direction of the stress.

Mckinstry (1953), and Moody and Hill (1956) also treated theoretically of the second fractures and described the similar results. The presumption of strike slip movement of the N15°W large faults is considered probable because of such a nature of these N15°W large faults as next; they are nearly vertical, remarkably rectilinear at the outcrop, they have much mylonitic rocks along the fault planes, they extend in remarkable straight lines and are accompanied by many smaller faults of the same character. De Sitter (1956, p. 173) described these characters are very common only in wrench faults or major strike slip faults. If this assumption is right, the fault pattern of the earlier faultings might have consisted of both the N15°W trending master

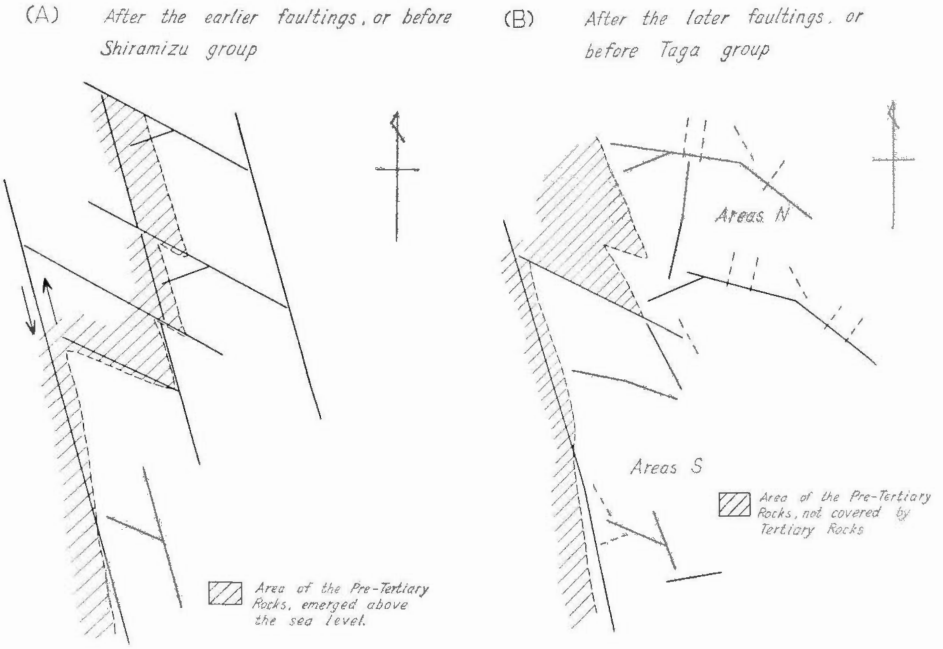


Fig. 19 Explanation of the structural development of fracture system

faults and the WNW-ESE trending second faults, and the latter is the tensile fractures resulted from the anti-clockwise strike slip displacements of the master faults. This WNW-ESE second faults tend to become a dip slip fault because of tensile fractures. The WNW-ESE faults are probably due to the Shirasaka set of the earlier faultings, and the N15°W faults are due to the Idozawa set of the earlier faultings. The faults of Karasudate set might have been formed at the same time in the area of depression formed by the normal dip slip displacements of the Shirasaka set. In this area of depression, the fault would have been formed in the strike of WSW-ENE by possible influence of the Idozawa set of the earlier faulting.

If the latter case were taken into consideration, then the Shirasaka fault set and the N15°W trending large faults must have been unrelated genetically and formed in different time during the earlier faultings. As to which case is right remain unsolved because the relation between the two in the Abukuma Plateau has not yet been determined.

In either case a rhombic frame pattern comprising Idozawa and Shirasaka fault sets was most possible pattern in the earlier faultings, and this structural feature must have controlled the sedimentation and the deformation of the Tertiary sedimentary rocks in the following time (Fig. 19). However, in more detail, the rhombic pattern was possibly different between the northern part such as Taira and Yumoto, and the southern part such as Nakoso. In the north, Shirasaka set might be as strong as Idozawa or a little stronger than Idozawa and the rhombic frame pattern was kept well, while in the south Shirasaka set might be much less predominate than Idozawa. Thus, during and after the sedimentation of Shiramizu group, possibly first movement of the later faultings, the fault lines of Shirasaka set in the north (or area N) was much influenced by the underlying rhombic framework to form a bending structure consisting of Shirasaka A and B sets. It is possible that Idozawa, Shirasaka fault sets and joint set III are genetically closely related one another.

It is probable that such faultings had been continued through the sedimentation of Yunagaya, and Shirado groups. And even at the time of the later faultings, the faults and the joints of the Tertiary rocks might have been formed in the same way, but more intensely by far.

After Taga group, as indicated by the observations at some surface exposures, the N15°W trending large faults might have changed in nature of displacement from strike slip formerly to reverse, dip slip at some places.

