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Stratigraphical and Sedimentological Studies of the Paleogene to Miocene Strata in Southwestern Shikoku, Japan

By

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with 4 Tables, 45 Text figures and 2 Plates

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ABSTRACT

In the Hata Peninsula, Kochi Prefecture, the thick strata of Tertiary age are widely distributed, occupying a part of the Shimanto Terrain, which is situated in the southern most part of the Outer Zone of Southwest Japan. The strata can be classified into the Hata Group, the Shimizu Formation and the Misaki Formation on the basis of their lithology and geological age.

The Hata Group includes the nearly contemporaneous Hirata, Tatsugasako, Kurusuno and Hiromi Formations, ranging in age from Eocene to Early Oligocene(?). The Hirata Formation is mud-dominated sequence containing shallow-marine molluscs. The Tatsugasako and Kurusuno Formations are composed mainly of alternating beds of sandstone and shale with various sand/shale ratios. The former includes pebbly sandstone in the Upper Member, while the latter is interbedded with acidic tuff at several horizons. The Hiromi Formation is pervasively sheared sequence which consists of chaotic deposits with minor intercalations of greenstone and red shale. The Hirata, Tatsugasako-Kurusuno and Hiromi Formations correspond to shelf facies, flysch facies and melange facies, respectively.

The Shimizu Formation consists mainly of chaotic deposits, accompanied locally with coherent beds. The chaotic deposits contain irregular-shaped blocks and clasts of various kinds of sedimentary and igneous rocks (mainly sandstone) dispersed in scaly and cloven muddy matrix. The coherent beds are less deformed, consisting of conglomerate, sandstone and mudstone. The Shimizu Formation is referable to an olistostrome ranging in age from Late Oligocene to Early Miocene.

The Misaki Formation is represented by shallow-marine sandstone and mudstone, and shows a coarsening- and thickening-upward cycle as a whole. The formation unconformably overlies the Shimizu Formation. Its lowest horizon is assigned to upper Lower Miocene (Burdigalian) on the basis of planktonic foraminifers.

Most of the sandstones of the Tertiary strata are rich in quartz and poor in rock fragment. They belong to feldspathic wacke. The sandstones of the Hiromi Formation are, however, exceptionally richer in feldspar and rock fragment than others. The paleocurrent directions in the Hata Group are clearly grouped into two systems: One is represented by longitudinal current from southwest to northeast with lateral current, and the other by southerly lateral current and westerly longitudinal current. The general sense of current flow in the Misaki Formation was dominantly to the south.

The result of the analysis of sedimentary facies suggests that a part of the Hata Group corresponds definitely to turbidite fan deposits, and that most of the group corresponds to non-fan deposits. The Shimizu Formation contains coherent olistoliths of non-marine deposits, shallow-water deposits and deep-water deposits. On the other hand, the Misaki Formation is interpreted as representing progradational deposition on beach to basin plain, affected by storm waves and tidal currents.

Lastly, the depositional history from Eocene to Middle Miocene is discussed from the stratigraphical and sedimentological viewpoints.

CONTENTS

I. INTRODUCTION

The Shimanto Supergroup is widely distributed in the outermost zone of Southwest Japan, and is represented by an extremely thick sequence of geosynclinal deposits. It had been called "unknown Mesozoic strata" for a long time, because of a scarcity of megafossils, complicated geologic structures and monotonous lithofacies. Recently, the stratigraphy and geologic structure of the supergroup, as well as the geological age, have fairly been clarified by energetic surveys and studies of many geologists.

Several pioneers made important investigations into the Shimanto Supergroup in their respective regions; HASHIMOTO (1962) in Kyushu, KATTO (1961) in Shikoku, HARATA (1964) in the Kii Peninsula, etc. The stratigraphy and geologic structure which they suggested in each region, were useful to the later workers. However, they explained the formation process of the supergroup by the use of the "classical" geosynclinal theory for some time; e.g. MINATO et al. (1965), KISHU SHIMANTO RESEARCH GROUP (1975).

Recently, in accordance with the developments of the plate-tectonics theory and submarine geology, the Shimanto Belt is paid attention to as the important terrain to throw light on the geology of the circum-Pacific regions. The stratigraphy and geologic structure of the Shimanto Supergroup have been reexamined, and consequently, many geological data have been newly accumulated. Furthermore, some models and hypotheses for its formation process have been also proposed; e.g. KANMERAand SAKAI (1975), SAKAI (1978), TAIRA et al. (1979, 1980), SUZUKI and HADA (1979). The data of detailed geological age on the basis of radiolarian fossils have greatly contributed to these studies. TERAOKA (1977, 1979) and KUMON (1983) clarified the stratigraphic change in properties of coarse clastic rocks during the Cretaceous and Paleogene. These studies are also useful for consideration of the geologic development of the Shimanto Terrain.

Most of the studies mentioned above concern the strata in the northern subbelt of the Shimanto Belt containing greenstone and chert. On the other hand, the study of the Paleogene-Lower Miocene strata in the southern subbelt falls far behind. To make matter worse, there are few works on the strata ranging from the later depositional stage of the Shimanto Supergroup to post-Shimanto period. As is wellknown, the Shimanto Supergroup is overlain by the Miocene Tanabe and Kumano Groups in the Kii Peninsula and the Upper Miocene-Pliocene Miyazaki Group in Kyushu with a remarkable clino-unconformity. The disturbance represented by this unconformity was called the Takachiho phase by KURODA and MATSUMOTO (1942). SHUTO (1963) emphasized that it has a significant meaning in view of the crustal movement in Cenozoic time, and termed it "Takachiho disturbance". SAKAI (1983) also confirmed its meaning from the viewpoint of the plate-tectonics theory.

Under such circumstances, the author has investigated the southern subbelt of the Shimanto Belt in the southwestern part of Shikoku in order to clarify the features of the Tertiary strata of the Shimanto Supergroup. The main purpose of this paper is to describe the stratigraphy of the Paleogene-Lower Miocene strata of the Shimanto Supergroup and the overlying Miocene strata. The sedimentological studies including facies analysis, sandstone petrography and paleocurrent analysis are also added. In conclusion, the discussion will be made in reference to the sedimentary processes and environments of these strata.

Acknowledgements

The author wishes to express his sincere thanks to Prof. A. HASE of Hiroshima University who gave him continuous guidance and encouragement and carefully read the typescript. The author is deeply indebted to Dr. T. MIYAMOTO of the same university for support and discussion in his field and indoor works. He is also grateful to Prof. S. KAKITANI , Prof. A. SOEDA, Prof. I. HARA and Associate Prof. Y. OKIMURA of Hiroshima University for their various help. Prof. T. SAITO of Yamagata University and Prof. K. MATSUMARU of Saitama University kindly identified foraminiferal fossils, Drs. M. SUZUKI and M. TOKUDA of Hiroshima University examined thin sections and Dr. K. TAKEDA of Yamaguchi University supported a part of the field survey. Mr. H. TAKAHASHI and Mr. A. MAGAI of Hiroshima University prepared thin sections. The author is, moreover, much obliged to Mr. T. OKAZAKI and his family in Tosashimizu City, Kochi Prefecture, who kindly helped him throughout his field survey.

II. GEOLOGIC SETTING AND PREVIOUS WORKS

The investigated area is situated in the Hata Peninsula, Kochi Prefecture, Shikoku (Fig. 1). This area belongs geotectonically to the southern subbelt of the Shimanto Belt, and is occupied mainly by the Paleogene strata, in which sandstone and shale are predominant with a negligible amount of greenstone and chert.

SUZUKI (1937, 1938) first revealed the outline of geology of the Hata Peninsula, and classified the strata developed there into the Jurassic-Cretaceous, C retaceous, Cretaceous-Tertiary and Tertiary Systems. KATTO et al. (1960) and KATTO (1961) revised the division of SUZUKI and distinguished the Cretaceous Suzaki Formation, the Paleogene Murotohanto Group (Tanokuchi and Shimizu Formations) and the Sukumo Group (Hirata, Tatsugasako and Misaki Formations).

TERAOKA (1977, 1979) guessed the geological age of the Shimanto Supergroup in the present area on the basis of marked change in sandstone composition according to the stratigraphic position. He suggested

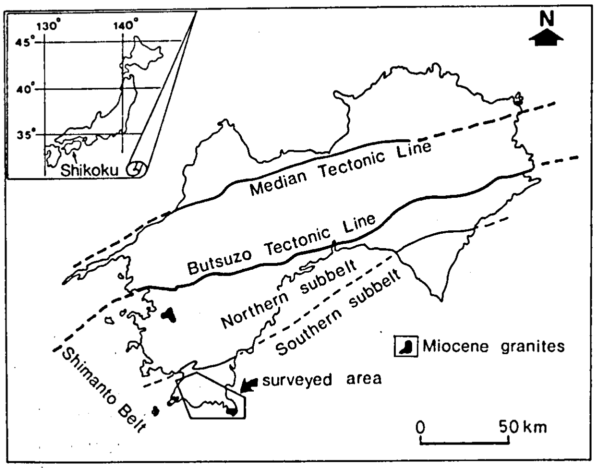


FIG. 1. Index map of the surveyed area.

that most of the Suzaki Formation of KATTO occupying the middle part of the Hata Peninsula is of Paleogene age, and the only northern part of it belongs to the Cretaceous. The Cretaceous strata mentioned above were termed the Hiromi Formation by TANAKA (1977). On the other hand, KATTO and MITSUI (1976) newly proposed the Kurusuno Formation. The Kurusuno Formation includes the Hiromi Formation of TANAKA and is nearly equivalent to the Suzaki Formation of KATTO. After that, some Eocene radiolarian fossils were reported from the Hiromi Formation by TANAKA (1980), and Eocene larger foraminifers from a limestone block in the Kurusuno Formation by KATTO et al. (1979). Recently, TANAKA (1980) and TAIRA et al. (1980) have summarized the stratigraphy of the Shimanto Supergroup in the Hata Peninsula. TAIRA et al. (1980) have collectively redefined the Paleogene in the peninsula under the name of the Hata Group, considering that it ranges in age from Eocene to Early Oligocene. However, the Shimizu Formation must be separated from the Hata Group, because it contains the Oligocene and Lower Miocene strata at least. In the Muroto Peninsula, TAIRA et al. (1980) have separated the Upper Oligocene-Lower Miocene Nabae Group from the Murotohanto Group.

In this paper, the author divides the Shimanto Supergroup in the investigated area into the Hata Group (Eocene-Oligocene) and the Shimizu Formation (Oligocene-Lower Miocene), the former of which is subdivisible into the contemporaneous but heteropic Hiromi, Tatsugasako and Kurusuno Formations.

The Misaki Formation had been regarded as a member of the Shimanto Supergroup (KATTO, 1961), but KIMURA (1985) made clear that the formation unconformably overlies the Shimizu Formation. The Misaki Formation is characterized by a coarsening-upward sequence composed of shallow marine deposits. It may be of upper Lower to Middle Miocene age. KATTO and TAIRA (1979) presumed the sedimentary environment and depositional process of the formation on the basis of lithologic features.

In the southeastern and southwestern parts of the Hata Peninsula, Tertiary igneous rocks are intruded into the Shimanto Supergroup. The K-Ar age of them is 13-15 Ma (KAWANO and UEDA, 1966; SHIBATA and NOZAWA, 1968a, b). Besides, the Pliocene Koe Formation (KATTO, 1952) and the terrace deposits unconformably overlie the Shimizu Formation. There are also the gravel beds overlying the Misaki Formation at the Chihiro-misaki.

III. STRATIGRAPHY

The Shimanto Supergroup in the Hata Peninsula is divided into the Hata Group below and the Shimizu Formation above. The two are in fault contact with each other. The Shimizu Formation is unconformably overlain by the Miocene Misaki Formation (KIMURA, 1985).

The generalized geological map of the investigated area is shown in Fig. 2, and the schematic columnar sections are summarized in Fig. 3. The descriptions of stratigraphy and lithology of each formation will be given in the following.

A. HATA GROUP

The Hata Group includes lots of the chaotically mixed rocks which are inferred to be submarine slide and slump deposits. In the surveyed area the group can be divided into the Hiromi, Tatsugasako and Kurusuno Formations based on lithofacies. Although the original stratigraphic relationship and the precise geological age are uncertain, it is possible that these three formations are contemporaneous but heteropic with one another.

In the northwest of the surveyed area are distributed the Hirata Formation (Nakatsuno Formation of TANAKA, 1980) and the Shikazaki Formation, which are, in the geological map (Fig. 2), illustrated as the undivided Paleogene. The Hirata Formation consists mostly of mudstone, and yields such molluscan fossils as *Crassatellites* cf. *yabei* Nagao and *Venericardia subnipponica* Nagao (KATTO, 1961) in addition to Upper Eocene calcareous nannofossils (OKADA and OKAMURA, 1980). To the northeast of the surveyed area the Tanokuchi Formation is distributed, which contains characteristic conglomerates including clasts of schist (KATTO, 1961) and is considered to be of Eocene age (TAIRA et al, 1980).

1. Hiromi Formation

The Hiromi Formation is distributed in the western part of the area, and is in fault contact with the Tatsugasako Formation on the northwest and the Kurusuno Formation on the southeast. The formation consists mainly of shale, with subordinate amount of sandstone and greenstone. It is characterized by a chaotic mixture, and stratal continuity is extensively disrupted. According to TANAKA (1980), the formation attains 4,200m in thickness and is lithologically divided into five members, but it is difficult to reconstruct the lithostratigraphy throughout the formation owing to its disturbed character. Therefore, the subdivision is not attempted in this paper.

The shale is pervasively sheared and has a scaly appearance. Secondary minerals such as muscovite and chlorite are often formed along cleavages. The sandstone commonly occurs as massive blocks, but occasionally alternates with shale. It is generally fine- to medium-grained, but sometimes pebbly and con-

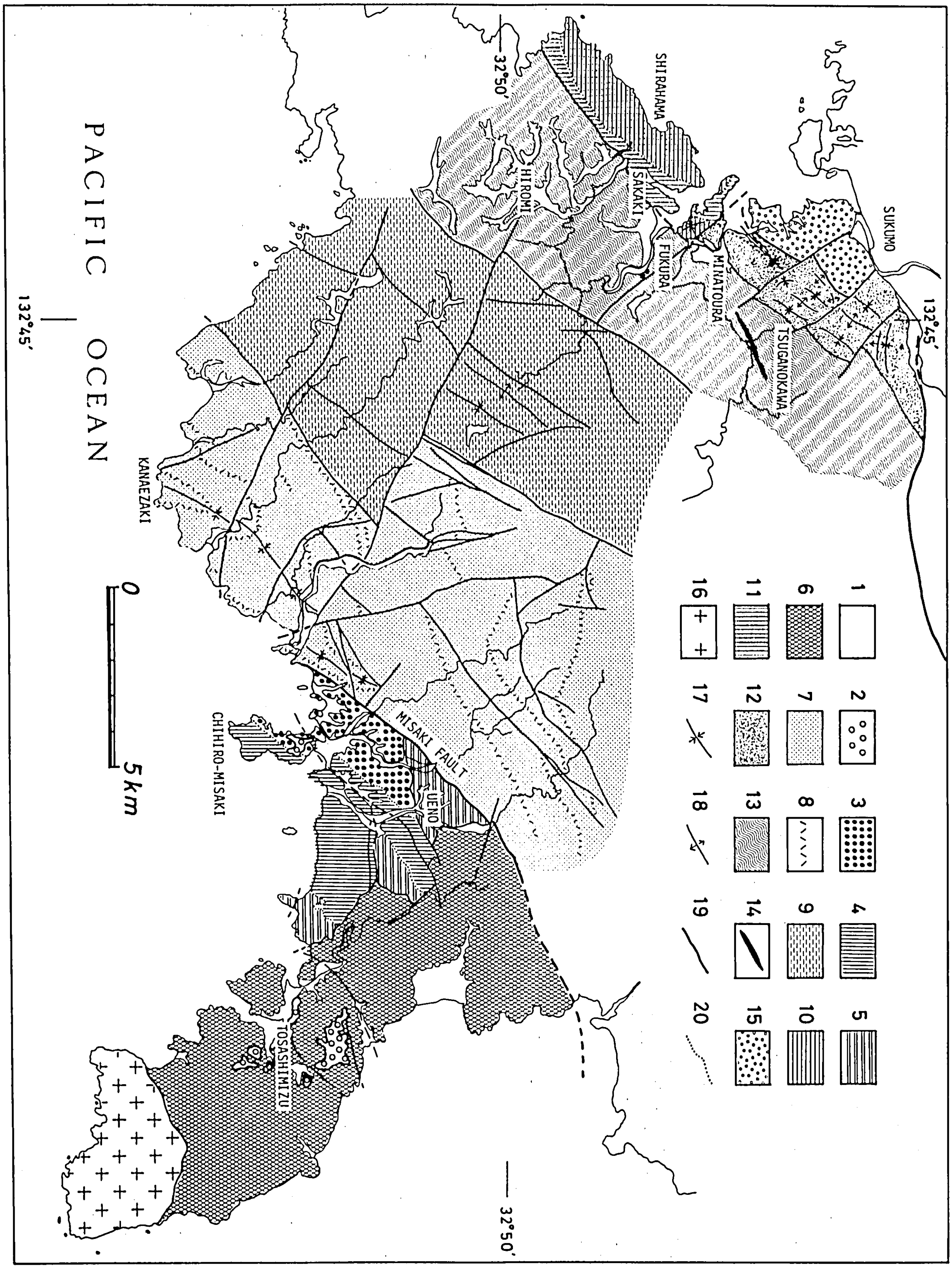


FIG. 2. Generalized geological map.
1: Alluvium, 2: Koe Formation (Pliocene), 3-5: Misaki Formation (3: Upper Member, 4: Middle Member, 5: Lower Member), 6: Shimizu Formation, 7-9: Kurusuno Formation (7: B Member, 8: Acidic tuff, 9: A Member), 10-12: Tatsugasako Formation (10: Shirahama Member, 11: Sakaki Member, 12: Tsuganokawa Member), 13: Hiromi Formation, 14: Basalt, 15: Undivided Paleogene, 16: Miocene granitic rocks, 17: Syncline, 18: Anticline, 19: Fault, 20: Member boundary.

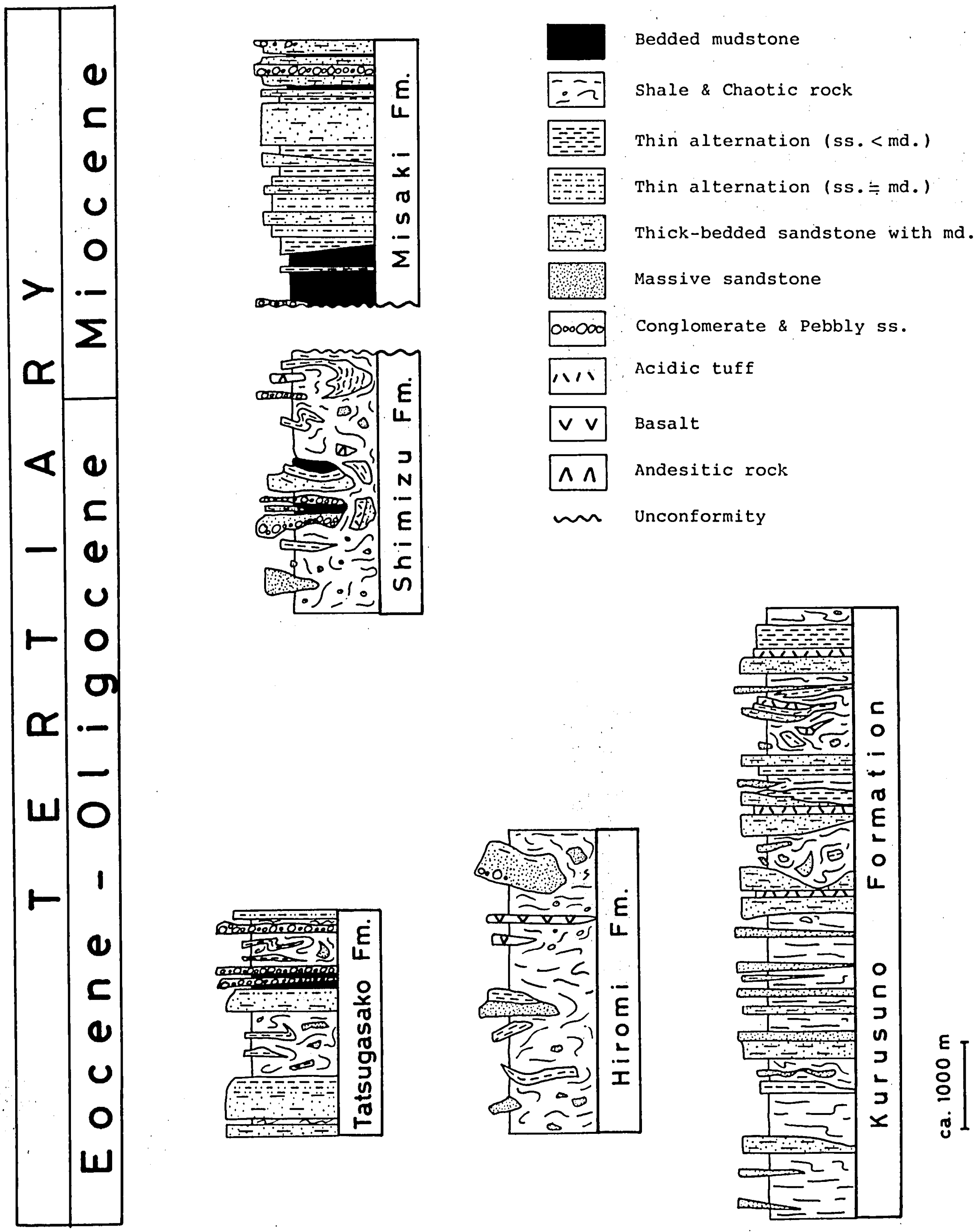


FIG. 3. Schematic columnar sections of the Tertiary strata in the investigated area.

tains angular fragments of shale. It is more or less feldspathic in composition.

The greenstone is typically exposed at Tsuganokawa and Fukura of Sukumo City. The greenstone at Tsuganokawa is composed of basaltic lava and tuff, accompanied closely by red, green and gray tuffaceous shale (Fig. 4). It is traceable for a distance of 1.8 km with variable thickness (maximum 50 m). Neither fault nor stratigraphic break is observable along the upper and lower boundaries. The basaltic lava is commonly massive, but occasionally shows a pillow structure. Under the microscope, the massive lava generally exhibits intergranular texture and is composed of phenocrysts of plagioclase laths and xenomorphic clinopyroxene (colorless). The constituents of the groundmass are plagioclase, clinopyroxene, opaque minerals, sphene, glass and secondary minerals. The secondary minerals are chlorite and calcite. Owing to alteration, the plagioclase is partially replaced by a saussuritic aggregate and the clinopyroxene is often turbid in the interior. The pillow lava is hyalocrystalline and aphanitic. Phenocrysts of plagioclase laths and minute clinopyroxene are embedded in a glassy groundmass. Secondary minerals are chlorite, calcite and epidote. Epidote often occurs along the outermost rim of a single pillow.

The greenstone at Fukura is exposed in a limited area (a distance of about 250m). It is composed of massive basalt, dolerite and tuff. Under the microscope, the basalt is holocrystalline or hyalocrystalline

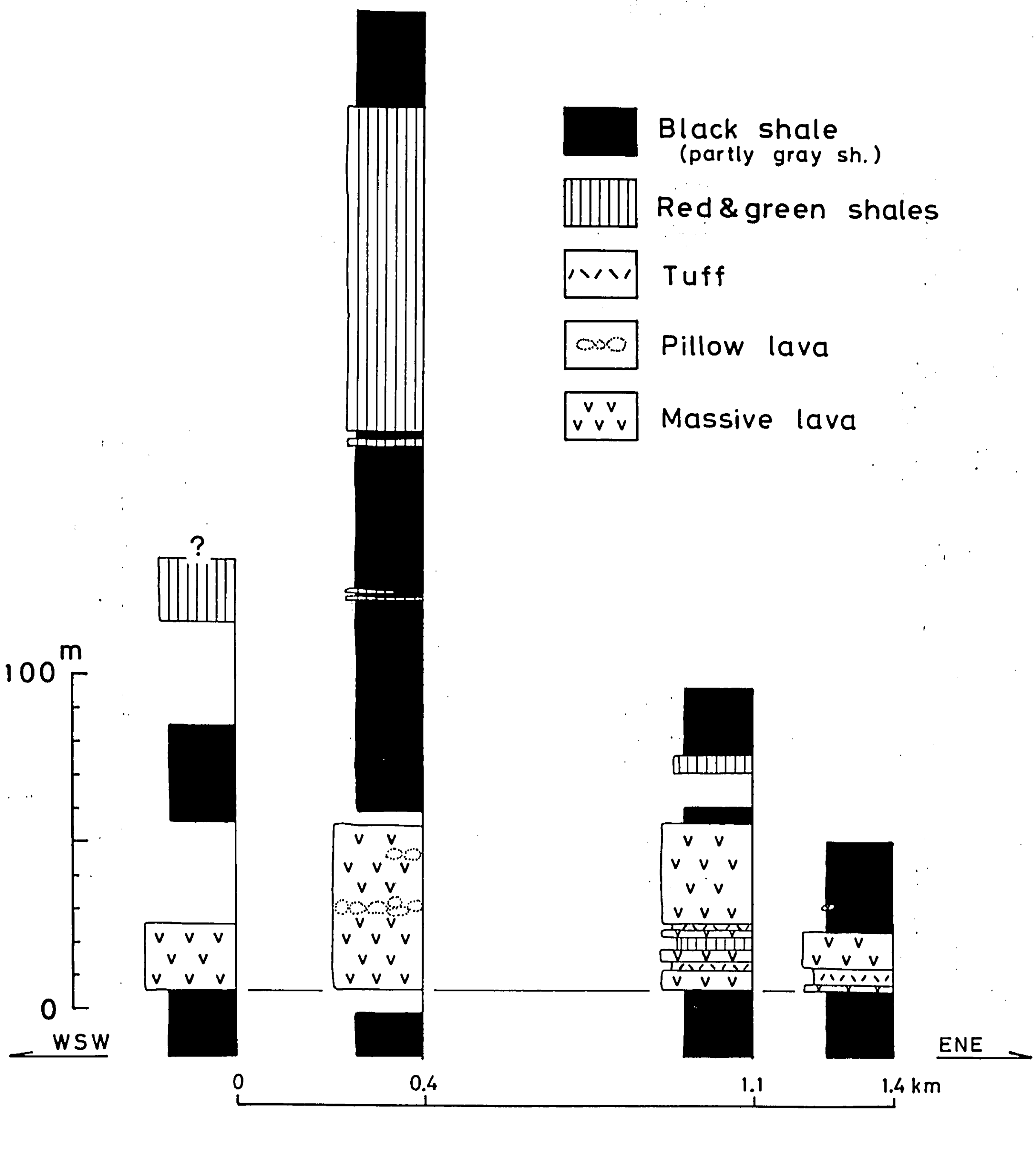


FIG. 4. Columnar sections of the Tsuganokawa greenstone body in the Hiromi Formation.

and exhibits ophitic or intersertal texture. Phenocrysts are composed of idiomorphic or hypidiomorphic plagioclase and xenomorphic clinopyroxene. Groundmass is made up of minute plagioclase, clinopyroxene, opaque minerals, glass and secondary minerals. The secondary minerals are prehnite, chlorite and calcite. The dolerite scarcely preserves original igneous texture because of fracturing, but an ophitic or subophitic texture is rarely observed. Phenocrysts of plagioclase and clinopyroxene are broken in fragments and partially altered. It seems that the greenstone at Fukura occurs as detached blocks. There are also a few blocks of greenstone, several meters in diameter, in other localities.

The Hiromi Formation seems to have suffered low-grade metamorphism of the prehnite-pumpellyite facies. This formation yields radiolarians such as *Dictyoprora mongolfieri* (Ehrenberg) characteristic of Middle to Upper Eocene (TANAKA, 1980).

2. Tatsugasako Formation

The Tatsugasako Formation is distributed in the westernmost part of the surveyed area, and is in fault contact with the Hiromi Formation on the southeast. It is composed of shale and alternating beds of sandstone and shale, accompanied with chaotic beds such as slump fold deposits and sand-mud mixed deposits. The total thickness ranges from 2,500 to 2,800 m. Folds of variable scale are observable, their axis-trend and shape being not necessarily constant. Most of them are regarded as slump folds resulting from removement after deposition. The formation can be divided into three members based on lithology. In this paper, they are tentatively termed the Tsuganokawa, Sakaki and Shirahama Members in ascending order.

a. Tsuganokawa Member

The Tsuganokawa Member consists mostly of alternating beds of fine- to medium-grained sandstone and shale, and sometimes contains muddy slump beds. The thickness is estimated to be 600 or 800 m. Each of the sandstone beds is generally 10 to 30 cm in thickness, and is internally massive or shows parallel lamination. The sandstone often attains 1 to 10 m thick, and is dominated by parallel lamination. Current marks such as flute marks and groove marks are observed on the basal surface of sandstone beds. Trace fossils are also recognizable at places. The shale is generally very thin (less than several cm in thickness), but becomes thicker at lower horizon. Muddy slump beds are chaotically mixed deposits characterized by the development of ruptures and folds. The Tsuganokawa Member grades upward into the Sakaki Member.

b. Sakaki Member

The Sakaki Member is composed of shale and chaotic beds such as slump fold deposits and sand-mud mixed deposits. The estimated thickness is about 800 m. The sandstone is fine-grained and massive or parallel-laminated. The shale generally has a scaly appearance. Molluscan fossils such as *Portlandia watasei* (Kanehara) and *Lucinoma* cf. *hannibali* Clark are found at Sakaki, Sukumo City (KATTO, 1961). The Sakaki Member is conformably overlain by the Shirahama Member.

c. Shirahama Member

The Shirahama Member is composed mainly of alternating beds of sandstone and shale. The thickness is 1,100 to 1,200 m. The following three rock-types occur repeatedly.

1) Pebbly sandstone and sandstone.
2) Alternating beds of fine-grained sandstone and shale.
3) Shale intercalated rarely with layers of sandstone.

The pebbly sandstone includes well-rounded granules and fine pebbles of chert, vein quartz, shale etc. Another type of the pebbly sandstone contains abundantly angular to subangular, pebble-sized clasts of shale derived from underlying bed. The former occurs in the upper stratigraphic horizon, while the latter in the lower horizon (Fig. 5). The alternating beds of sandstone and shale are variable in sand/shale ratio. A pale-greenish gray (tuffaceous?) shale, 1 to 8 m thick, is intercalated in the black shale.

Various sedimentary structures such as flute marks, tool marks, parallel lamination, cross lamination, convolute lamination, graded bedding and water-escape structure are observed. Slump structures develop especially in the shale facies. Trace fossils also occur in various places.

3. Kurusuno Formation

The Kurusuno Formation is widely distributed in the central part of the surveyed area (Fig. 2). It is in fault contact with the Hiromi Formation on the northwest, and with the Shimizu and Misaki Formations on the southeast. The lithologic map, geologic profiles and columnar sections are shown in Figs. 6, 7 and 8 respectively.

The Kurusuno Formation is composed mainly of shale and alternating beds of sandstone and shale, with interbedded layers of acidic tuff. The total thickness varies from 6,500 to 8,000 m or more. As the slump and resedimentation are common, the continuity of individual beds is often disrupted and the original stratigraphy is disordered. The formation is severely deformed by many faults and folds (wave-length 0.2 to 3 km or more). The structural trend is generally NE-SW. Beds dip predominantly to the northwest or southeast at a high angle, and are often overturned. Slaty cleavages are developed remarkably in the pelitic rocks. The strike of them is nearly uniform throughout the formation, being parallel to the fold-axis.

The Kurusuno Formation is subdivisible into the A and B Members lithologically and geotectonically. They are bounded by a fault of NE-SW direction. Acidic tuff is often intercalated in the B Member. There is also a slight difference in sandstone composition between the two members. Although the original stratigraphic relationship is not necessarily obvious, it seems that the B Member rests conformably upon the A Member in the north of the mapped area.

The Kurusuno Formation is poor in fossil, but yields Middle to Upper Eocene larger foraminifers such as *Asterocyclina* cf. *stella* (Gumbel) (KATTO et al., 1979; MATSUMARU, 1980).

a. A Member

The A Member occupies the northwestern part of the distributional area of the Kurusuno Formation. It is composed of sandstone, shale and alternating beds of sandstone and shale, with accompanied chaotic beds. The estimated thickness ranges from 3,000 to 4,000 m. It is difficult to build up the detailed

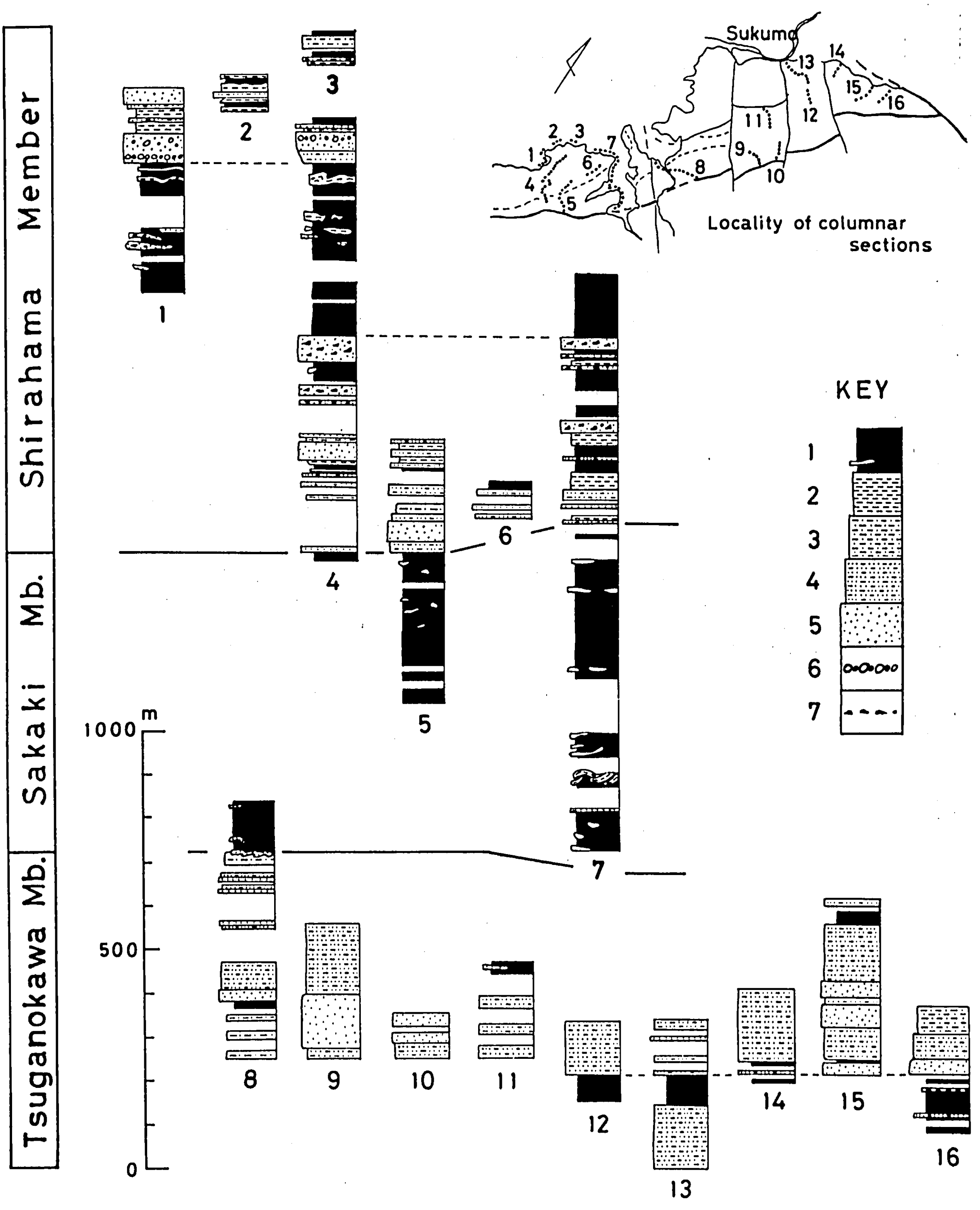


FIG. 5. Columnar sections of the Tatsugasako Formation.
1: Shale & chaotic rock, 2: Shaly flysch, 3: Normal flysch, 4: Sandy flysch, 5: Thick-bedded & massive sandstones, 6: Pebbly sandstone, 7: Angular clast-bearing sandstone.

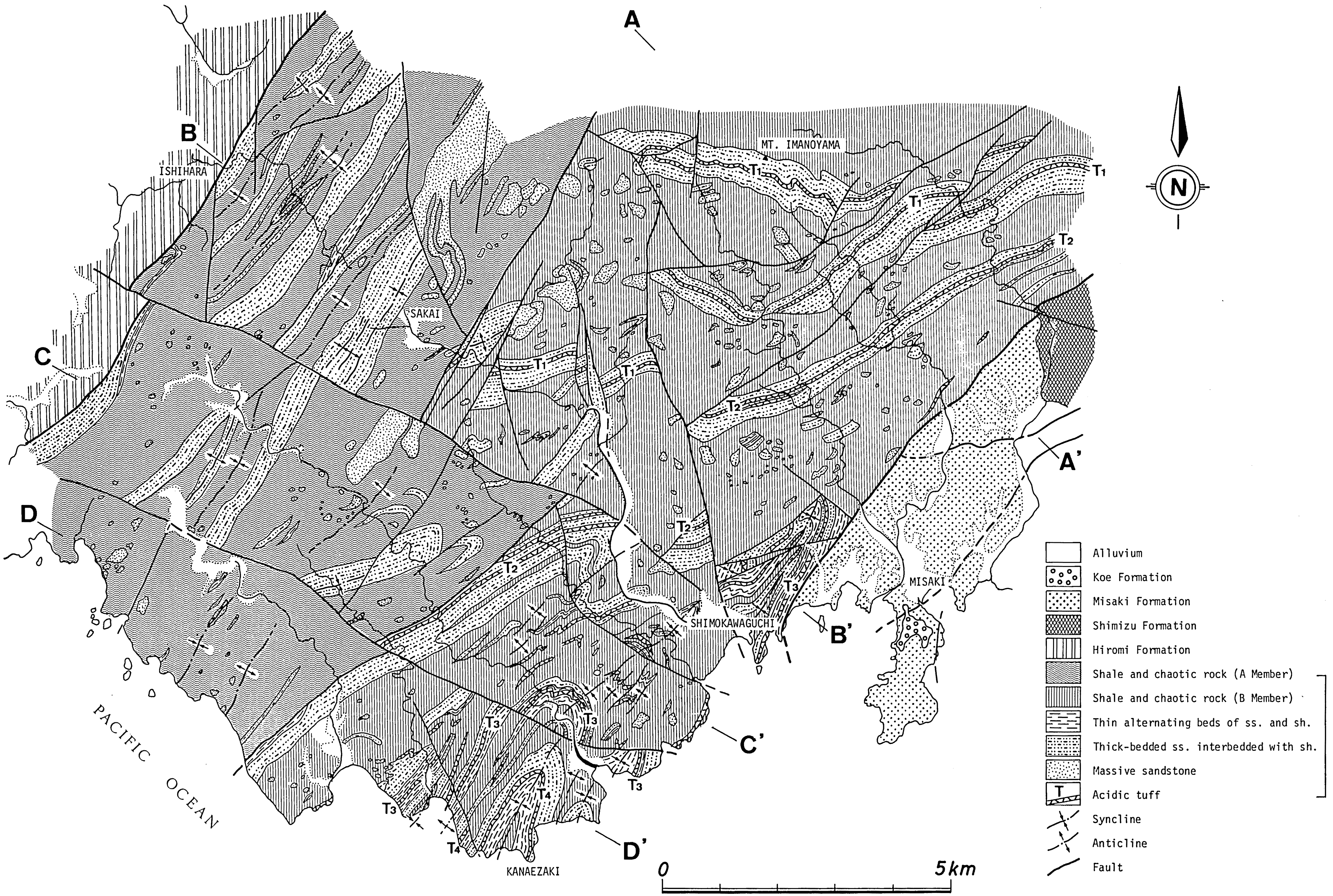


FIG. 6. Lithologic map of the Kurusuno Formation.

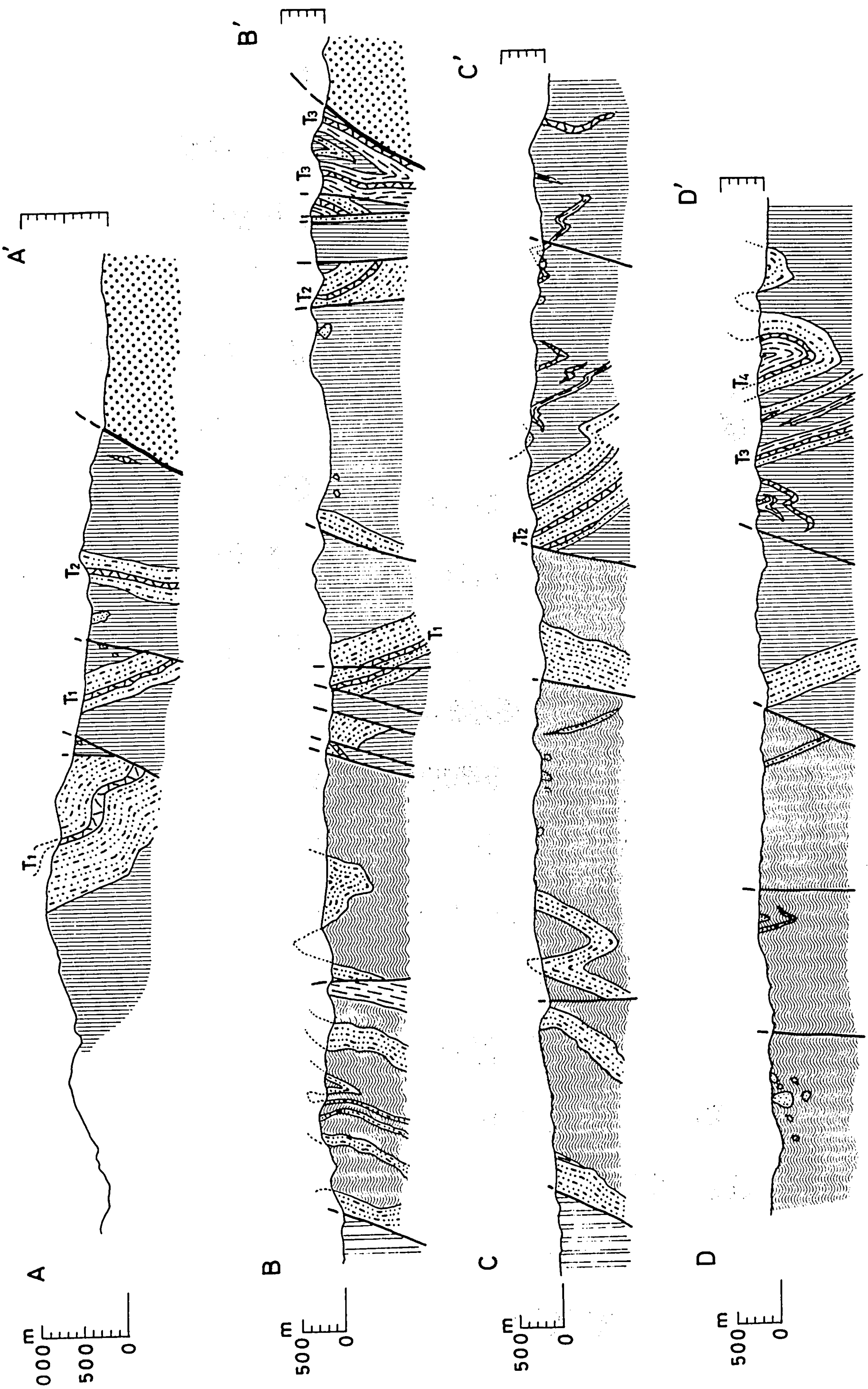


FIG. 7. Geological profiles of the Kurusuno Formation. See FIG. 6 for legend and location of the profiles.

FIG. 8-A. Columnar sections of the A Member of the Kurusuno Formation.

FIG. 8-B. Columnar sections of the B Member of the Kurusuno Formation.
See the legend of FIG. 8-A.