Minor Fractures

The above interpretation about the development of the regional fracture system contains some postulations which should be ascertained by further studies. Nevertheless, if it is accepted, we could find it reasonable why the successful wells have been found specially with respect to Idozawa fault set and Shirasaka B fault set.

Idozawa fault set includes the faults that faulted more intensively than any other at the time of the earlier faultings and could act most strongly upon Shiramizu group during the following sedimentation and deformation of the group. The coarse sandstone of Iwaki formation that has been accepted as the gas reservoir bed, being only about 150–250 m high from the basement rocks might have been easily affected by the faultings of the basement rocks.

The fractures that are closely related to the pay reservoir are perhaps *minor fractures*, in other words, joints and minor faults. In some productive gas areas in the northern part such as Nakajio, Hashirikuma, and Sumiyoshi, the abundant minor fractures responsible for gas accumulation might be joint I and joint II. In the southern productive areas such as Izumi-Shimofunao, Eguri, and Kubota, the important minor fractures would be the joints and minor faults of both Idozawa and Shirasaka sets.

Most of these minor fractures are very steep or nearly vertical in dip and in the loose, coarse sandstone like that of Iwaki formation, they tend to form irregularly curved planes to cross each other. This fracturing will get the loose, coarse sandstone collapsed extensively and make abundant spaces or long paths more easily than in any other rock material.

VIII. Conclusion

Idozawa and Shirasaka fault sets, either in the Tertiary sedimentary rocks or in the underlying basement rocks might have been responsible for the concentration of abundant minor fractures and the formation of natural gas reservoirs in the Joban coal field.

At the time of the earlier faultings, or before the sedimentation of the Tertiary sedimentary rocks, Idozawa and Shirasaka fault set exhibited a fault pattern of rhombic framework in the basement rocks, in which Shirasaka fault set had been formed less extensively and intensely than Idozawa fault set, and perhaps the former had been resulted from the latter.

The faults and joints during and after the sedimentation of Shiramizu group and further even after that of Yunagaya, Shirado, and Takaku groups was formed under control of the earlier pattern. In the areas S (Fig. 19b), where Idozawa fault set had been formed more intensively than Shirasaka fault set in the earlier pattern, the faults in the Tertiary rocks exhibited nearly similar pattern as the earlier; while, in the areas N, where Shirasaka set formed intensively so much as Idozawa set, the Shirasaka set became more conspicuous feature than the Idozawa apparently because of larger dip slip movement of Shirasaka set, but the Shirasaka set differenciated into two subsets, A and B, probably upon the fault lines of the Idozawa set of the earlier. The faultings in the Tertiary both areas S and N, must have been made most intensively particularly in the places, under where the both sets join in the basement rocks.

Areas S are related to such a productive natural gas area in the southern part as Izumi-Shimofunao, Eguri, Kubota, and Sekimoto. In these areas the minor fractures that have been closely related to the formation of gas reservoirs are perhaps the minor faults and joints of Idozawa and Shirasaka sets. Areas N are related to such productive areas as Nakajio, Hashirikuma, and Sumiyoshi. In these areas the minor fractures closely related to the formation of gas reservoirs are perhaps the joints of set I, II, III.

The relation of the productive wells in Takai to the fractures is hardly determined. They may be related to the other causes that include minor fractures by drag folding; or may be unrelated to minor fractures. However, it is structurally interesting that they are on the southern elongation of Kumando fault (Fig. 4b) and this possibly indicates that they may be related to Idozawa fault set likely to underlie in the basement rocks.

For the advanced study of fracture system in this coal field, it is necessary to do with experimental analysis that contains the study of clay model and that of rock behaviour under artificial high pressure, and quantitative treatments for the intensity of jointing as caused by faulting. The interpretation concerning the development of the fracture system of this field, described in this paper should be a working hypothesis for these advanced studies. Problems of structural control, when they are referred with respect to prospection of natural gas, is attributed to the problems of fractures. They may be related to regional folds, regional faults, or any local structural features in a gas field. Quantitative treatment of fractures is also related to fracture porosity and permeability. All these studies should be necessarily done for the structural control of natural gas accumulation.