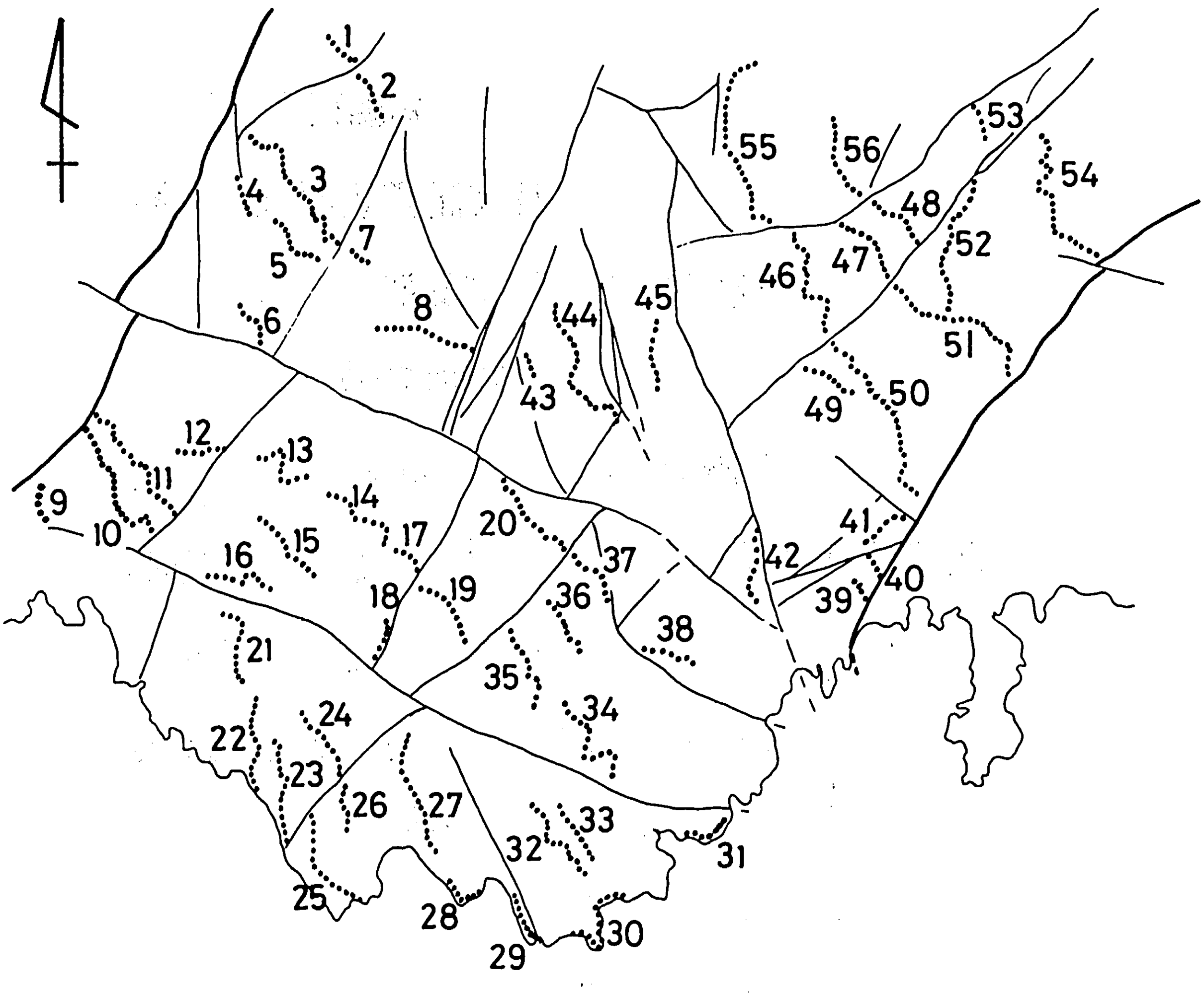


FIG. 8-C. Locality map of columnar sections of the Kurusuno Formation.

stratigraphy, because the effective key bed is lacking. In this paper, the author chose the area from Ishihara to Sakai as the standard (1 to 8 in Fig. 8-A). The alternating beds are divided into two types. One is sandstone-rich alternation, where the sandstone exceeds 1 m in thickness and the interbedded shale is very thin (several cm or less). The other is thin alternation, where the sandstone is less than 1 m (generally 5 to 30 cm) thick. The sandstone is generally fine-grained, but very rarely medium- to coarse-grained. Thicker sandstones are mainly massive or structureless, but occasionally show parallel lamination. Most of thinner sandstones have internal sedimentary structures such as parallel lamination and ripple cross lamination. Graded bedding is sometimes observed. Current marks such as flute marks and groove marks are occasionally recognizable on the basal surface of sandstone beds. Trace fossils such as *Helminthoida* also occur at places.

b. B Member

The B Member occupies the southeastern part of the distributional area of the Kurusuno Formation. It resembles the A Member in lithology, but is characterized by the intercalation of acidic tuff at several horizons. Furthermore, a few exotic blocks of andesitic tuff breccia and limestone are included. The estimated thickness is 3,500 to 4,000 m.

Alternating beds of acidic tuff and shale, 20 to 50 m in thickness, are useful as well-defined key bed. The main key beds are tentatively termed T1-T4 in ascending order (Figs. 6, 7 and 8). The acidic tuff itself is 1 to 30 cm in individual thickness, and is grayish white to greenish gray in color and hard.

Current marks such as flute marks and groove marks are observed on the sharp basal surface of sandstone beds. Ripple marks are uncommon. Internally, thicker sandstones are usually massive or show parallel lamination, while thinner sandstones exhibit grading, parallel lamination, convolute lamination and ripple cross lamination. The shale is generally black, but occasionally gray.

Small-scale folds and boudinages are often recognizable in the southern coastal area. The folds are tight and have a uniform axis-trend. They are distinguished from slump folds from their features. The axis trends in a direction of NE-SW and plunges to the southwest or partially to the northeast at an angle of 50-60 degrees (Fig. 9). Their trend agrees in general with that of larger-scale folds. Some boudinages or pinch and swell structures are present on the limbs of folds. The plunge of their neck-line ranges from 0 to 30 (mostly less than 10) degrees (Fig. 10).

B. Shimizu Formation

The Shimizu Formation is distributed in the southeastern part of the surveyed area (Fig. 2). It is in fault contact with the Kurusuno Formation on the northwest, and with the Miocene Misaki Formation on the southwest. The original unconformable relationship between the Shimizu and Misaki Formations is, however, locally preserved (Fig. 11). In Cape Ashizuri, the formation is intruded by the Tertiary igneous rocks; a contact aureole of 100 to 300m in width is formed.

The Shimizu Formation is characterized by the dominance of chaotic rocks with subordinate amount of coherent rocks. There is a little difference in lithofacies among the north, central and south districts (Kimura, 1985), and the beds seem to dip generally toward the northwest, but it is difficult to establish the detailed stratigraphy throughout the formation owing to the complicated geologic structure.

The chaotic rocks contain lots of angular to subrounded blocks and clasts of sandstone and mudstone in scaly and cloven muddy matrix. Blocks and clasts of conglomerate, andesitic pyroclastic rocks, andesite, acidic tuff, tuffaceous shale and calcareous mudstone are also locally included. The size of blocks and clasts ranges from a few millimeters to more than several hundred meters. The lithology of main blocks has already been described by the author (Kimura, 1985). Andesitic pyroclastic rocks are composed of tuff breccia, lapilli tuff and tuff, containing abundant andesite fragments and minor basalt fragments. These fragments often exhibit a sign of rapid cooling and are sometimes vesicular. Acidic tuff is thinly alternated with black shale, and is similar in lithology to that of the Kurusuno Formation.

The coherent beds are stratigraphically continuous beds with little structural disruption. They are composed of conglomerate, sandstone and mudstone (Fig. 12). Pebbly mudstone or angular clast-bearing mudstone is also intercalated. The characteristics of these rocks will be described later in detail. The coherent beds are well exposed in the central district, having a mappable extent of more than several hundred meters. Beds generally strike in a direction of NE-SW, and dip to the northwest. From the mode of occurrence, the coherent beds themselves are regarded as huge blocks due to resedimentation, like the smaller blocks and clasts in the chaotic beds (Kimura, 1985). Therefore, the Shimizu Formation would be regarded as olistostrome. There are many folds and faults in the Shimizu Formation. Most of the folds are considered to be resulted from slump, although some are of tectonic origin.

Numerous plant remains have been reported by Matsuo (1980). Moreover, the author obtained some foraminiferal and molluscan fossils from a few localities (Kimura, 1985).

C. Misaki Formation

The Misaki Formation is typically exposed along the southern coast from Yoro to Tsumajiro, Tosashimizu City. It is bounded on the west by the Kurusuno Formation with the Misaki Fault of NE-SW trend. It is also in fault contact with the Shimizu Formation on the east, though the latter is locally unconformably overlain by the former (Kimura, 1985). The geological map and columnar sections are shown in Figs. 11 and 13 respectively.

The formation is composed of alternating beds

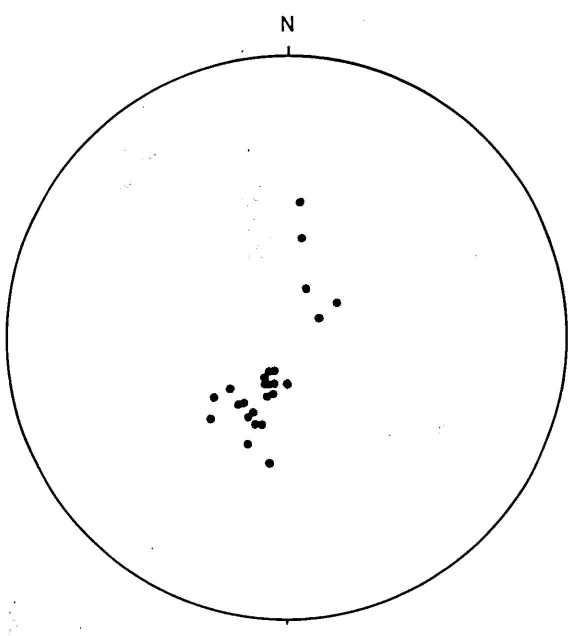


Fig. 9. Stereographic projection (equal angle) of plunges of hinge lines of minor folds on the lower hemisphere. B Member of the Kurusuno Formation.

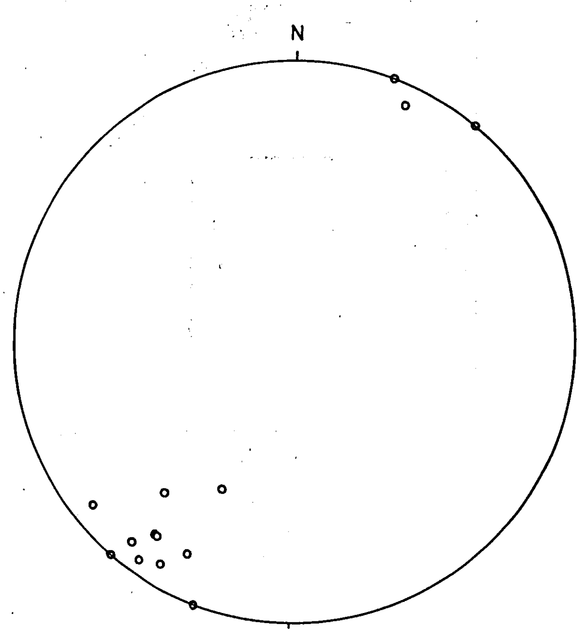


Fig. 10. Stereographic projection (equal angle) of plunges of neck-lines of boudinages on the lower hemisphere. B Member of the Kurusuno Formation.

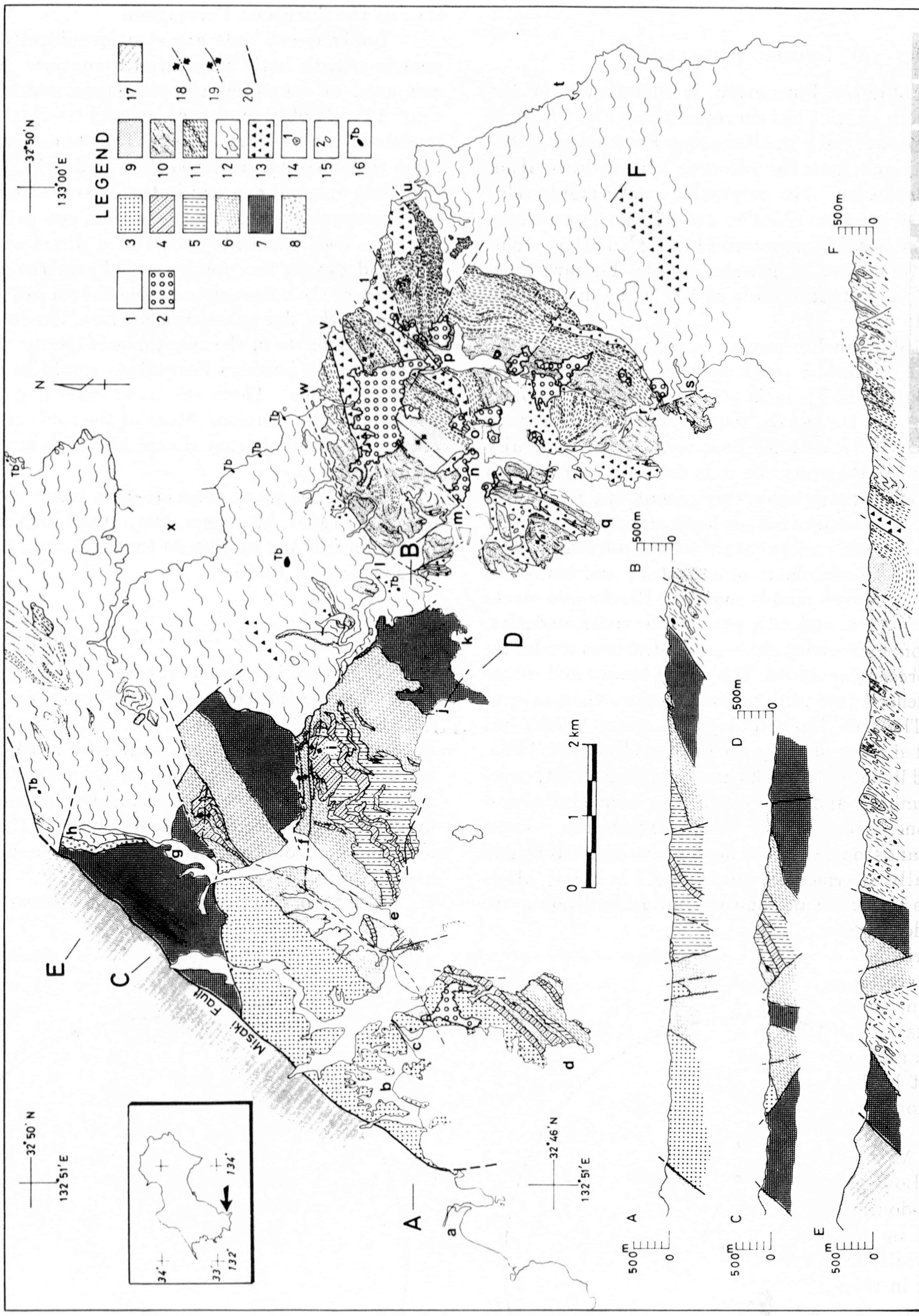


FIG. 11. Lithologic map and geological profiles of the Shimizu and Misaki Formations (after KIMURA, 1985).
1: Alluvium, 2: Koe Formation and terrace deposits, 3-8: Misaki Formation (3: Thick-bedded sandstone — Upper Member, 4: Sandstone-dominated alternation, 5: Alternation of equal sand mud ratio, 6: Mudstone-dominated alternation — Middle Member, 7: Mudstone interbedded with thin sandstone, 8: Conglomerate & sandstone — Lower Member), 9-16: Shimizu Formation (9: Sandstone, 10: Mudstone interbedded with thin sandstone, 11: Alternation of conglomerate, sandstone & mudstone, 12: Chaotic rocks, 13: Pebbly mudstone, 14: Acidic tuff, 15: Andesite, 16: Andesitic pyroclastic rocks), 17: Kurusuno Formasion 18: Syncline, 19: Anticline, 20: Fault. a: Shimokawaguchi, b: Tsumajiro, c: Tatsukushi, d: Chihiro-misaki, e: Hamamashino, f: Nakamashino, g: Ueno, h: Takahata, i: Kurinomori, j: Matsuzaki, k: Yoro, l: Kakumi, m: Shiomi-cho, n: Tenjin-cho, o: Asahimachi, p: Urashiri, g: Ourazaki, r: Nakahama, s: Ohama, t: Tsuro, u: Kubotsu, v: Iyodaba, w: Iburi, x: Oki.

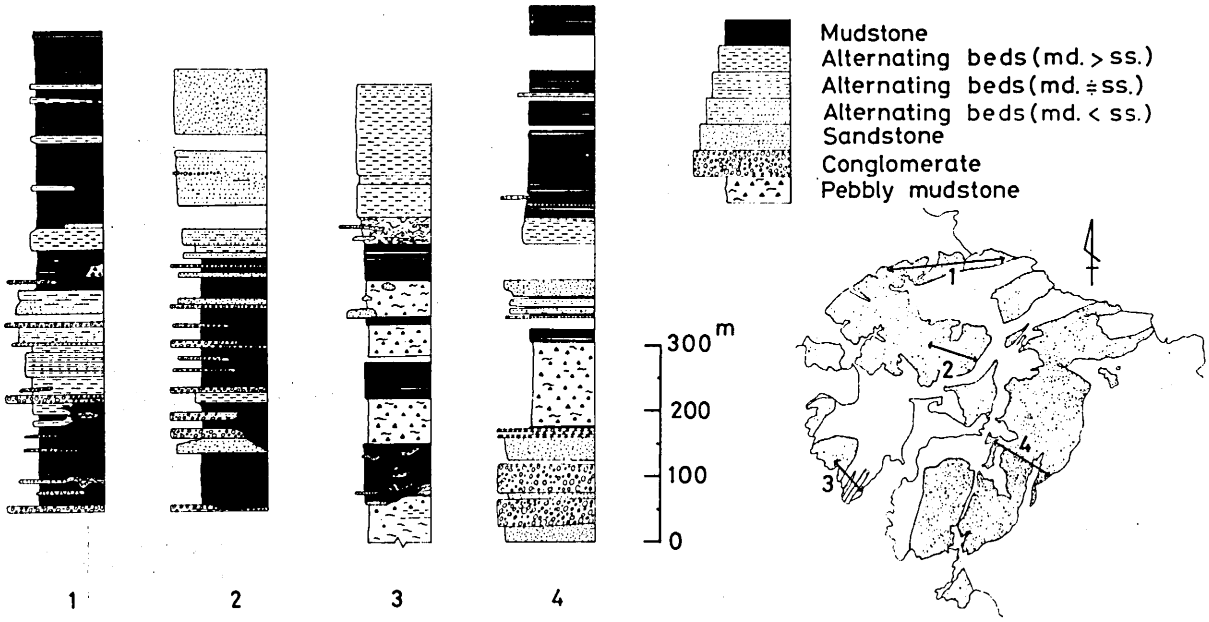


FIG. 12. Columnar sections of the coherent rocks in the Shimizu Formation (after KIMURA, 1985).

of sandstone and mudstone with various sand/mud ratios, representing a coarsening- and thickening-upward sequence as a whole. The total thickness is about 3,000m. The beds generally strike in a direction of NE-SW and dip to the northwest. The formation is subdivided lithologically into the Lower, Middle and Upper Members. The Lower Member consists mainly of mudstone, with intercalated thin layers of siltstone and/or sandstone. The Middle Member consists of rhythmically alternating beds of sandstone and mudstone. The Upper Member is dominantly composed of thick-bedded sandstone, intercalating conglomerate at higher horizons. A number of sedimentary structures such as parallel lamination, various kinds of cross lamination, convolute lamination, ripple marks and sole marks (e.g. flute marks) are observed. Slump structures and small channel structures are also recognized at horizons. Trace fossils and bioturbation are common. Graded bedding is poorly developed.

1. Lower Member

The Lower Member is composed of mudstone and mudstone-dominated alternation, and ranges from 600 to 1,000m in thickness. The mudstone frequently intercalates silty laminae and or sandy layers (less than several cm in thickness). Weathered mudstone shows an onion structure. The sandstone in alternating beds is very fine- to fine-grained and is mostly several to 20cm (sometimes up to 50cm) in thickness, while the mudstone is 10cm to 2 m. The sand/mud ratio becomes larger toward the upper. Internally, the sandstone shows parallel lamination and cross lamination (small ripple lamination and wave ripple lamination). Ripple marks are occasionally present on the upper surface of sandstone beds. Slump beds (1 to several m in thickness) are intercalated at a few horizons. Trace fossils are rare. In the northern area, the sandstone and muddy sandstone associated with pebble- to granule-conglomerate of 50cm thick are developed above the unconformity. This characteristic basal unit is absent in the southern coastal area.

This member yields molluscan and foraminiferal fossils listed in Table 2.

2. Middle Member

The Middle Member is composed of rhythmically alternating beds of sandstone and mudstone with various sand/mud ratios. It ranges from 1,000 to 1,200m in thickness. The lateral change in thickness and lithofacies is fairly remarkable. Sedimentary structures vary also in different localities.

The sandstone in alternating beds is fine-grained and is 10 to 50cm in thickness, often attaining 0.5 to 2m in sandstone-dominated alternation. The mudstone is several to 50cm in individual thickness, with frequent intercalation of silty laminae. Fragments of plant remains are occasionally contained in mudstone. Ripple marks and flute marks are better developed in this member than in others. Internally, the sandstone often shows parallel lamination and ripple cross lamination, and sometimes convolute lamination. Various species of biological hieroglyph such as dwellings and tracks (e.g. *Nankaites kochiensis* Katto, *Thalassinoides* sp.) occur throughout the member. A bioturbation is also developed.

3. Upper Member

The Upper Member, about 1,200m thick, consists mainly of thick-bedded sandstone, intercalating layers of mudstone and mudstone-dominated alternation of several meters thick. The sandstone is fine- to coarse-grained and is stratified at intervals of 0.5 to several meters. The dominant internal sedimentary structures are low-angle cross lamination, hummocky cross stratification (HARMS et al., 1975) and convolute lamination. In some cases, climbing ripple lamination and water-escape structure are observed. Small erosional structures and multiple grading units without muddy partings are present in some thick-bedded sandstones. Larger sand-pipes (e.g. *Ophiomorpha* sp.) and concretions of hard sandstone (a few to 30cm in diameter) also occur. The sandstone in upper part of

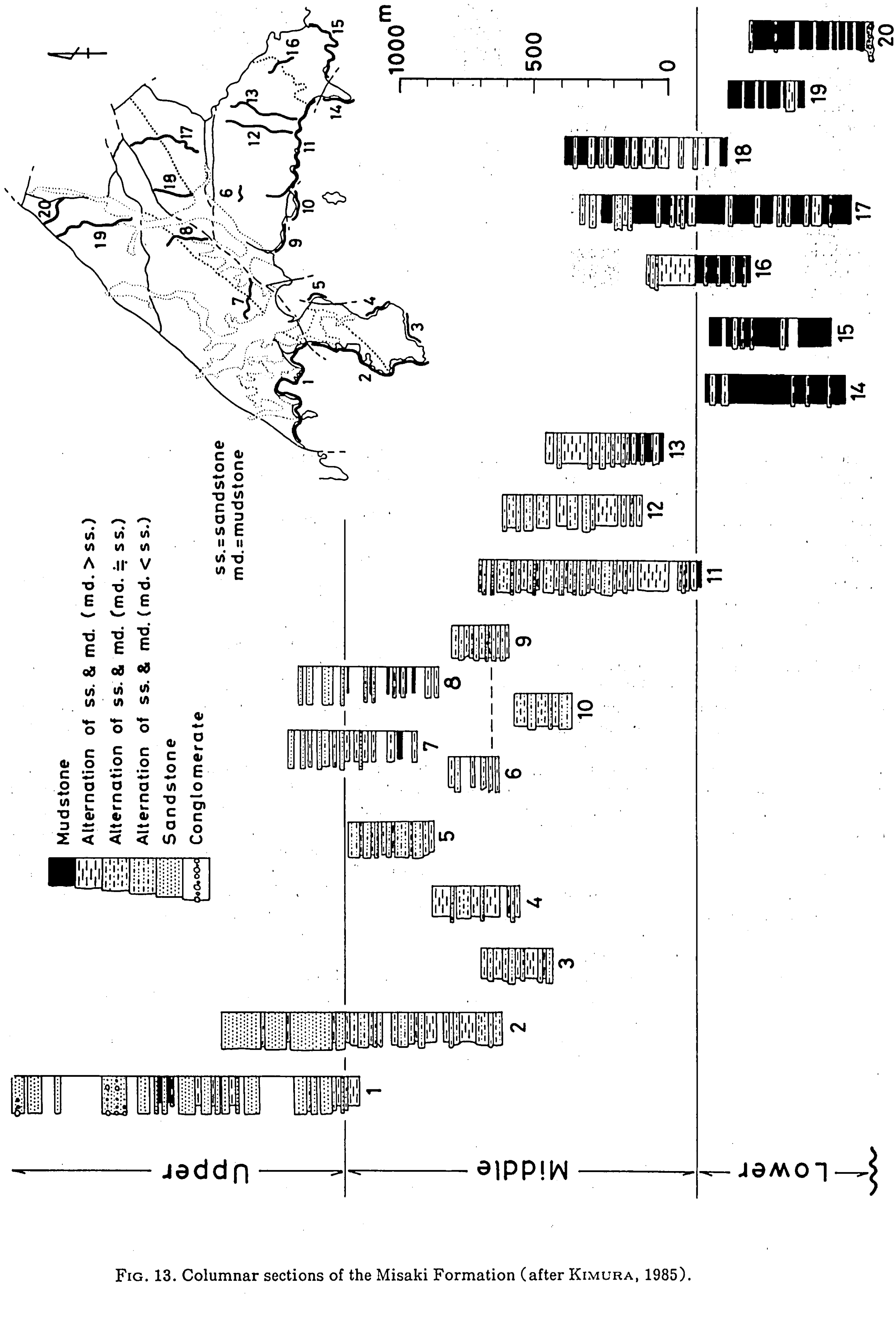


FIG. 13. Columnar sections of the Misaki Formation (after KIMURA, 1985).

this member often includes granules and/or pebbles, which are arranged in a lamina or concentrated like a lens. In mudstone-dominated alternation and mudstone, parallel lamination, cross lamination and ripple marks are recognized. Some species of molluscs have been reported by KATTO and TAIRA (1979). In addition, plant remains and thin lenses or streaks of coal are included in the sandstone.

IV. Geological Age and Correlation

The correlation of the Tertiary strata in the Shimanto Terrain in Kyushu, Shikoku and the Kii Peninsula is shown in Table 1. For this correlation, not only the fossil evidence but also the lithologic features are taken into consideration. Some remarks are given below.

1. Hata Group

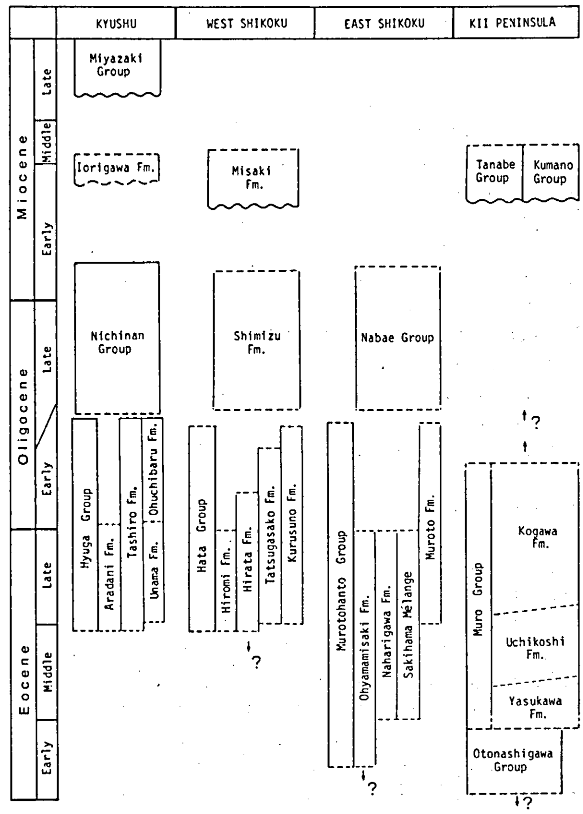
Although some previous workers reported a small amount of molluscs, radiolarians, foraminifers etc. from the Hata Group, the author has not yet obtained available fossils. Accordingly, the correlation between this group and other formations of the Shimanto Supergroup depends mainly upon the lithologic data.

As mentioned in the preceding chapter, the Hiromi Formation is characterized by pervasively sheared shale, accompanied with greenstone. It contains also a small amount of red and green shale possibly of pelagic origin. On the other hand, the Tatsugasako and Kurusuno Formations are represented by turbidite sequences and slump deposits. The former includes coarser clastic rocks such as pebbly to coarse-grained sandstone, while the latter is characterized by fine-grained, well-sorted sandstone with intercalation of acidic tuff. Both formations yield trace fossils such as *Nereites* and *Helminthoida* suggesting deep-water condition.

The greenstone-bearing Paleogene strata have been known to occur in the Aradani Formation of the Hyuga Group in Kyushu (TSUCHIYA et al., 1979) and the Sakihama Melange of the Murotohanto Group in eastern Shikoku (TAIRA et al., 1980). TANAKA (1980) reported the occurrence of *Dictyoprora mongolfieri* (Ehrenberg) and other Paleogene radiolarians and foraminifers from the Hiromi Formation. Some of them were also obtained from the Hyuga Group (SAKAI et al., 1984) and the Murotohanto Group (TAIRA et al., 1980). *D.mongolfieri* (Ehrenberg) indicates Middle to Late Eocene age. Coarse facies with conglomerate and pebbly sandstone are developed in the Oyamamisaki Formation of the Murotohanto Group, and the Otonashigawa and Muro Groups in the Kii Peninsula. The Kurusuno Formation, characterized by fine-grained turbidite sandstone and acidic tuff, strongly resembles in lithology the Naharigawa Formation of the Murotohanto Group. The occurrence of acidic tuff was also described in the Ohuchibaru Formation of the Hyuga Group by SAKAI and KANMERA (1981).

The Tatsugasako and Kurusuno Formations yield molluscan fossils such as *Portlandia watasei* (Kanehara) and *Lucinoma* cf. *hannibali* Clark (KATTO, 1961). Furthermore, KATTO et al. (1979) reported the occurrence of larger foraminifers such as *Asterocyclina* cf. *stella* (Gumbel) from the Kurusuno Formation. This species suggests Middle Eocene (Lutetian) age (MATSUMARU, 1980). The Asterocyclina-fauna was obtained from blocks of limestone in chaotic rocks. Therefore, the Kurusuno Formation is considered to have been formed in Middle Eocene or a little younger age.

Table 1. Correlation of the Tertiary strata of the Shimanto Belt in Kyushu, Shikoku and the Kii Peninsula.



Judging from the fossil evidence mentioned above, though insufficient, the geological age of the Hata Group is safely assigned to Middle Eocene to Oligocene (presumably Early Oligocene). Besides, shallow marine deposits (Hirata Formation) belonging to this group are distributed to the north of the mapped area. Therefore, the Hata Group is composed of formations of the nearly same age in different environments. It can be classified into three facies: chaotic facies, turbidite facies and shallow marine facies. In short, it is considered that the Hata Group corresponds roughly to the Hyuga, Murotohanto, Otonashigawa and Muro Groups (Table 1).

2. Shimizu Formation

The Shimizu Formation yields several foraminiferal and molluscan fossils at a few localities (KIMURA, 1985) (Table 2 and Fig. 14). All of them were obtained from the muddy matrix of chaotically mixed rocks. Besides, plant remains are contained in silty sandstone (MATSUO, 1980).

Judging from the planktonic foraminifers, the main part of the Shimizu Formation is considered to be Oligocene to early Early Miocene in age, although occurrence of them is dispersive and the precise stratigraphic horizon remains settled. *Asterocyclina* sp., a genus indicating Middle Eocene, was found at one locality (s-3 in Fig. 14), but it is regarded as resedimented fossils, judging from its mode of occurrence (KIMURA , 1985). As for molluscs, *Chlamys, Callista, Clementia, Acila* and oysters occur in Ueno, Tosashimizu City (s-4 in Fig. 14).

The planktonic foraminifers similar to those from the Shimizu Formation were reported from the Nichinan Group in Kyushu (NISHI, 1985). The Nichinan Group is represented by a large-scale gravity-slide complex or olistostrome (KANMERA et al., 1983; NAKAGAWA et al., 1983; etc.). Further, the radiolarian and foraminiferal faunas suggesting Oligocene-Early Miocene age were reported from the Nabae Group in eastern Shikoku (ISHIKAWA , 1982; SAITO, 1980). This group also appears to be olistostrome (SAKAI, 1981).

In short, the Shimizu Formation may safely be correlated with the Nichinan and Nabae Groups.

3. Misaki Formation

KATTO (1961) reported the occurrence of some molluscan fossils from the Misaki Formation. Recently, several planktonic and larger foraminifers have been found in the Lower Member of the formation (KIMURA , 1985) (Table 2 and Fig. 14). The rocks containing foraminifers are mudstone, siltstone and silty sandstone. The lowest fossil horizon of the Misaki Formation is correlated to Zone N.7 of BLOW (1969) by the occurrence of *Globigerinoides altiapertura* Bolli, *Globorotalia zealandica* Hornibrook and *Praeorbulina sicana* (de Stefani), being assigned to the upper Lower Miocene (Burdigalin). The precise age of the upper limit of the formation cannot be

TABLE 2. LIST OF FORAMINIFERAL FOSSILS FROM THE SHIMIZU AND MISAKI FORMATIONS.

specific name \ locality number	Shimizu Fm.				Misaki Fm.				
	s-2	s-3	s-4	s-5	m-3	m-5	m-7	m-8	m-9
Globigerina ampliapertura Bolli			x						
G. anguliofficinalis Blow			x						
Globorotalia opima opima Bolli				x					
Catapsydrax stainforthi Bolli, Loeblich & Tappan								x	
Globigerinoides altiapertura Bolli							x		
G. immaturus LeRoy	x				x			x	
G. subquadratus Brönnimann							x		x
Globorotalia zealandica Hornibrook						x			
Globorotaloides suteri Bolli								x	
Praeorbulina sicana (de Stefani)									x
Asterocyclina sp.		x							
Lepidocyclina (Nephrolepidina) sumatrensis (Brady)					x				

determined, but the sedimentation of the Misaki Formation is considered to have finished before the intrusion of granitic rocks (13±2 Ma) in Cape Ashizuri. Therefore, the formation does not range up in age to Late Miocene. Thus, the Misaki Formation may correspond to the Tanabe and Kumano Groups in the Kii Peninsula and the Saigo and Kurami Groups in Shizuoka Prefecture. All of them overlie the Shimanto Supergroup with a remarkable clinounconformity.

V. SEDIMENTOLOGICAL ANALYSES

In this chapter, the sedimentological study is focused to three points: sedimentary facies, properties of sandstone and paleocurrent. Such analyses may be very effective for elucidating the sedimentary envi-

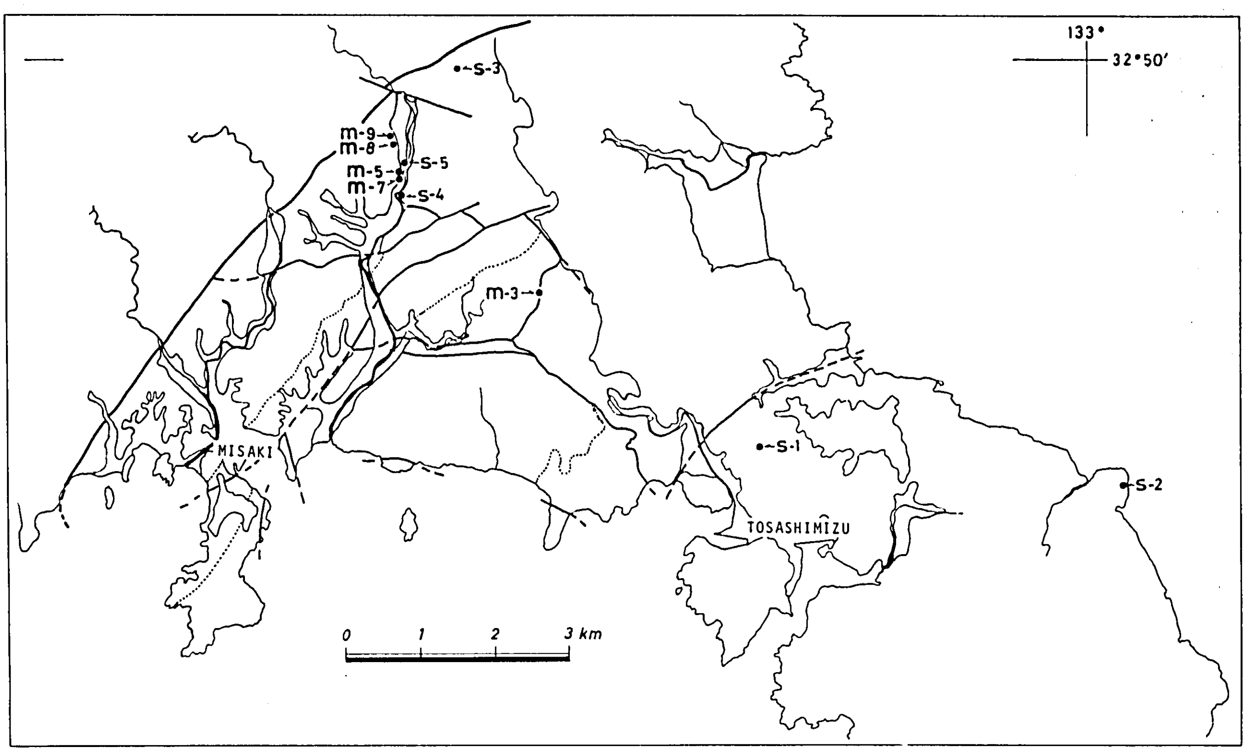


Fig. 14. Fossil-localities in the Shimizu and Misaki Formations.

ronment and process.

A. SEDIMENTARY FACIES

1. Hata Group

The Hata Group has some lithologic features comparable with turbidites and associated coarse clastic deposits of WALKER (1979). Since MUTTI and RICCI-RUCCHI (1972), there have been many studies reconstructing the sedimentary environment of those clastic deposits by means of sedimentary facies and facies association. The author also attempts to classify the Hata Group into several main sedimentary facies.

The following five facies are recognized in the Tatsugasako and Kurusuno Formations of the Hata Group. The Hiromi Formation is excluded from this study, because it is deficient in coherent rocks.

A) Pebbly sandstone facies
B) Thick-bedded sandstone facies
C) Thin alternation facies
D) Shale facies
E) Acidic tuff facies

The examples of columnar sections are shown in Fig. 15 to 18. The general characteristics of the facies are summarized in Fig. 41

a. Tatsugasako Formation

Four facies from A to D are developed in the Tatsugasako Formation.

Facies A

This facies is characterized by coarse- to medium-grained sandstone and pebbly sandstone. It is subdivided into two types, A1 and A2, based on the characteristic features of the pebbly sandstone.

A1: The pebbly sandstone of this subfacies contains well-rounded, fine pebble-to granule-sized clasts, which are dispersed in sandy matrix. It is thickly bedded. Each bed ranges from 0.5 to 5 m in thickness, and is characterized by sharp and scoured base (Fig. 15). The basal surface is sometimes ornamented with flute marks. The top of the sandstone bed is either sharp or gradual into the overlying silt or shale. Internally, the graded bedding is commonly well developed, the basal pebbly sandstone (including clasts up to 1 cm) passing upward into medium- to fine-grained sandstone (Fig. 15). The most characteristic internal sedimentary structure is parallel lamination. The middle to upper part of the bed often exhibits such water-escape structures as pillar and dish structures. Cross lamination or convolute lamination is occasionally recognized near the top.

A2: The pebbly sandstone of this subfacies contains abundantly angular to subangular, pebble-sized (rarely cobble-sized) clasts of shale. It is stratified and interbedded with shale. The stratification is often represented by alternation of pebble-rich and pebble-poor layers (Plate I-1). Each layer ranges from several to 30 cm in thickness. Sand-sized grains are dispersed in the interbedded shale.

Facies B

This facies consists of thick-bedded, fine- to medium-grained (rarely coarse-grained), well-sorted sandstone. Each bed, being composite, ranges from 1 to 10 m in thickness, and is separated from the next by thin shale parting (up to 5 cm thick) (Fig. 16). Commonly, the base and top are flat, but current marks and feeding trails are occasionally recognized on the basal surface. Internally, the sandstone is almost ungraded and includes two types: one is massive sandstone sometimes with crude lamination, and the other is parallel-laminated sandstone containing frequently angular fragments of shale less than 5 cm in diameter.

Facies C

This facies is composed of thinly alternating beds of fine- to medium-grained sandstone and shale, showing a flysch-like appearance (Fig. 16). The sand/shale ratio varies from about 10:1 to 1:10. Each of the sandstone beds is several cm to 1 m in thickness, and is uniform laterally. The basal surface is generally sharp, and has often current marks such as flute marks and tool marks (e.g. grooves). In view of internal sedimentary structure, the sandstone can be divided into two types. One is characterized by parallel lamination. If the bed can be split along lamination, parting lineation is occasionally observed. Parallel lamination often grades upward into convolute lamination or ripple cross lamination. In terms of BOUMA sequence (BOUMA, 1962), the basal division Ta is missing (base-cut-out sequence). The other is nearly massive throughout the thickness, and rarely shows parallel lamination in the upper part. Namely, it corresponds to the truncated sequence of BOUMA. The latter type is well developed in the Tsuganokawa Member, where the Facies C is poorer in intercalation of shale than in the Shirahama Member. Biogenic structures such as burrows and trails are often recognizable. The most typical trace fossil is *Nereites*.

Facies D

This facies consists mainly of black shale with occasional intercalation of thin beds of fine- to medium-grained sandstone. Each of the intercalated sandstone beds is up to several cm in thickness. Flute marks occasionally occur on the basal surface of sandstone bed. Slump structures such as intrastratal folding and chaotic mixing of sediments are well developed.

b. Kurusuno Formation

Facies A is lacking and Facies B, C, D and E are developed in the Kurusuno Formation. They are similar to those of the Tatsugasako Formation, but there are some difference in lithology.

Facies B

This facies consists of thick-bedded, fine-grained sandstone, which is well-sorted and mineralogically mature but contains occasionally angular fragments of shale up to several millimeters (very rarely 5 cm) in diameter. Each bed attains 1 to 10 m or more in thickness, and is separated from the next by thin shale layer, or never interbedded with shale (Fig. 17, I & J in Fig. 18). Internally, the sandstone is largely massive or parallel-laminated, and rarely exhibits cross lamination or convolute lamination near the top of the bed. The base is sharp and either flat or irregular, often having sole structures such as flute marks and groove marks, together with trace fossils. Commonly, the top of the bed is not graded, but is in sharp contact with the overlying shale. In the B Member, this facies is often intercalated with Facies E (H in Fig. 17).

Facies C

This facies consists of thinly alternating beds of fine-grained sandstone and shale. The sand/shale ratio varies from about 3:1 to 1:10(H in Fig. 17, Fig. 18).

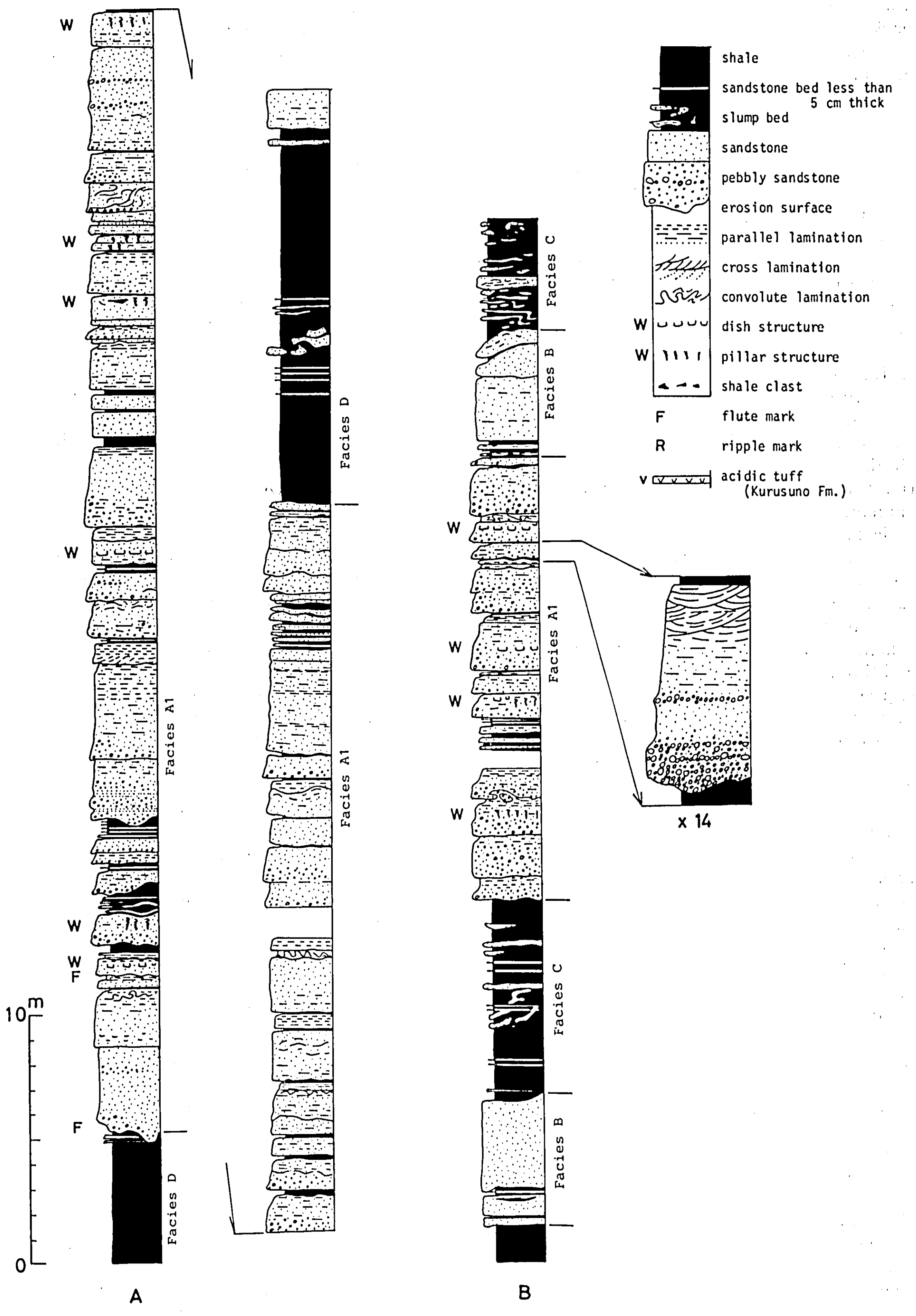


FIG. 15. Detailed columnar sections of the Shirahama Member of the Tatsugasako Formation.