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常磐炭田におけるフラクチュアー系と天然ガス産出状況

星野　一男

要　旨

戦後，本炭田で天然ガスの開発が進むにつれ，成功井の位置が断層系と非常に関係していることが注目されるようになった。成功井は南部では北北西-南南東方向に排列し，より微弱ではあるが西北西-東南東方向の要素も見られる。北部では西北西-東南東方向と北西-南東方向の断層の交差点付近に存在する。(第4図)

フラクチュアー調査では，フラクチュアーを規模から大断層，小断層，節理に分け第1図に示した地域をえらんで，地表，坑内の既存資料の整理，および地表の断層，節理の統計調査を行ない，それぞれ顕著な方向を求めて，全般的な地質構造と対比した。調査の結果は第 5～16 図に示される。

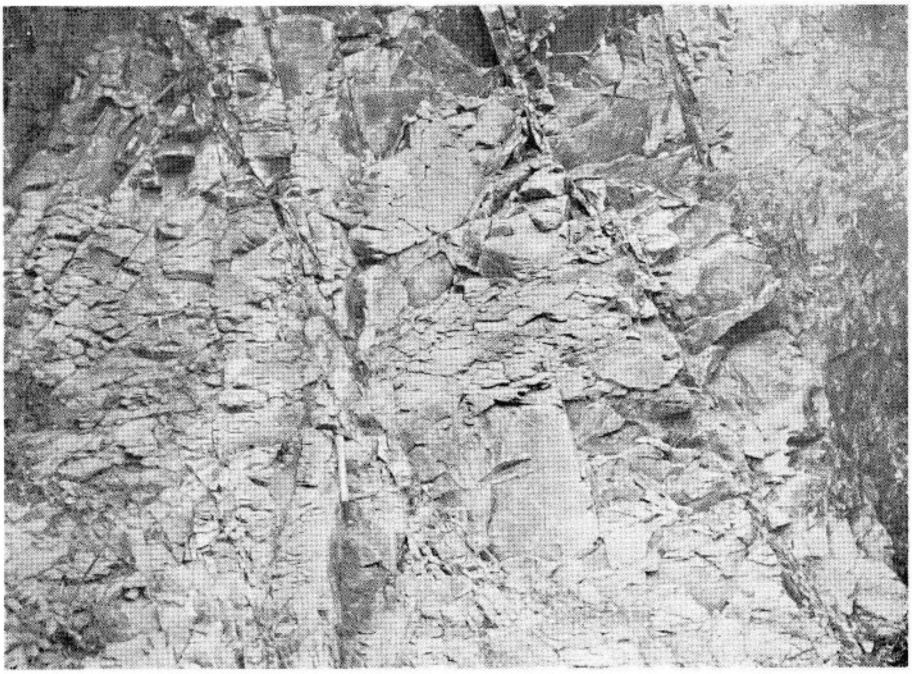
断層の顕著な方向は西北西-東南東，北西-南東，北北西-南南東，東北東-西南西，および北北東-南南西。節理の顕著な方向は北北東-南南西，北東-南西，および北北西-南南東である。これらを本文では便宜上，第 18 図に示すように白坂A，白坂B，井戸沢，鳥館，および湯本，断層群，第 1，第 2，および第 3 節理群と呼ぶことにしてある。

断層のうち，井戸沢，白坂および鳥館断層群は，第3系下部の堆積状況，“および”潜丘の分布状況から第3系の堆積前に生成されていたと考えられる。鳥館断層群の分布は局限されていたようで，第3系以前の主要断層系統は第 19 図に示すように井戸沢，白坂の両断層群からなる菱形構造であったろう。第3紀の断層運動には何回かの波が考えられるが最大のものは高久層群と多賀層群の間，中新世後期と考えられる。この運動（本文でいう後期断層運動）後現在のようなフラクチュアー系統が完成された。この際先の菱形構造が大きな影響を与えた。炭田の南部では菱形構造は，ほぼそのままの形で第3系の断層系統に転移して行なったが，北部では，おそらく基盤中の白坂断層群が湯沢断層群よりも強く保存されていたために，第19図 b に示すように，第3系中には白坂断層群が強く現われながらも，白坂断層群は基盤中の湯本層群に影響されて，やや走向を変え，白坂 A および白坂 B の2群に分れたものと考えられる。

本炭田のフラクチュアー系発展に関するこの考え方はむしろ作業仮説というべきもので今後の研究によって実証されなければならないものである。しかしこのように，基盤中の井戸沢および白坂の両断層群が第3系のフラクチュアー系の成立にもっとも重要な役割を演じていると考えると，現在までに発見された成功井の分布状況をよく説明することができる。

天然ガス鉱床の成立に重要なフラクチュアーはむしろ，小断層や節理のような minor fractures である。北部の中塩，走熊，住吉のような産ガス地帯では，第 1，第 2 の節理群が主要な minor fractures である。第 1，第 2 節理群は白坂A，白坂 B 断層群にほぼ直交しており，白坂断層群の垂直ズレ正断層運動に伴う横圧力によって作られた extension joints と考らえれる。中南部の泉-下船尾，江栗，窪田などの地帯では白坂および井戸沢の両群に平行する小断層および節理がガス鉱床と関係が深いものと考えられる。

Photo 1. Joints in loose, coarse sandstone of Iwaki formation. The sandstone is found to form reservoir beds at most wells. Interval among joints is wider than any other rocks in this field. A cap in the middle is a scale indicator. View at the roadside in Idekura, Nakoso city.