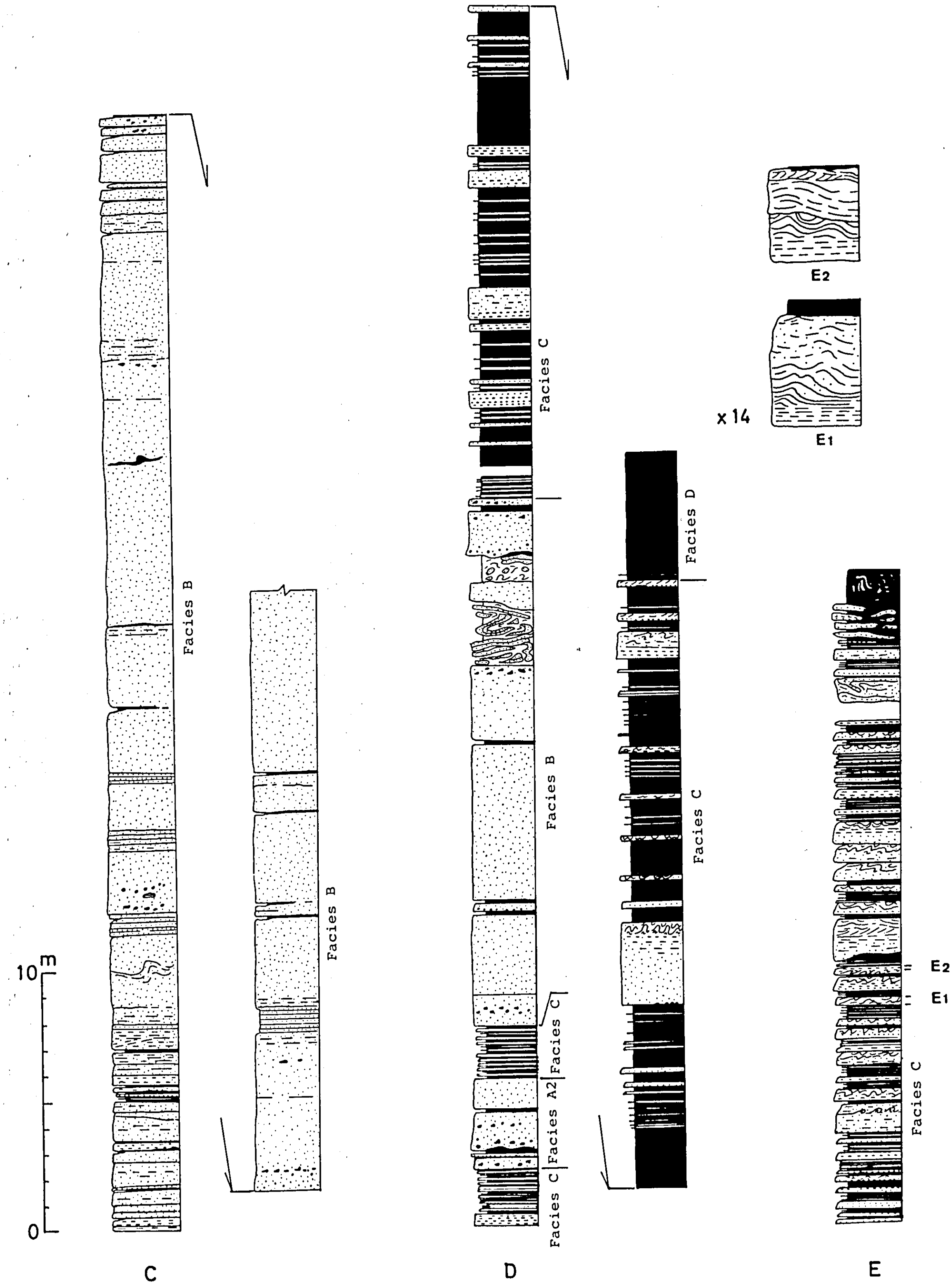


FIG. 16. Detailed columnar sections of the Tatsugasako Formation. See the legend of FIG. 15.

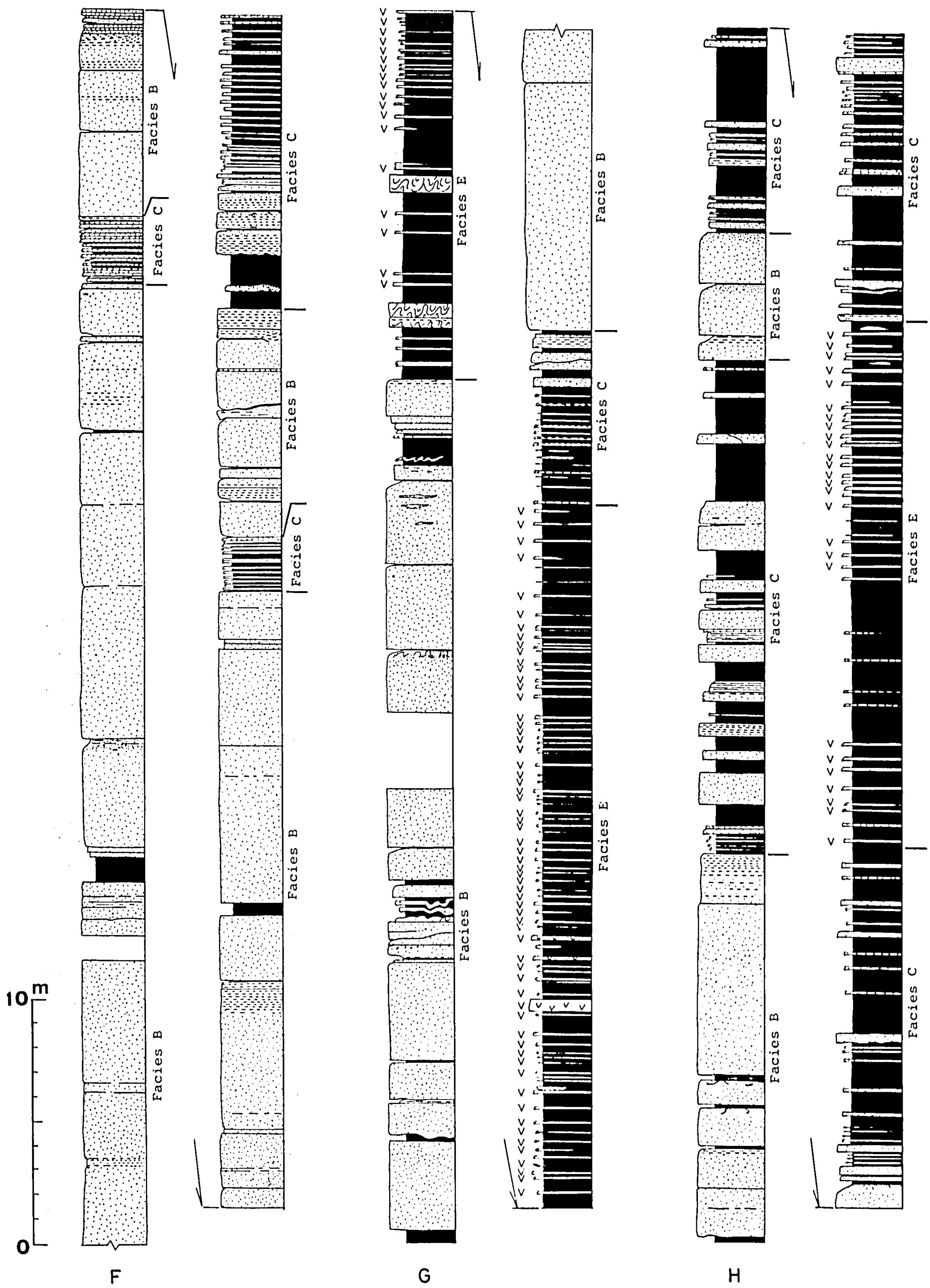


FIG. 17. Detailed columnar sections of the Kurusuno Formation. See the legend of FIG. 15.

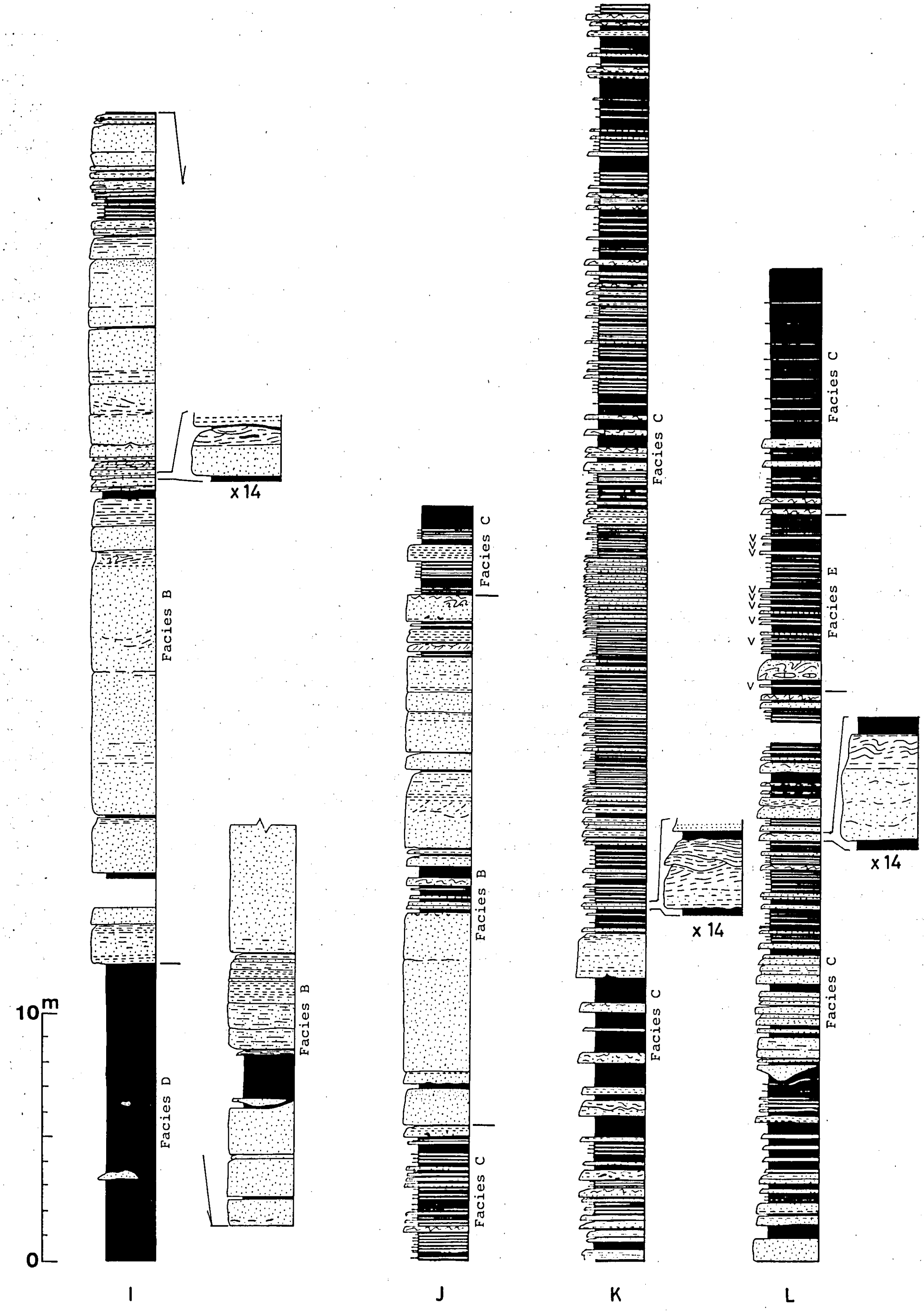


FIG. 18. Detailed columnar sections of the Kurusuno Formation.
See the legend of FIG. 15.

Each of the sandstone beds is several cm to 1 m (mostly less than 30cm) in thickness. Parallel lamination is dominant in the sandstone, with subordinate convolute and cross laminations. The base of the sandstone bed is sharp, while the top is gradual into the overlying shale. Most of the sandstone beds may belong to the base-cut-out sequence of BOUMA (1962). Current marks such as flute marks and groove marks are sometimes observed. Trace fossils including horizontal *Helminthoida* are occasionally recognized on the basal surface of sandstone.

Facies D

Facies D is composed predominantly of shale (I in Fig. 18). The shale is generally massive and unstratified, but occasionally contains thin layers of sandstone or siltstone of less than 1 cm thick. These layers are irregularly folded or interrupted. Blocks and clasts of massive sandstone are also included. The original stratification is disarranged. From these features, this facies is considered to have suffered downslope mass movement after deposition.

Facies E

Facies E is characteristic of the Kurusuno Formation, and is composed of thinly alternating beds (flysch-type alternation) of acidic tuff and shale. It ranges from 20 to 50m in total thickness. The ratio of acidic tuff to shale does not exceed 1 (G & H in Fig. 17, L in Fig. 18). The tuff itself varies in individual thickness from 1 to 30cm The base of the tuff bed is sharp, while the top is often gradual into the overlying black shale. Internally, some of the tuff beds look like massive, but parallel and convolute laminations are often recognizable. The typical exposure is shown in Plate I-6. The acidic tuff might have been deposited as a kind of turbidite, judging from its occurrence. It contains a small amounts of radiolarian fossils.

2. Shimizu Formation

In current usage, the Shimizu Formation may be regarded as olistostrome and contains huge blocks of coherent rocks of mappable extent. The coherent rocks show various lithofacies. In order to reconstruct the primary depositional environments, it is important to examine the sedimentary facies of coherent rocks in detail. The coherent rocks of the Shimizu Formation are classified into the following five facies:

I) Conglomerate facies
II) Sandstone facies
III) Thin alternation facies
IV) Mudstone facies
V) Pebbly mudstone facies

The examples of columnar sections are given in Figs. 19 and 20.

Facies I

Facies I is composed of conglomerate (Fig. 19), which contains sub-rounded to rounded, granule- to cobble-sized (mostly pebble-sized) clasts of sandstone and shale scattered usually in silty or muddy matrix (sometimes in sandy matrix) (Fig. 33). The conglomerate is thickly bedded. Each bed ranges from about 1 to 3m in thickness, attaining a maximum of 25m The lateral extent is limited to several to hundreds of meters, and the variation in thickness is frequent. Internally, the thicker conglomerates are generally massive, and poor in sedimentary structures, while the thinner ones (1m or less in thickness) bear sedimentary structures such as grading (normal and inverse), crude parallel lamination and cross lamination. The base of the bed generally shows an erosional or irregular surface, but occasionally a non-erosive planar surface (Fig. 19). Inverse grading part, developed in most cases near the base, is up to 20cm in thickness, and is composed of fine pebbles and granules. The top of the bed is either gradual into the overlying sandstone or sharp from the mudstone. Clast orientation is occasionally observed on the upper surface. This facies is generally alternated with Facies IV.

Facies II

Facies II is well exposed in Asahi-machi, Tosashimizu City. It consists mainly of fine- to coarse-grained sandstone (sometimes pebbly), with intercalated very fine-grained sandstone, siltstone and mudstone (P in Fig. 20). The sandstone is bedded, each bed being 0.5 to 4 m thick. The mudstone bed is generally thinner than the sandstone, but occasionally attains about 2 m thick. Internally, the sandstone is commonly massive or parallel-laminated, and shows grading(normal and inverse). Lamination tends to develop better in the finer-grained sandstone. Rounded pebbles, 7cm in maximum diameter, are sporadically contained. The bottom and top surfaces of the sandstone bed are sharp or gradual. The basal scouring is not remarkable. Ripple marks are occasionally recognizable on the top surface. The pelitic parts in this facies contain carbonaceous fragments and plant remains.

Facies III

Facies III is well exposed along the coast of Ourazaki (Fig. 11). It is made up of rhythmically and thinly alternating beds of fine- to very fine-grained sandstone and mudstone (Q in Fig. 20). The sand/mud ratio is less than 1:1. Each of the sandstone beds is usually 1 to 30cm thick. The dominant sedimentary structure is parallel lamination, with subordinate grading and cross lamination (mainly ripple cross lamination). Parallel lamination tends to develop better in finer-grained sandstone. In some cases, the sandstone bed is composed of a set of lower massive division and upper parallel-laminated (rarely ripple-laminated) division. This set is comparable with the Ta-b or Ta-c of BOUMA sequence. In some other cases, the bed consists only of either massive or parallel-laminated part throughout the thickness. The lower surface of the sandstone bed is generally sharp and planar, and is occasionally ornamented with flute marks. On the other hand, the upper surface is sharp or gradual into the overlying mudstone, rarely exhibiting ripple marks. Slump structures such as intraformational folds, broken sandstone layers and small-scale gravity faults are often recognizable in this facies (Q in Fig. 20). Trace fossils such as *Tosalorbis* sp. occur occasionally.

Facies IV

This facies consists of stratified mudstone with silty and sandy intercalations. The mudstone commonly contains carbonaceous fragments. The silty or sandy intercalation is generally a few to 10mm in thickness, and is often discontinuous horizontally. The mudstone intercalated with Facies I generally lacks stratification and contains some scattered, sand-sized grains.

Facies V

Facies V is represented by massive and structureless pebbly mudstone, which contains various-shaped clasts dispersed randomly in muddy matrix. The clasts are mainly angular to subangular, granule- to boulder-sized, and are composed mostly of sandstone and shale. Blocks of alternating beds of sandstone and mudstone (5m in maximum diameter) are also sometimes contained. The pebbly mudstone of Facies V can easily be distinguished from the conglomerate of Facies I by means of roundness, sorting and clast content. The pebbly mudstone is excellently exposed in the coastal area to the east of Yoro, where it ranges from 1 to 30 m or more in thickness and is alternated with Facies III and IV showing occasionally slump fold structure (Fig. 21). The lateral extent is limited to ten to hundreds of meters, and the variation in thickness is considerable.

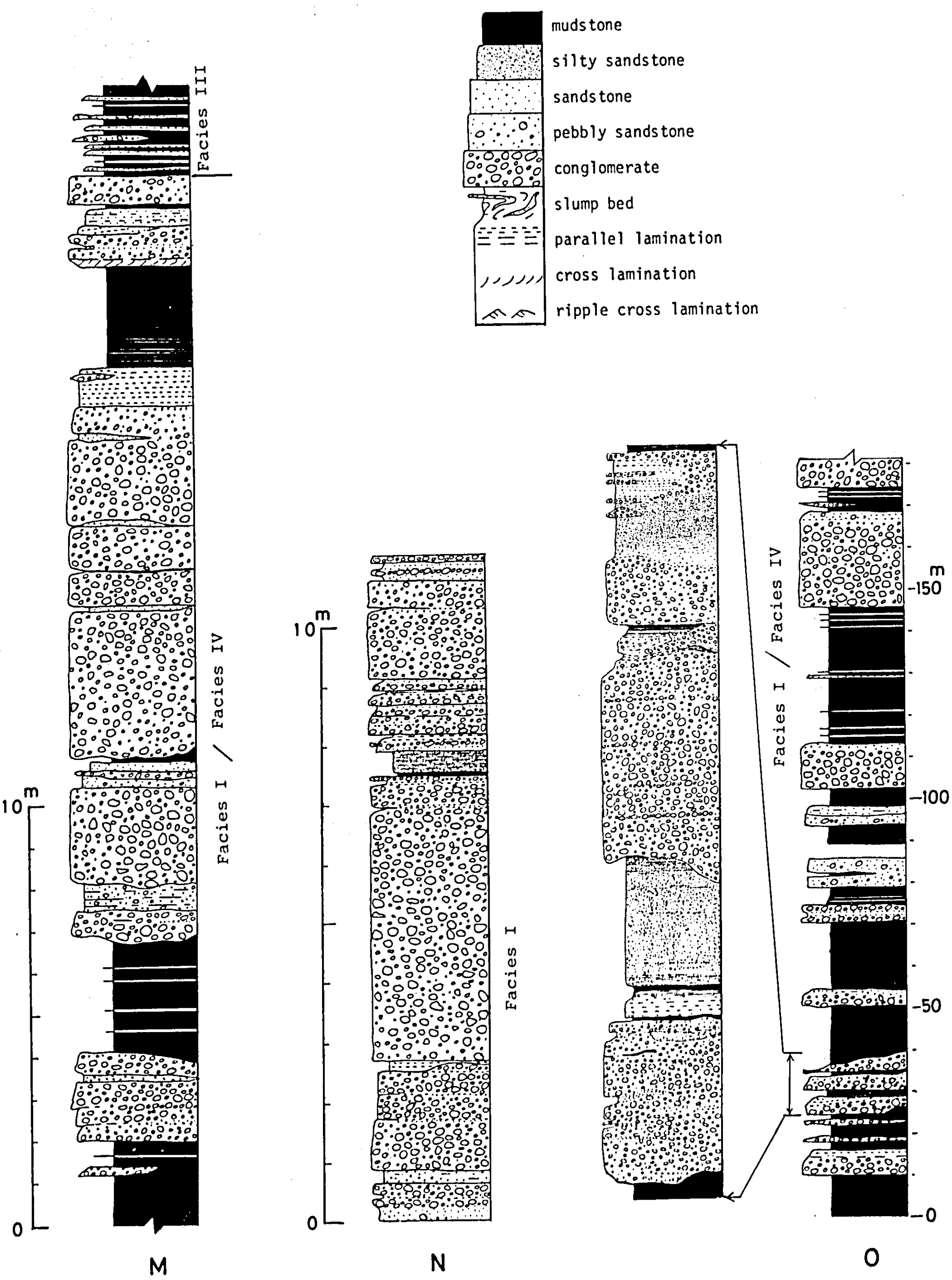


FIG. 19. Detailed columnar sections of the Shimizu Formation.

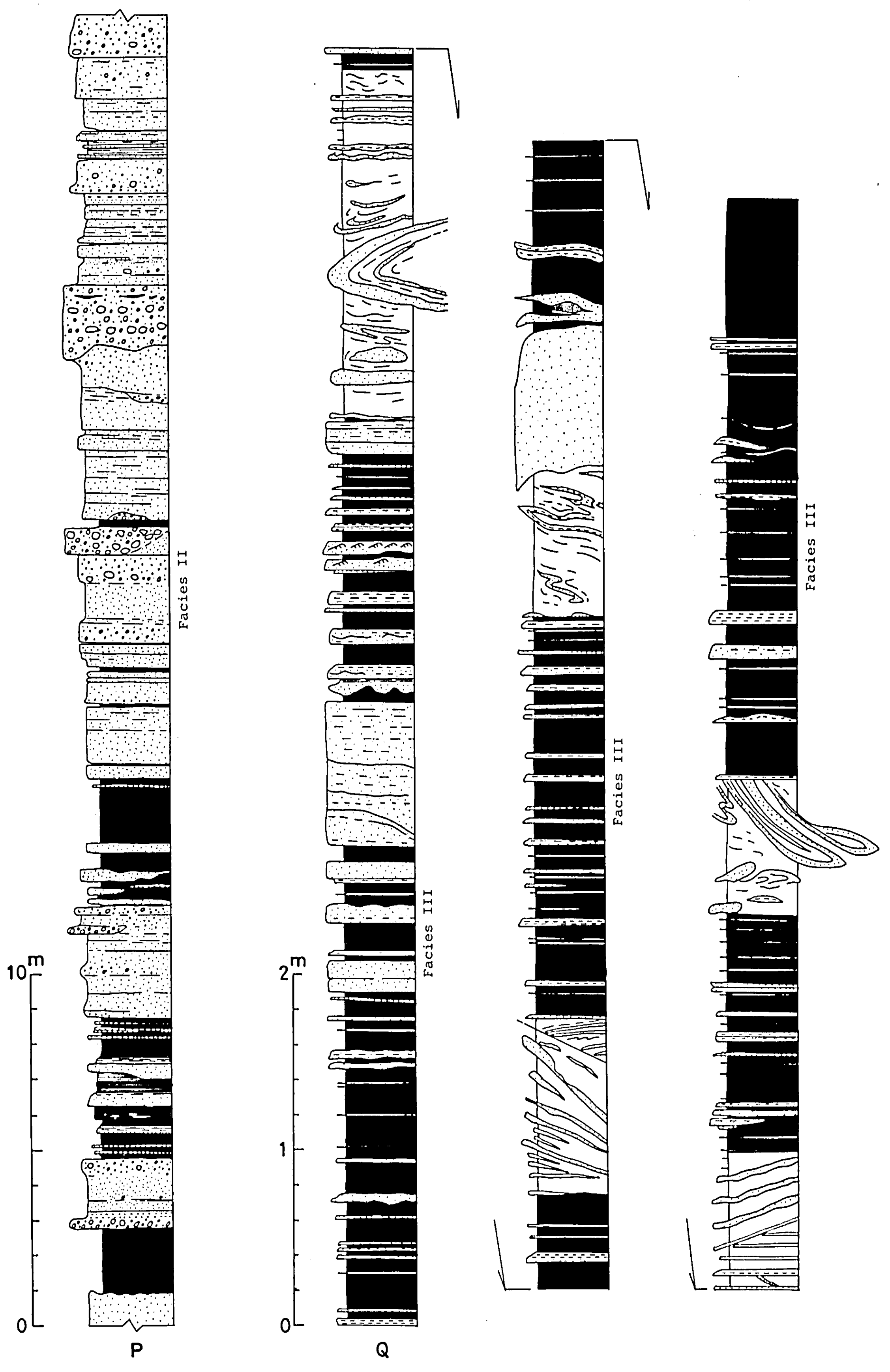


FIG. 20. Detailed columnar sections of the Shimizu Formation.
See the legend of FIG. 19.

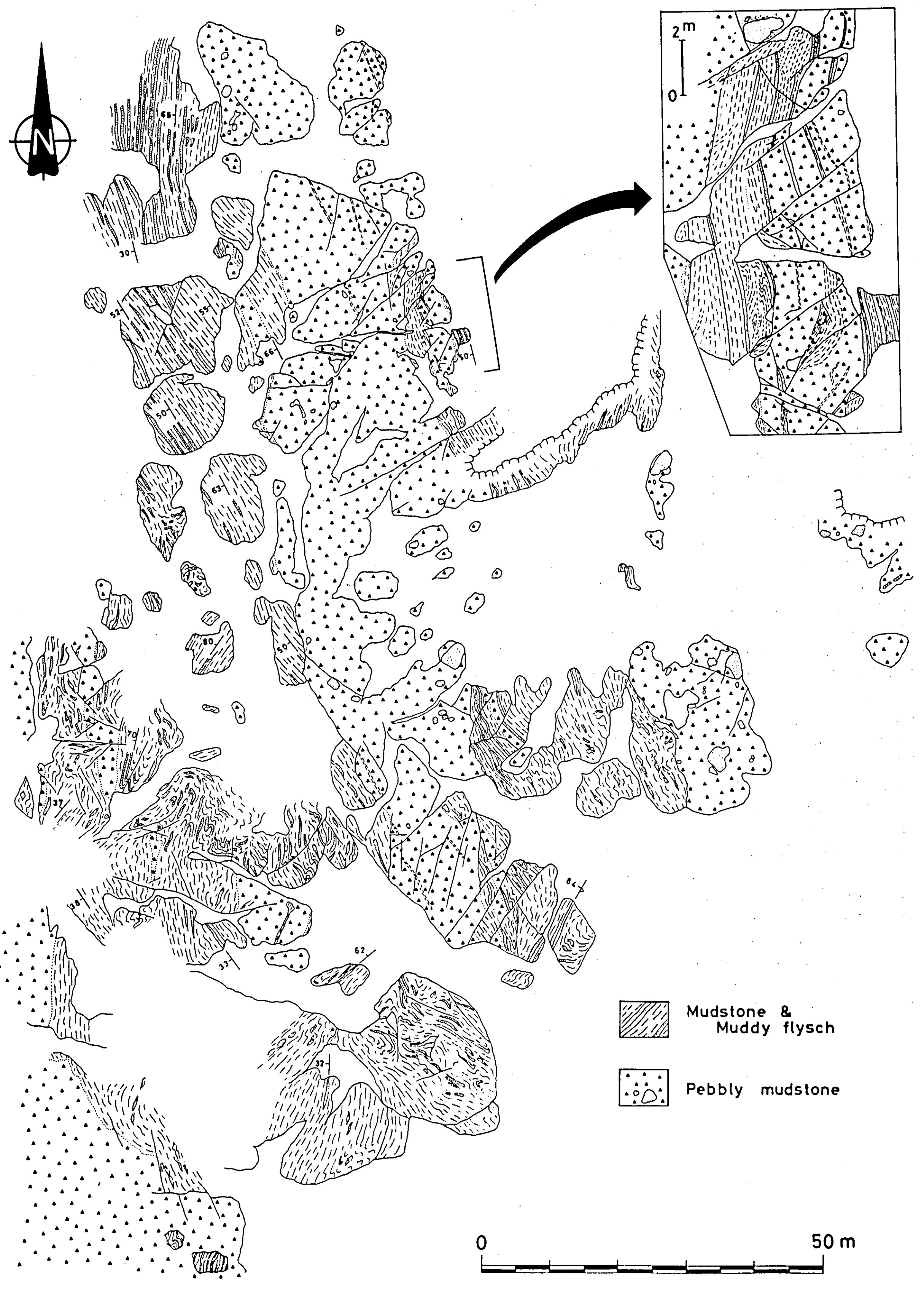


FIG. 21. Lithologic map showing the occurrence of pebbly mudstone in the Shimizu Formation at the coastal area near Yoro, Tosashimizu City.

3. Misaki Formation

As described previously, the Misaki Formation is subdivided into three members, and represents a coarsening- and thickening-upward sequence as a whole. The formation has some characteristic features of shallow marine deposits. Furthermore, more detailed observations indicate that several sedimentary facies can be discriminated in the formation. Before entering into the description of sedimentary facies, explanations of typical current marks, small channel-like structures and biogenic structures are given below.

The most prominent current structure in the Misaki Formation is a ripple mark. Sole marks, such as flute and groove marks, are also recognized at places. Ripple marks frequently occur in thinly bedded, fine-grained sandstone throughout the formation except the lowermost and uppermost parts. Ripples are mostly wave ripples and rarely linguoid-shaped current ripples. Wave ripples are symmetrically or slightly asymmetrically undulated, and are relatively straight-crested, frequently showing bifurcation. They are generally 5.5-9.5cm in wavelength, and 0.3-0.8cm in height (Fig. 22). Flute marks are occasionally observed on the lower surface of massive or stratified sandstone beds. Flutes are generally small in size, ranging from 3 to 5cm in length, and crowded, accompanying groove marks.

Channel-like structures are observed in excellent exposures in the coastal area. The representative structures are illustrated in Fig. 23. The structures generally show the following features: 1) the scouring depth is shallow (0.5-3m); 2) the outcrop trace of the basal surface is smooth, gently curved and concave upward; 3) the sedimentary fills overlying the channel base are composed of fine-grained sandstone, silty sandstone and mudstone, and they are similar in lithology to the surrounding deposits; 4) the coarse-grained channel lag deposits at the base of the sedimentary fills are absent; 5) no apparent thinning-upward sequence or fining-upward sequence is developed in the deposits overlying the channel base. Furthermore, the channel-like structures are classified into three types of Ca, Cb and Cc on the basis of the more detailed lithology of the sedimentary fills. Ca-type has a very well-defined scour surface. The sedimentary fills consist of laminated, fine-grained sandstone containing a large amount of rip-up clasts of the underlying strata near the base. Slump blocks are also occasionally included. The scour surface of Cb-type is not clear. The sedimentary fills are composed of thinly alternating beds similar to the surrounding sediments cut by channels. Cc-type has an even, long basal surface, and is filled with structureless silty sandstone including pseudo-pebbles. The lithology of the filling sediments is very similar to that of the contorted beds in the Misaki Formation.

In the Misaki Formation, any kinds of biogenic sedimentary structures are observed. Among them, four main trace fossils are described below. In addition, there are many other ichnospecies.

A-type: This type of trace fossil is a slightly flat, cylindrical full relief in cross section, 3-5mm in diameter, and 4-10cm or more in length. It is smooth-sided, longitudinally sinuous and never branches. These fossils occur in dense concentrations within the light-colored, fine-grained feldspathic sandstone, and interpenetrate one another. A-type is referred to *Nankaites kochiensis* Katto (KATTO, 1965), and extremely resembles *Macaronichnus segregatis* (CLIFTON and THOMPSON, 1978).

B-type: This type is a flat, cylindrical burrow which regularly branches, with Y-shaped bifurcation on horizontal surface. The burrow is a full relief (or convex epirelief), 15 to 35mm in diameter in vertical cross section. The surface of the burrow is smooth. This fossil occurs on the upper surface of sandstone and its downward branching is indistinct. B-type is comparable with *Thalassinoides* sp. These burrows are regarded as feeding and dwelling traces of crustaceans, which generally live in sublittoral environment (HANTZSCHEL, 1975).

C-type: This type is a three-dimensional, cylindrical burrow system which dichotomously branches. The burrow is 30 to 40mm in diameter, and its outer surface is characteristically fringed with many mammillae (1 to 5mm in diameter). The burrows occur within thickly bedded fine- to medium-grained sandstone, obliquely to the bedding plane and lamination. C-type is comparable to *Ophiomorpha* sp., which is similar in form to the burrows of modern callianassids. *Ophiomorpha* is regarded as an indicator of littoral, sublittoral or upper neritic condition (HOWARD, 1972; etc.).

D-type: This type of trace fossil is an irregularly sinuous, shoestring-like trail, 2 to 3mm in width, and 10 to over 20cm in length. The trail has a longitudinal groove at the middle, and never branches. These fossils occur on the top surface of sandstone beds, and are often crowded on the rippled sandstone bed, interpenetrating one another.

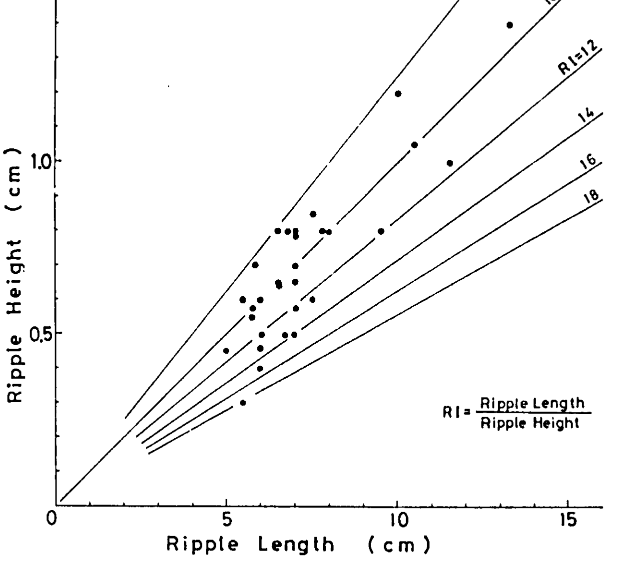


FIG. 22. Scatter diagram of ripple height versus ripple length for wave ripple marks in the Misaki Formation.
RI: ripple index.

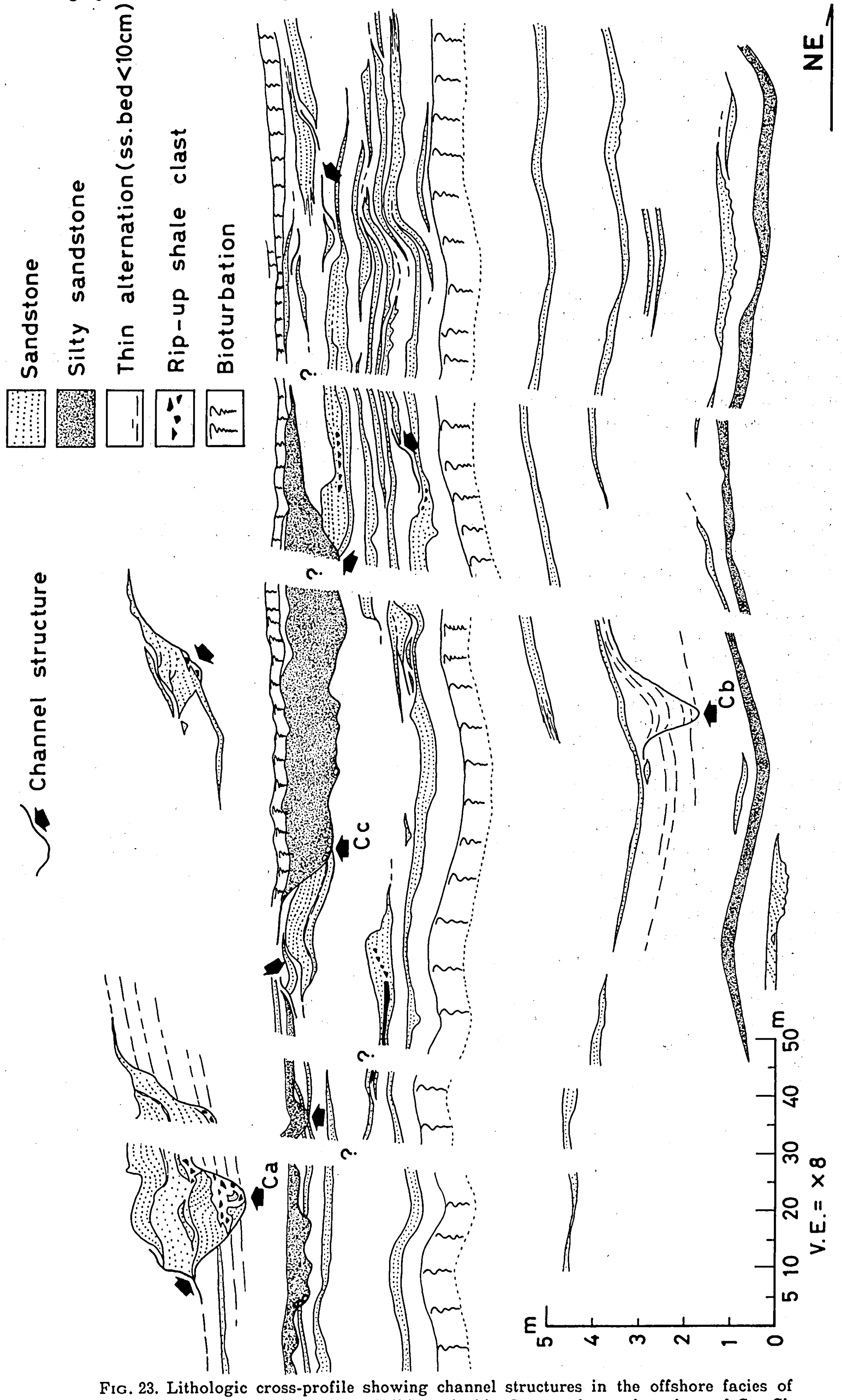


FIG. 23. Lithologic cross-profile showing channel structures in the offshore facies of the Misaki Formation at Chihiro-misaki. See text for explanations of Ca, Cb and Cc.

The following 9 facies (Facies 1 to 9) are discriminated in the Misaki Formation. The examples of columnar sections are illustrated in Fig. 24 to 28. And the principal characteristics of the facies described below are summarized in Fig. 43.

Facies 1 (a in Fig. 24)

Facies 1 occurs above the unconformity in the northern part of the distributed area of the Misaki Formation. It consists of dark gray pebbly sandstone and silty sandstone, with an ill-sorted conglomerate of 0.5 m thick at the base. Thin layers of mudstone are also intercalated. Internally, the sandstone is massive or laminated, with crude planar lamination and subordinate cross lamination. The sandstone shows characteristically bimodal grain-size distribution (Fig. 37). There are often many tubular, full relief burrows (several mm in diameter) within the sandstone beds. As mentioned in Chapter IV, some molluscan and foraminiferal fossils are found in the silty sandstone.

Facies 2

Facies 2 is well exposed in the coastal area near Yoro, Tosashimizu City (Fig. 11). This facies consists of mudstone with silty and sandy intercalations (Plate II-2). The silty and sandy layers are well traceable laterally, though they are very thin (1 to 30mm thick). They are sometimes parallel-laminated, rarely with subordinate ripple cross lamination. Ripple marks and trace fossils cannot be observed. Facies 2 is about 30 m thick in the lowermost part of the Misaki Formation, and grades upward into Facies 3.

Facies 3 (Figs. 24, 25, 26 & 27)

Facies 3 is exposed typically in the coastal area from Yoro to Matsuzaki, and is developed repeatedly throughout the Misaki Formation. It is composed of alternating beds of thin, fine-grained sandstone (each bed being 1 to 50cm thick) and thicker mudstone. Sedimentary structures within the sandstone are characterized by parallel, wavy, flaser lamination and ripple cross lamination (partly climbing ripple lamination). The base of the sandstone bed is usually sharp, and the top is sharp or gradual. Ripple marks are well preserved on the upper surface. Flute marks exist on the bottom surface of some sandstone beds. Trace fossils are characterized by intrastratal burrows and such surface trails as D-type. Some deposits of Facies 3 in the Middle and Upper Members, especially those intercalated in Facies 4 and 5, are intensively bioturbated (Plate II-4). Facies 3 in the Upper Member commonly includes carbonaceous detritus.

Facies 4 (Figs. 24, 25, 26 & 27)

Facies 4 is composed of alternating beds of fine-grained sandstone (each bed being 10 to 100cm thick) and thinner mudstone. The dominant internal structure of the sandstone is parallel lamination, which is occasionally associated with low-angle (several degrees) cross lamination and hummocky cross stratification of HARMS et al. (1975). Another common sedimentary structure is ripple cross lamination. Tabular cross lamination is also recognized, and its foresets sometimes display bidirectional dips with two modes approximately 180° apart (h in Fig. 25). The base of the sandstone bed is sharp and is sometimes ornamented with flute marks. On the other hand, the top is sharp or gradual, and occasionally exhibits ripple marks. Amalgamation of sandstone beds occurs; two sandstone beds separated by a thin mudstone laterally suddenly change to one amalgamated bed, where the boundary between the two original beds is indicated only as lamination. Moreover, penecontemporaneous deformation structures, such as contorted bedding and ball-and-pillow structure, are often recognized. Biological activity is commonly preserved in this facies, in the form of trails and burrows on and within the sandstone beds. The most characteristic trace fossils are *Nankaites* and *Thalassinoides*. Some of the sandstones are calcareous, and yield oyster shells.

Facies 5 (Figs. 26 & 27)

Facies 5 consists of thick-bedded, fine- to medium-grained sandstone with intercalation of thin layers of mudstone. Lenses of conglomerate, which contains well- to very well-rounded, fine to coarse pebbles, are included. This facies is typically developed in the lower half of the Upper Member (locally in the Middle Member), and is often intercalated with Facies 3. Each of the sandstone beds is generally 0.5 to 10m or more in thickness. Thick sandstone is often composed of plural sandstone layers (amalgamated or composite bed). Such amalgamation makes it difficult to discriminate individual depositional event. The base of the sandstone bed is often erosional. Rip-up clasts (up to 4cm in diameter) of the underlying mudstone are often found near the base. The top surface is nearly horizontal and is either erosional or gradational into the overlying siltstone or mudstone.

Characteristic sedimentary structures are low-angle cross lamination, hummocky cross stratification and parallel lamination, rarely accompanied with ripple cross lamination and trough cross lamination. The lamina is generally defined by alternation of lighter-colored, relatively well-sorted feldspathic sand and darker sand containing abundant carbonaceous detritus and mica. Another important feature of this facies is the development of contorted bedding (ex. convolute lamination) and concretion. The top surface of the convolute bed is always truncated by a depositional surface of the overlying sandstone (metadepositional convolute lamination, ALLEN, 1982). This indicates that the convolute lamination had been formed before the deposition of the overlying sandstone. The carbonaceous laminae or thin lenses and streaks of coal are intercalated in the thick-bedded sandstone.

A typical cyclic deposition is observable as follows from the base upward: 1) medium-grained to pebbly sandstone with a sharp, erosional base; 2) hummocky cross-stratified or low-angle cross-laminated sandstone; 3) parallel-laminated, fine- to very fine-grained sandstone; 4) rippled or ripple cross-laminated sandstone; and 5) mudstone. This sequence is similar to an idealized sequence of a hummocky bed described by DOTT and BOURGEOIS (1982), but there is an omission of some units. Burrowing and bioturbation by benthonic organisms are often observed not only in the mudstone but also in the sandstone. The burrowed and bioturbated unit is terminated by the erosional base of the overlying bed. The most characteristic trace fossil in this facies is *Ophiomorpha*.