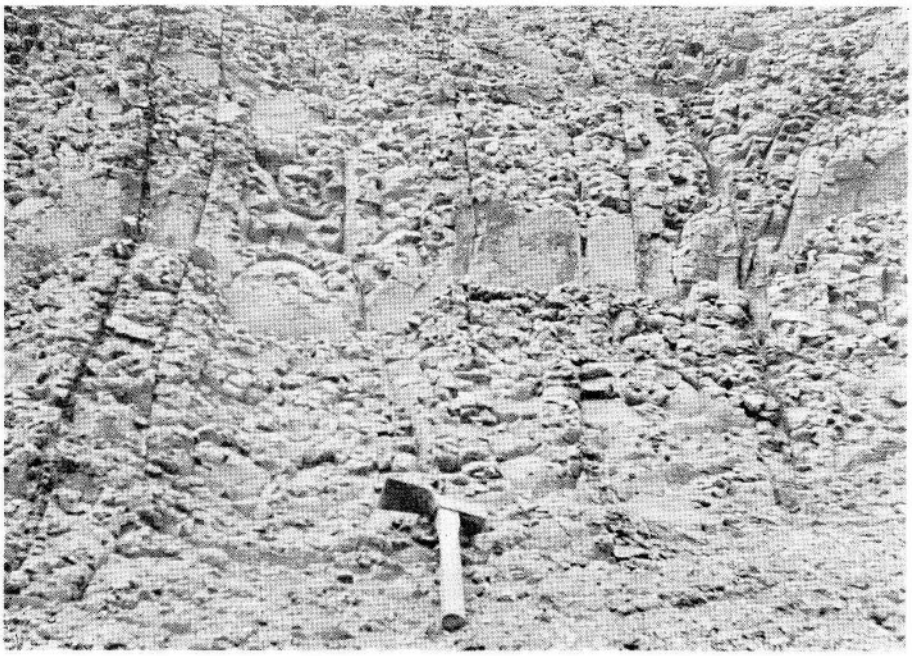


Photo 2. Joints in shale of Shirasaka formation. Numerous *weathering joints* are formed among larger, straight-lined *systematic joints* which have nearly vertical or steep dip. The weathering joints of this kind were excluded from measurements. Both views are found near Hattan, Nakoso city.

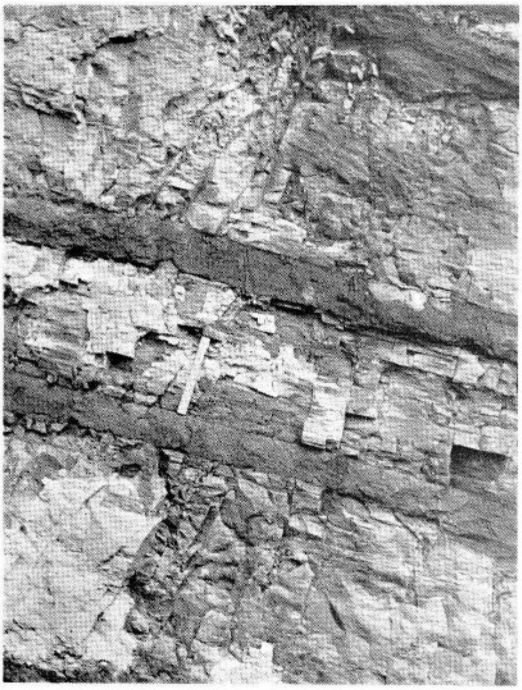


Photo 3. Joints in shale and sandstone of Kameno-o formation. The shale, a little tuffaceous, is harder than that of Shirasaka formation, and the joints are formed more numerously. Some of the joints in the shale occur through the sandstone. View at the roadside from Ohtsu to the old barrier of Nakoso.

Photo 4. Sand dykes in Kameno-o formation. A wider, steep one by the man is 1 meter in width and formed of coarse, dark green sandstone. A thinner one which intrudes like sheet is 0.1 meter in width. View at Otaka, Nakoso city. Further explanation is on page 24.

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  - 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
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- B. Applied geology
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Kazuo Hoshino

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21 illus., 3 pl., 3 tab.

Successful natural gas wells in the Joban coal field are found along the NNW trending faults in the southern area, and near the junction of WNW and NW faults in the northern area. On the other hand, prominent trends of faults in the coal field area, Tertiary in age, are WNW, NW, NNW, ENE and NNE, and those of joints except that parallel to the faults are NNE, NE and NNW. Among them, the WNW and NNW faults (Shirasaka A and Idozawa fault sets) are as old as pre-Tertiary and considered to be most important to the occurrence of the natural gas.

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