Facies 6 (Fig. 28)

Facies 6 is the most coarse facies in the Misaki Formation, and is typically developed in the middle part of the Upper Member near the Marine Observation Tower, west of Tatsukushi. It consists of thick-

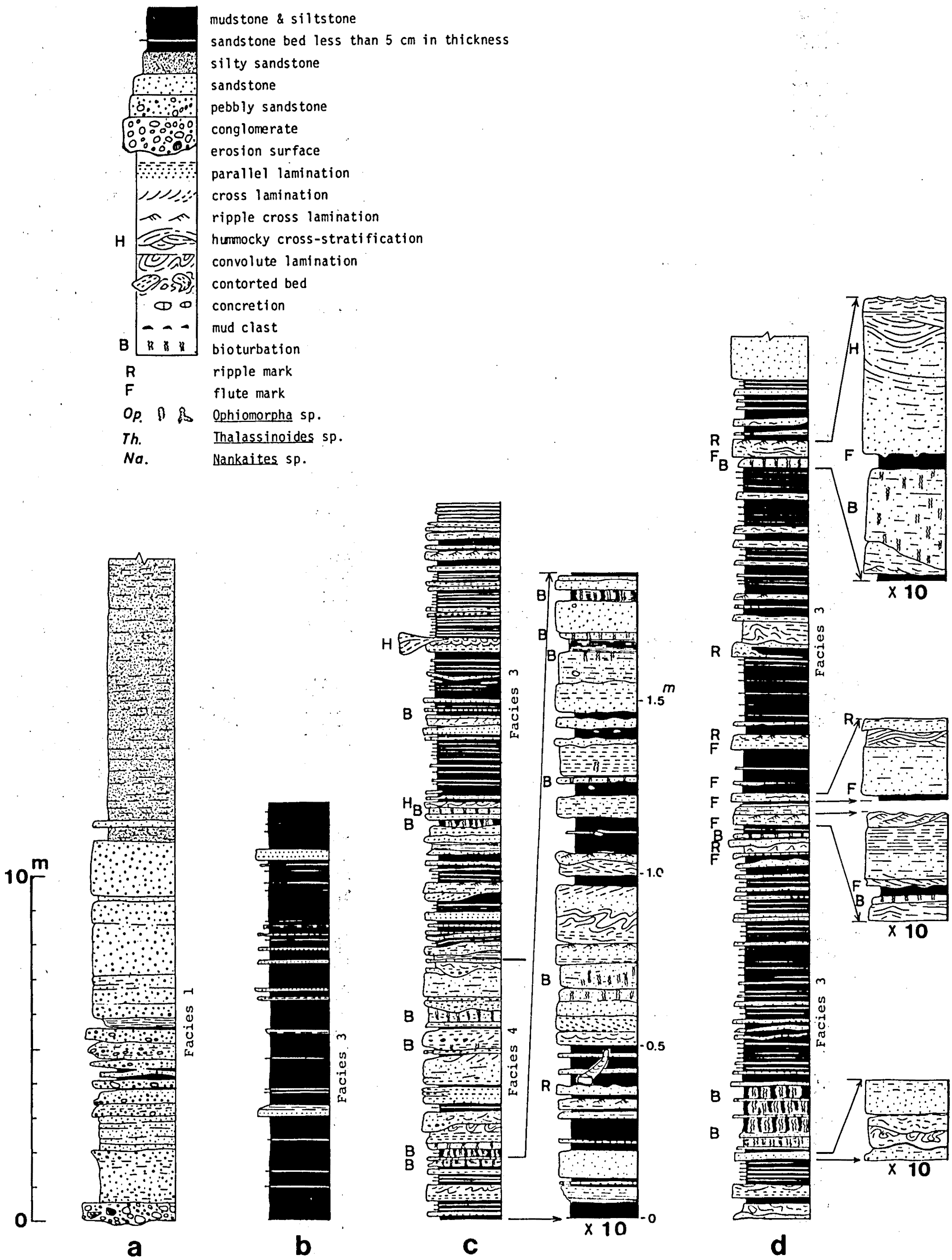


FIG. 24. Detailed columnar sections of the Lower (a, b) and Middle (c, d) Members of the Misaki Formation.

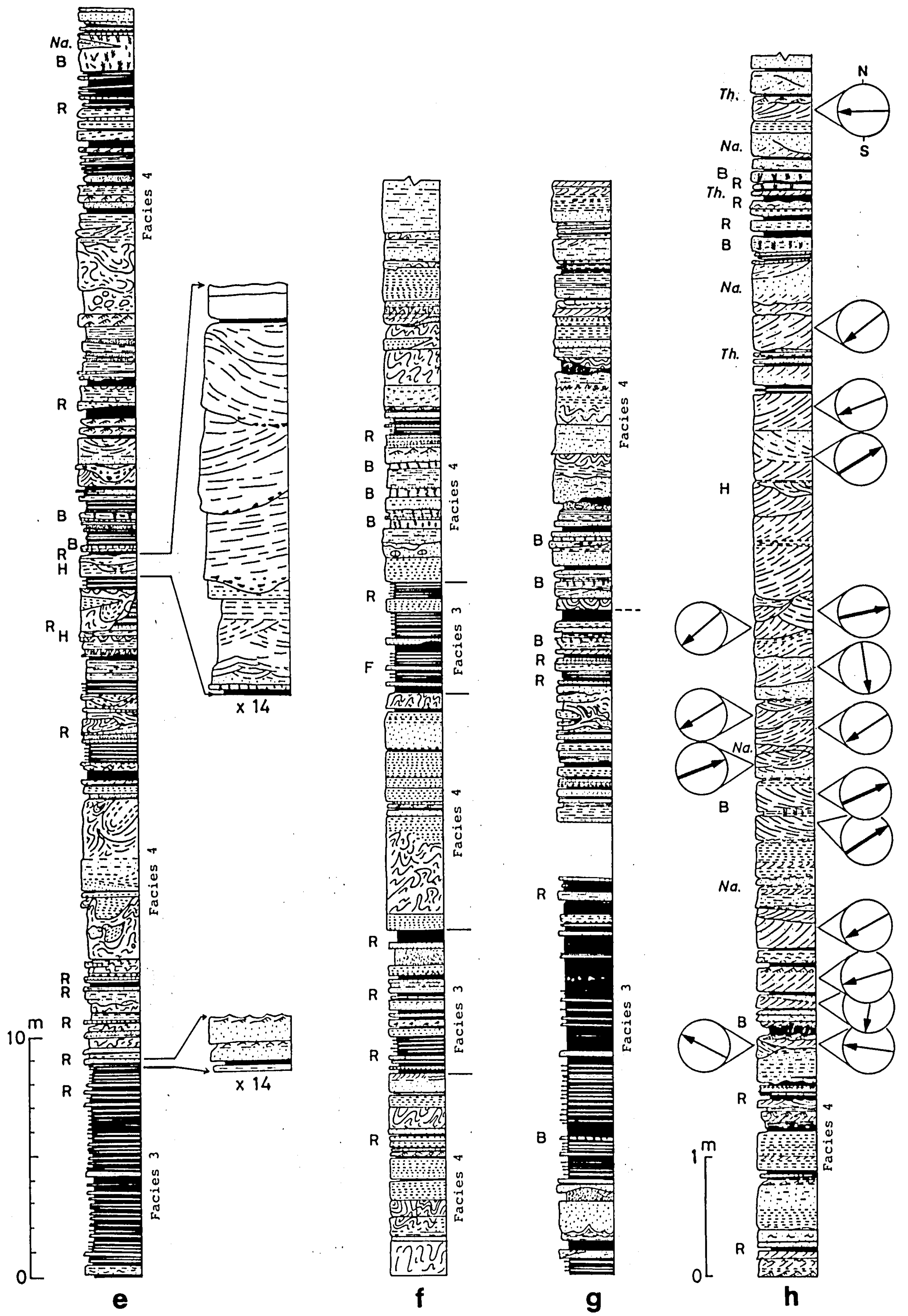


FIG. 25. Detailed columnar sections of the Middle Member of the Misaki Formation.
See the legend of FIG. 24.
Arrows show directions of paleocurrents.

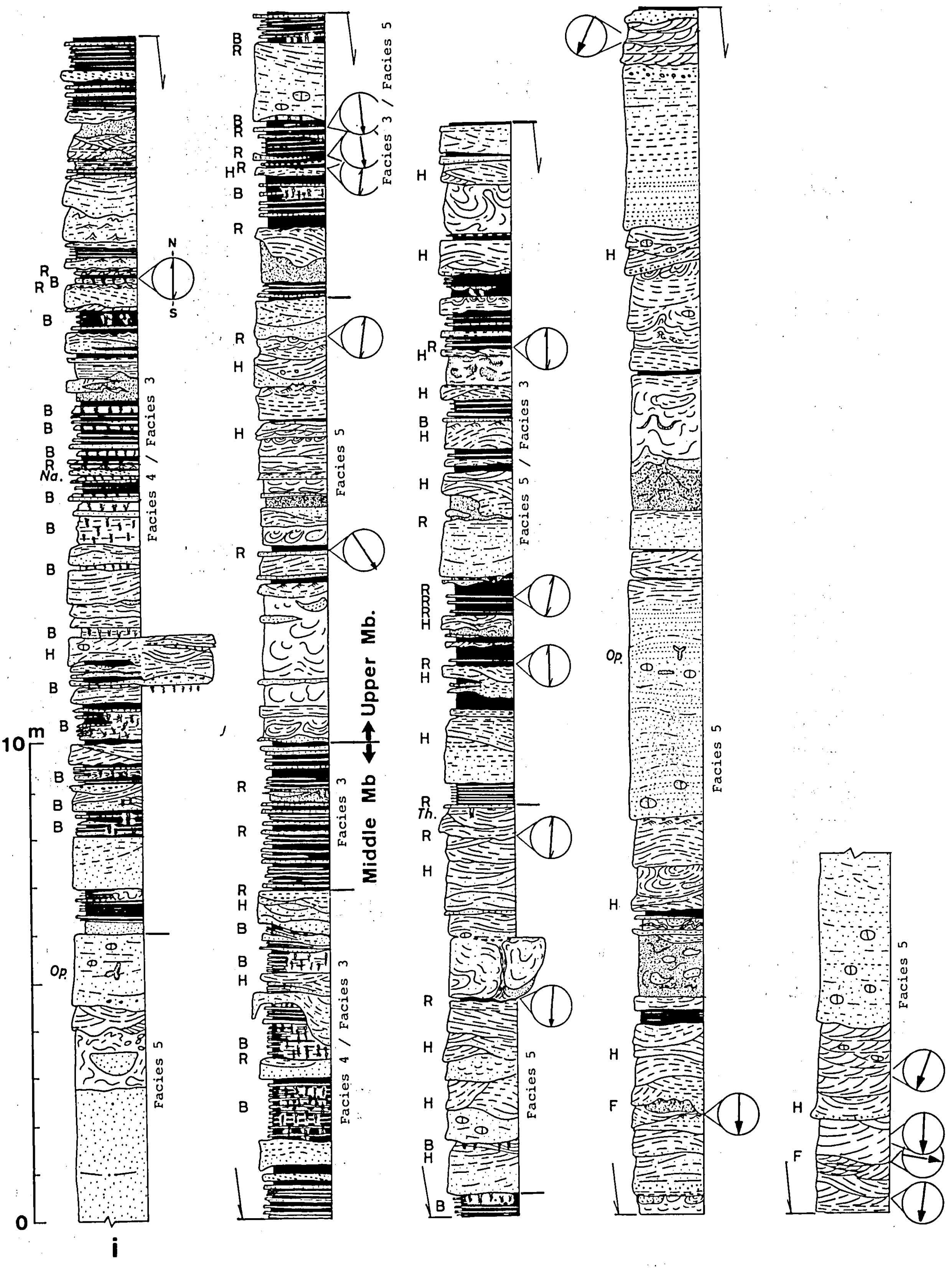


FIG. 26. Detailed columnar section of the boundary strata between the Middle and Upper Members of the Misaki Formation at Chihiro-misaki.
See the legend of FIG. 24. Arrows show directions of paleocurrents.

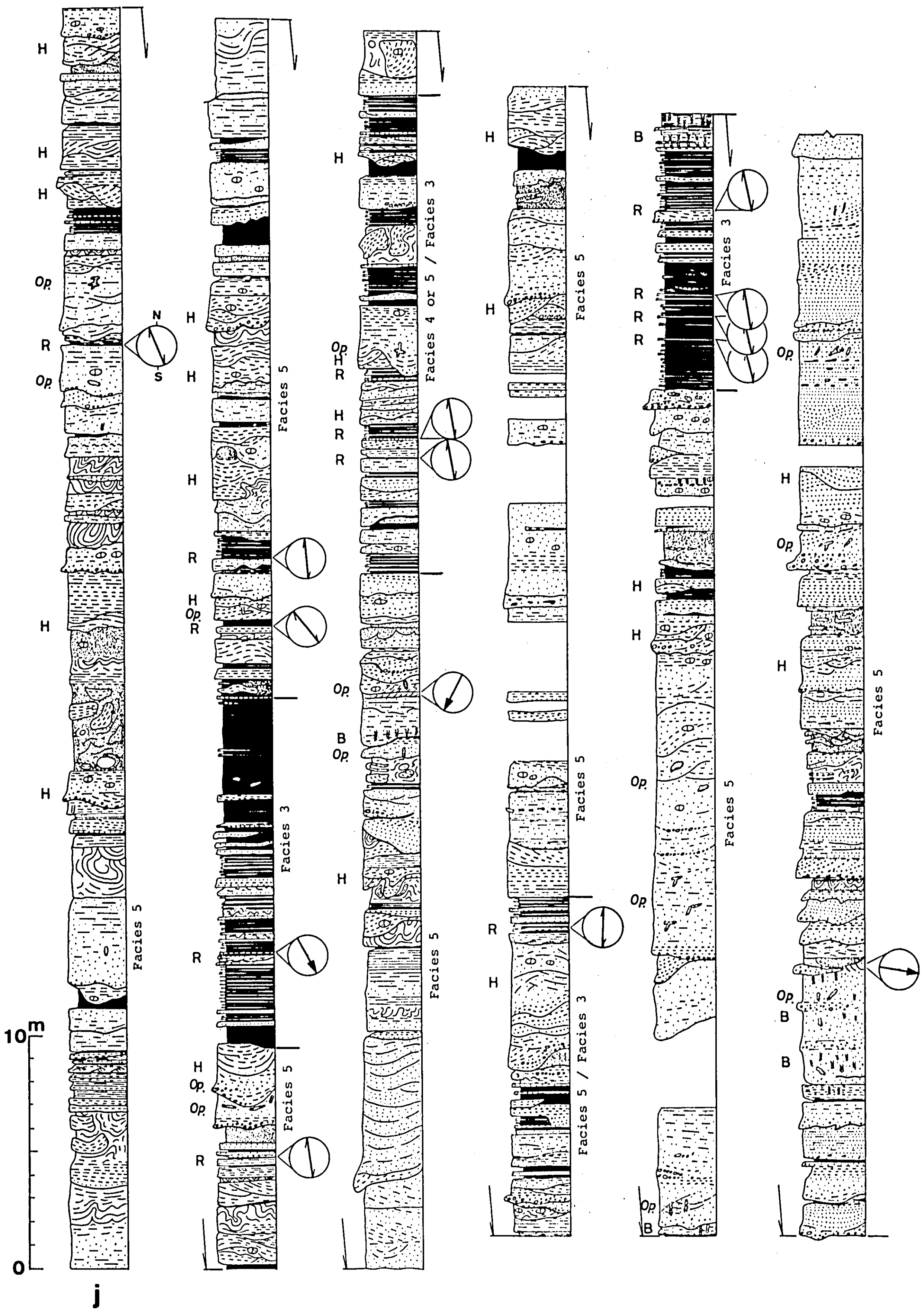


FIG. 27. Detailed columnar section of the Upper Member of the Misaki Formation at Tatsukushi. See the legend of FIG. 24. Arrows show directions of paleocurrents.

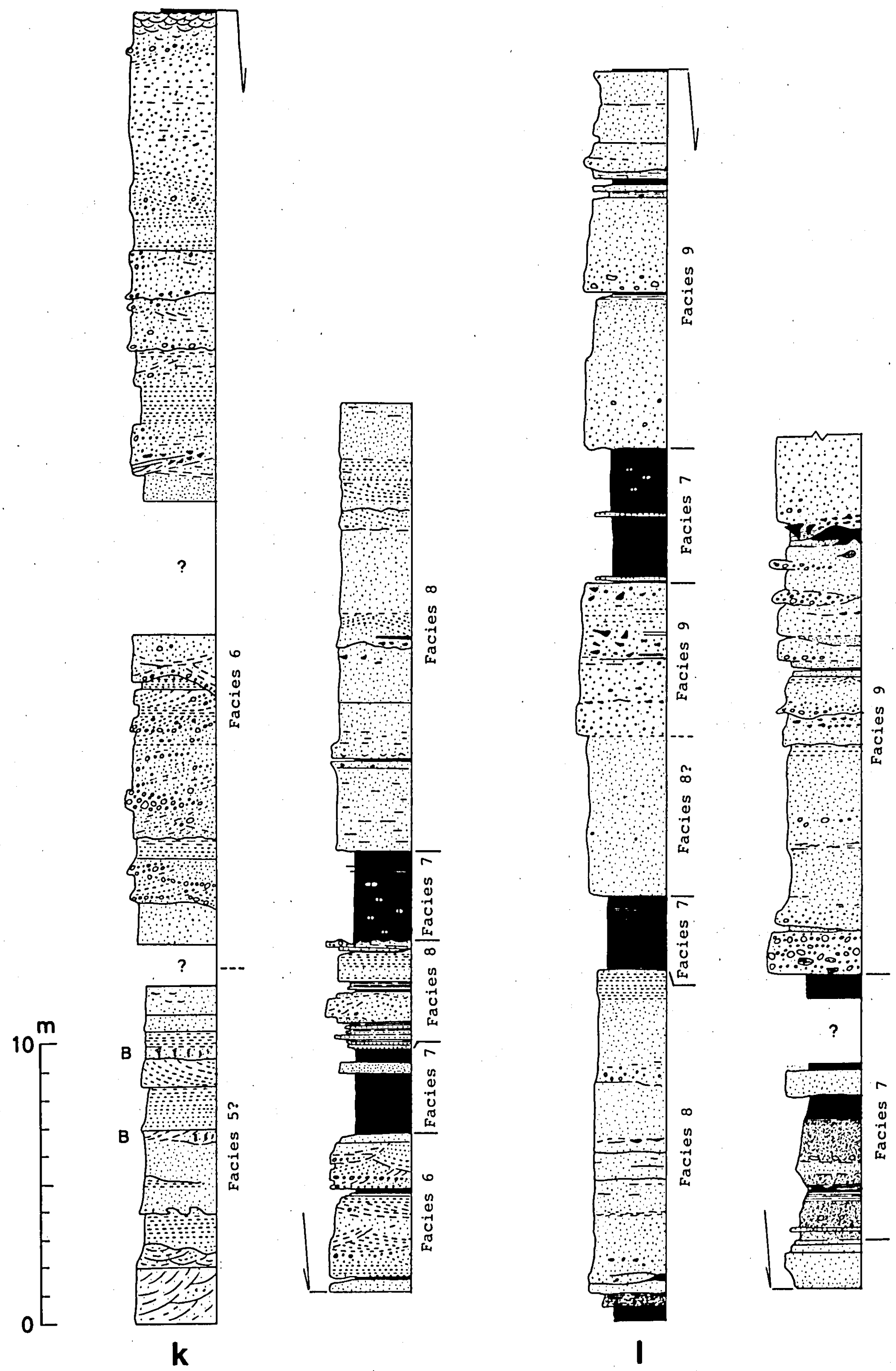


FIG. 28. Detailed columnar sections of the Upper Member of the Misaki Formation at Tsumajiro.
See the legend of FIG. 24.

bedded, amalgamated, coars- to very coarse-grained sandstone with pockets of pebble conglomerate to peddly sandstone. Mudstone is hardly intercalated. A large-scale trough and tabular cross-bedded sandstone with sharp, channeled base is characteristic of this facies. Most of the cross-laminated sets display unidirectional currents. The fine- to medium-grained sandstone is dominated by parallel lamination. Granule- to pebble-sized clasts are generally arranged along cross laminae. Clasts are also concentrated above the erosional surface or within the middle part of the bed, or are interspersed sporadically. The clasts are poorer in roundness than those of Facies 5. Trace fossils are very rare.

Facies 7 (Fig. 28)

Facies 7 consists of black to dark gray, carbonaceous mudstone and siltstone interbedded with thin layers of very fine-grained sandstone. The mudstone includes pseudopebbles of grayish, hard silty mud showing onion structure and pseudo-nodules containing ore-mineral (pyrite ?). This facies occurs in the upper half of the Upper Member, where Facies 7, 8 and 9 are repeatedly alternated. Trace fossils are lacking.

Facies 8 (Fig. 28)

Facies 8 is composed of thick-bedded, fine-grained, well-sorted sandstone, which occasionally contains mudstone clasts up to 1cm in diameter. Internally, the sandstone is commonly massive or crudely laminated. Gently inclined planar lamination is occasionally recognized in the lower part. Although erosional truncation at the bace of the sandstone bed is not remarkable, low-angle discordance occurs at places. Carbonaceous laminae are included in the sandstone, and thin layers of interbedded mudstone are also rich in carbonaceous detritus.

Facies 9 (Fig. 28)

Facies 9 is composed of medium- to coarse-grained sandstone with subordinated conglomerate and shows fining-upward tendency at intervals of less than 10 m. It lithologically resembles Facies 6, but the sandstone is poor in internal stratification, and especially lacks tabular and trough cross laminations. The sandstone sometimes contain rip-up clasts of mudstone (8cm in maximum diameter). Carbonaceous laminae and plant fragments (rarely cardonized wood) are often included. The conglomerate generally occurs near the basal surface or in form of pocket within the sandstone bed.

B. Properties of Sandstone

1. Mineral composition

The analysis of mineral composition of sandstone was carried out in order to obtain much information on provenance. In this study, specimens for examination were collected from massive or stratified sandstone. In order to distinguish potash feldspar from plagioclase without difficulty, the author etched uncovered thin sections with hydrofluoric acid, and dipped them into a solution of cobaltinitrite. By this procedure, potash feldspar is stained yellow. The modal composition was obtained by counting 1,000 to 1,100 points per one thin section with a Swift point-counter under the microscope. The major constituents of sandstone are classified into quartz, potash feldspar, plagioclase, rock fragments and matrix. Opaque minerals, heavy minerals and secondary minerals (except for biotite flakes) were excluded, because the total amount of them was less than one percent of the whole composition in each specimen. Detrital grains smaller than 0.03mm (about 5 phi) were included in matrix.

The numbers of the analyzed specimens are as follows:

Hiromi Formation	31
Tatsugasako Formation	41
Kurusuno Formation	135
Shimizu Formation	18
Misaki Formation	16

The results are shown in Fig. 29 to 32, and Table 3.

Almost all of the sand grains are angular to subrounded. Quartz contains many undulose and polycrystalline ones. Secondary growth is rarely observable. Potash feldspar consists mainly of orthoclase with a little amount of microcline and perthite. Plagioclase often shows albite twinning, but zonal structure cannot be recognized. It is partially replaced by sericite and frequently corroded with calcite. Grains other than quartz and feldspar were counted in a category of rock fragments, which consist mostly of chert, slate and fine-grained sandstone with subordinate amount of igneous rocks (mainly rhyolitic and andesitic rocks). Additionally, clastic biotite flakes were also regarded as rock fragments. Matrix is made up of clay minerals, carbonate cement and detrital grains smaller than 0.03mm

Most of the sandstones in the surveyed area are rich in matrix, and belong to feldspathic wacke of OKADA's classification (OKADA, 1968, 1971). Generally speaking, the sandstones contain larger amount of quartz and less amount of feldspar (especially potash feldspar) and rock fragments. Such a tendency has also been pointed out about the Paleogene sandstones of the Shimanto Supergroup in other areas (TERAOKA, 1977, 1979; OKADA, 1977; KUMON, 1983).

a. Hiromi Formation

The sandstones of the Hiromi Formation are generally richer in feldspar and rock fragments than those of the other formations. Igneous rock fragments are commonly contained, and the ratio of igneous rock fragments to other rock fragments is prominently larger in this formation than in other formations of the Hata Group (Fig. 32). The ratio of potash feldspar to plagioclase is over 1/2 for 35 percent of sandstone specimens. Exceptionally, a few specimens collected near the greenstone body are poor in potash feldspar and rock fragments.

b. Tatsugasako Formation

The sandstone composition of the Tatsugasako Formation is most diverse among the Hata Group, and generally shows intermediate character between the sandstone compositions of the Hiromi and Kurusuno Formations. It may be influenced by the variety of grain size, sedimentary facies and paleocurrent direction. The sandstones of the Tsuganokawa Member below tend to be relatively richer in quartz and poorer in feldspar and igneous rock fragments than those of the Shirahama Member above, although the difference is not so remarkable. In a word, the sandstones of the Tsuganokawa Member resemble those of the Kurusuno Formation, and the sandstones of the Shirahama Member resemble those of the Hiromi Formation in mimeral composition.

c. Kurusuno Formation

The sandstones of the Kurusuno Formation are dominant in quartz and feldspar, and are very poor in rock fragments. The ratio of quartz to feldspar is, though variable, greater than 1 for most of the specimens (87.4%). The ratio of potash feldspar to plagioclase is less than 1/2 for 95 percent of specimens. The content of rock fragments is less than 10 percent except for 2 specimens, and the content of igneous rock fragments is less than 1 percent except for 3 specimens (Fig. 32).

d. Shimizu Formation

The sandstone composition of the Shimizu Formation is similar to that of the Hata Group. There is no difference in mineral composition between the coherently stratified beds and the mixed blocks. The ratio of potash feldspar to plagioclase does not exceed 1/2 for all of the specimens. The content of igneous rock fragments is less than 1 percent for all but one specimen of lithic wacke. Rock fragments of the lithic wacke are composed mostly of very fine-grained sandstone and shale, igneous rock fragments being poor (1.2%) (Fig. 32). By the way, as the Shimizu Formation contains lots of conglomerate, the conglomerate composition was examined at 3 localities. The compositional diagram is shown in Fig. 33. The conglomerate of this formation shows homogeneous composition everywhere, clasts of sandstone and shale being predominant. Additionally, the sandstone clasts are similar to the Paleogene sandstone in mineral composition (Fig. 31), and can be distinguished from the Cretaceous sandstone.

e. Misaki Formation

As well as the Paleogene sandstones of the Shimanto Supergroup, the sandstones of the Misaki Formation are much dominant in quartz and feldspar, and are poor in rock fragments, except for pebbly sandstone in the Upper Member. Clasts of sandstone, shale, chert and vein quartz are predominant in the pebbly sandstone and conglomerate, with a small amount of felsic and intermediate volcanic rocks, schists and granitic rocks. The horizontal and vertical changes in mineral composition are not recognizable.

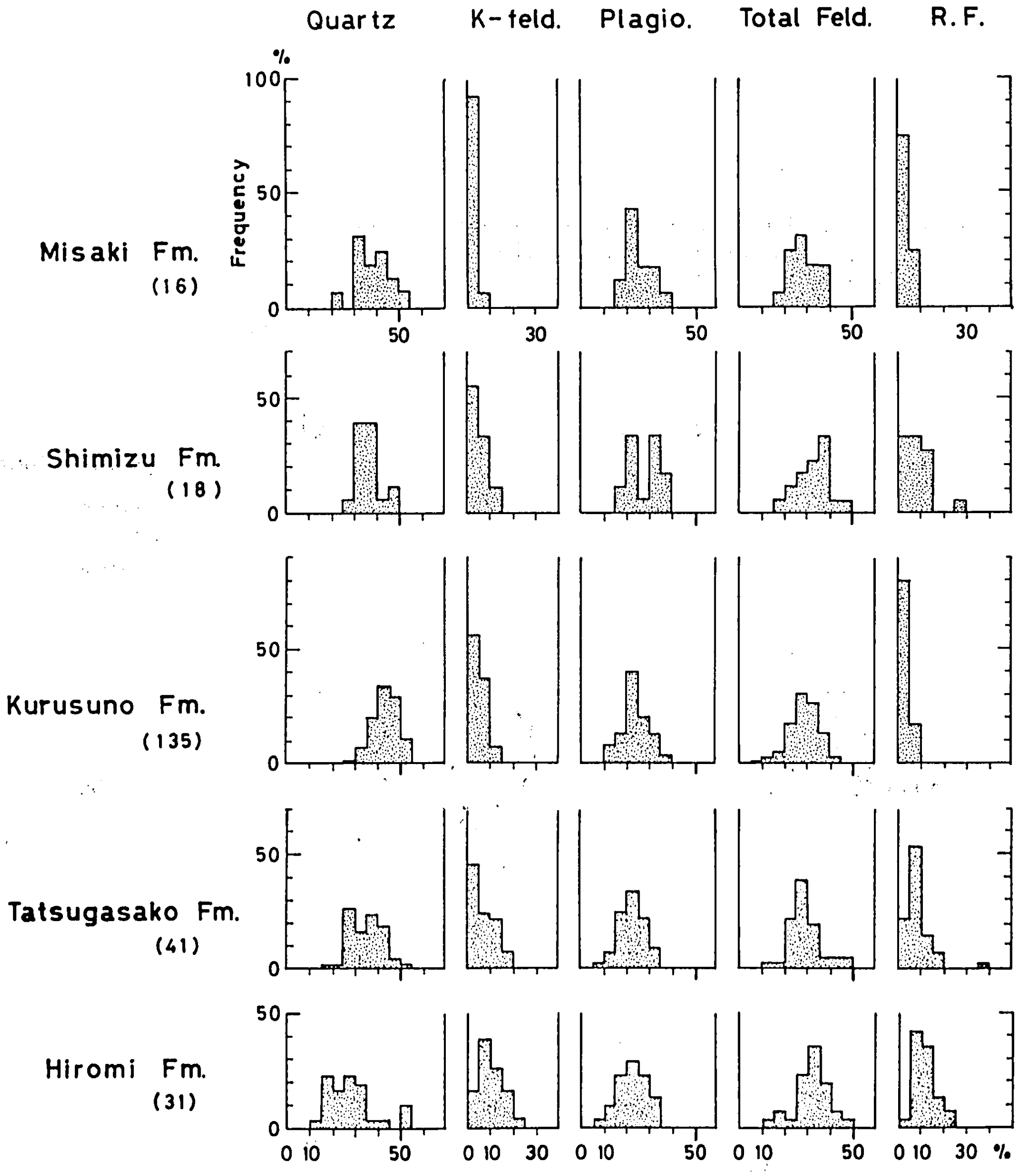


FIG. 29. Histogram showing the composition of sandstones in the studied area.

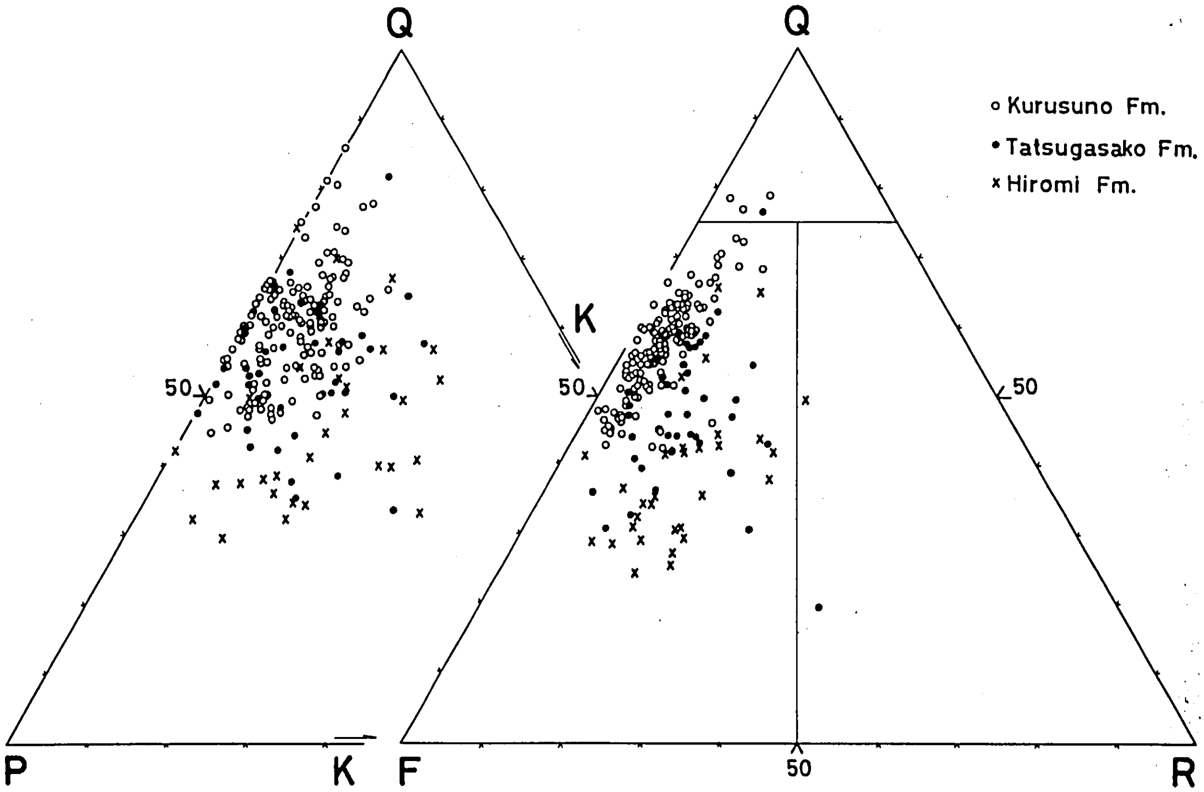


FIG. 30. Compositional diagrams for sandstones in the Hata Group.
Q: Quartz, P: Plagioclase, K: Potash feldspar, F: Total feldspar,
R: Rock fragments.

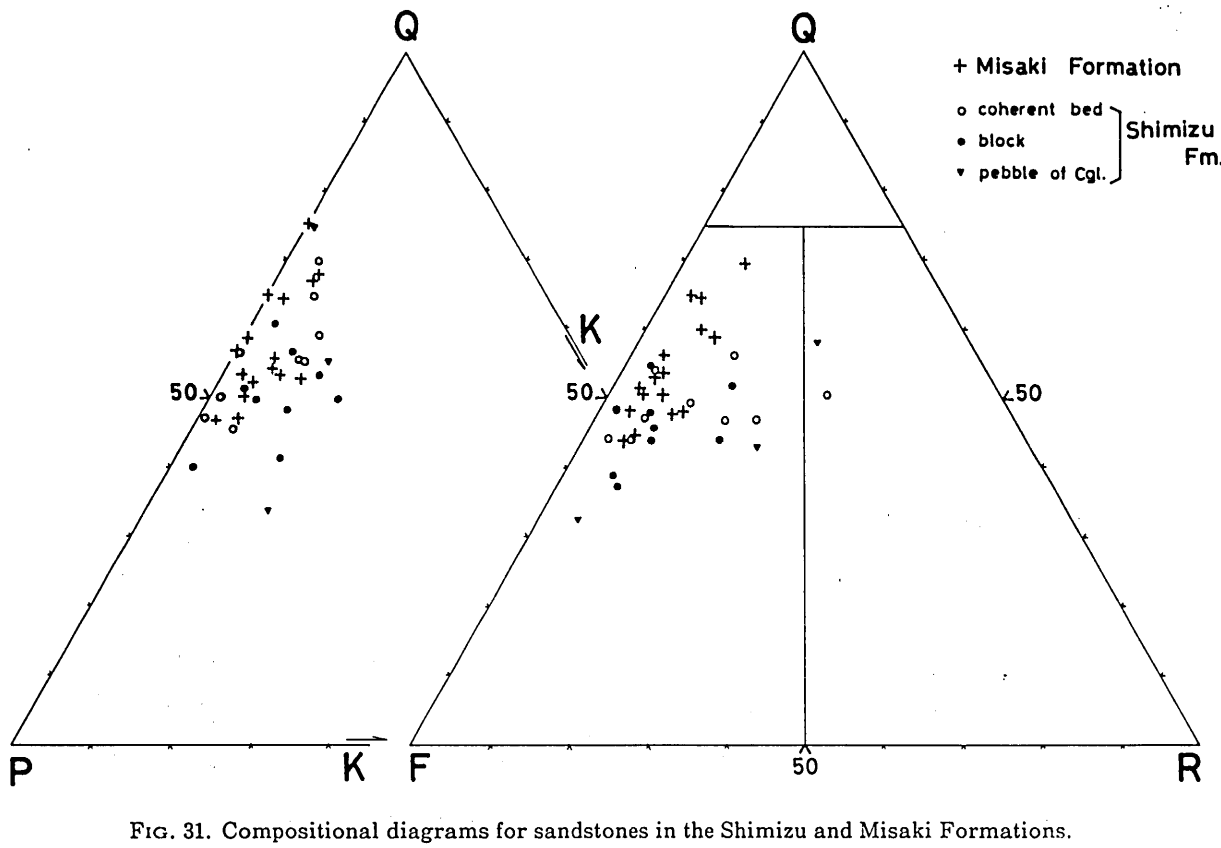


FIG. 31. Compositional diagrams for sandstones in the Shimizu and Misaki Formations.

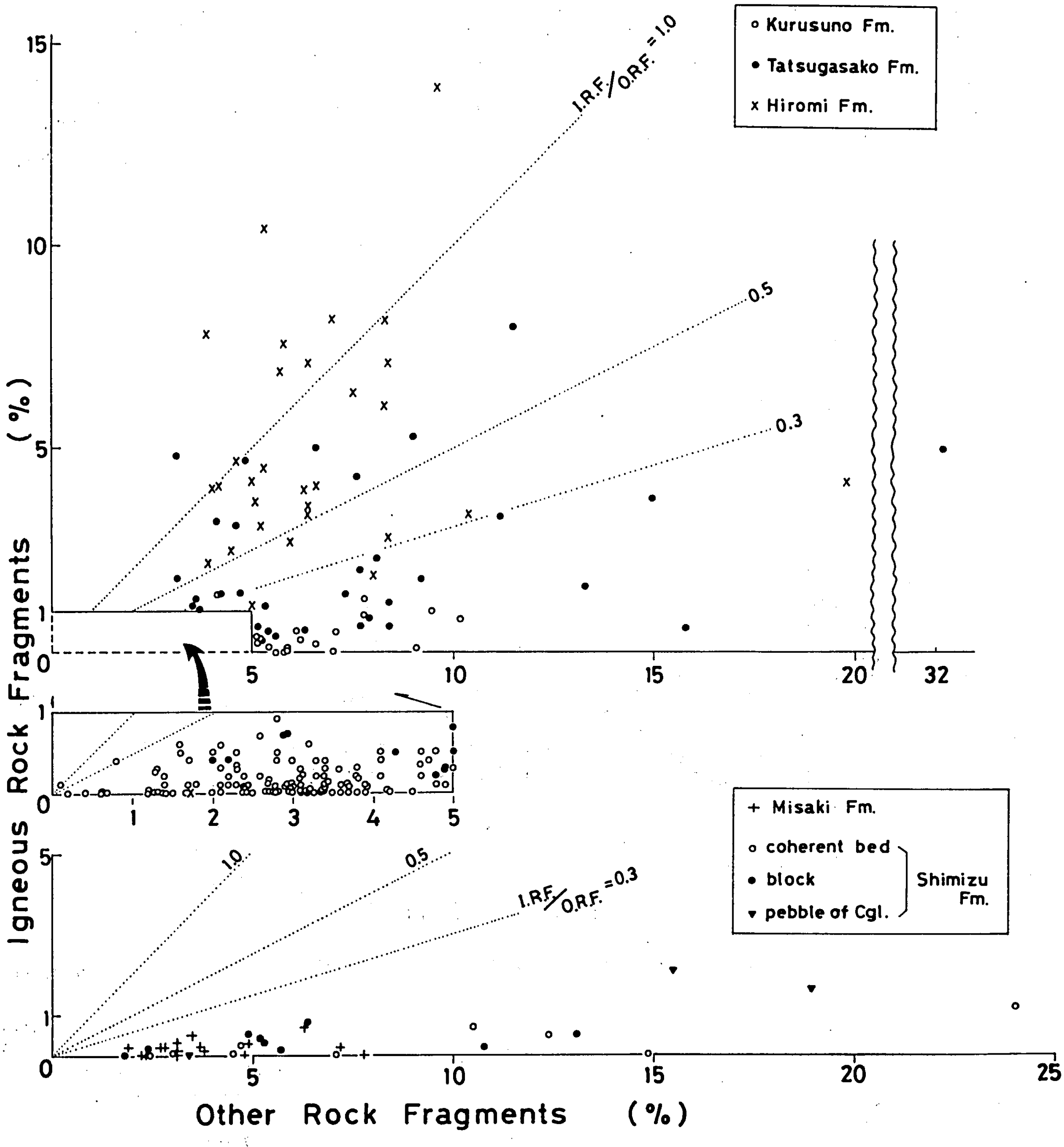


FIG. 32. Relation between the contents of igneous and other rock fragments for sandstones in the studied area.

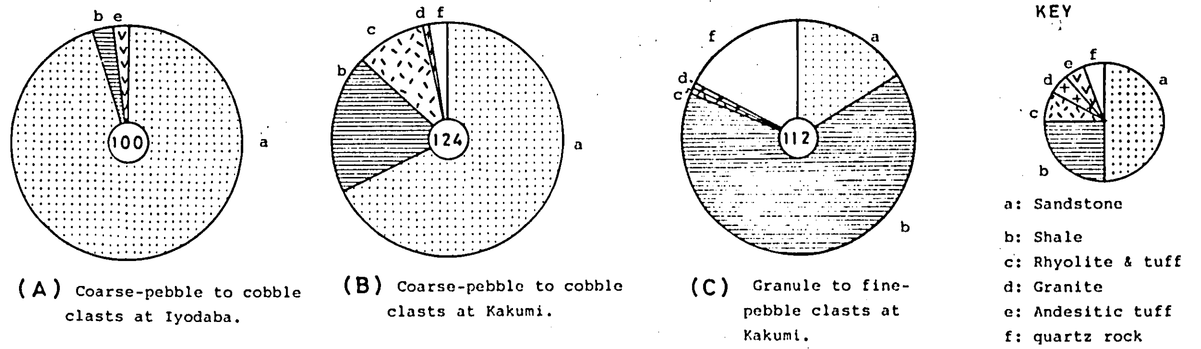


FIG. 33. Clasts composition of conglomerates in the Shimizu Formation. Numerals at the center show the number of clasts examined.

2. Grain size

In the grain size analysis, the apparent maximum length of quartz grains larger than 5 phi was measured under the microscope. After more than 250 grains per one thin section were counted, some particular percentiles were read from the cumulative frequency curves in order to calculate the statistical parameters of mean size, sorting index, skewness and kurtosis according to the formula of FOLK and WARD (1957). Grain size analysis was made mainly on the sandstones of the Tatsugasako and Misaki Formations. As two examples of the scatter diagram, the relations between mean size and sorting, and between skewness and kurtosis are illustrated in Figs. 34 and 35, respectively.

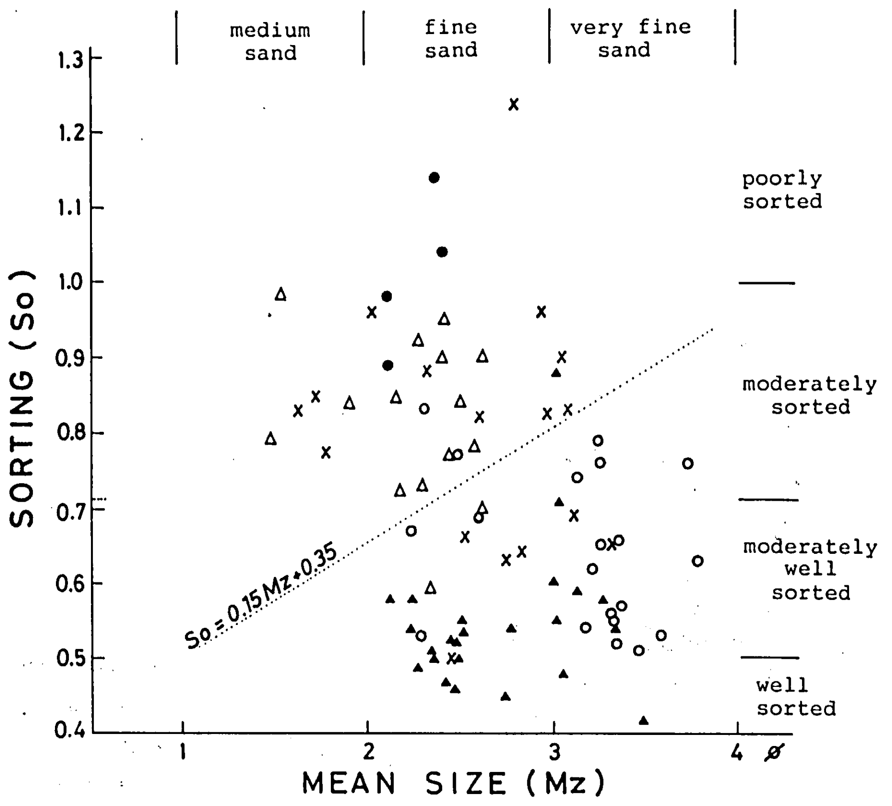


FIG. 34. Scatter diagram of mean grain-size versus sorting.

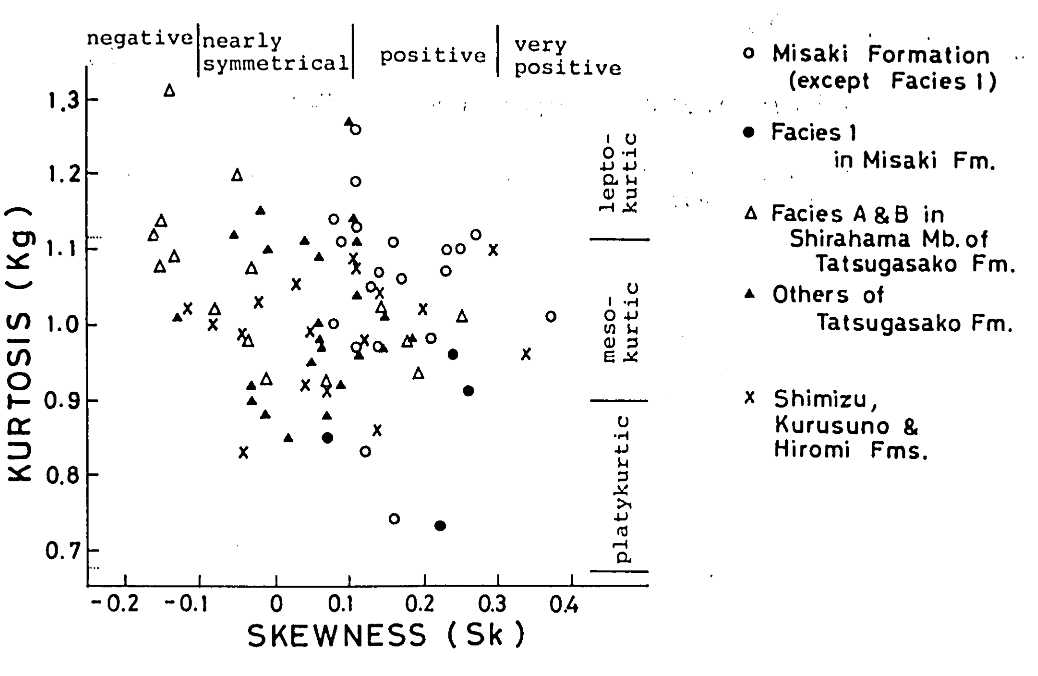


FIG. 35. Scatter diagram of skewness versus kurtosis.

Most of the analyzed specimens are fine to very fine in mean grain size.

Samples of the Tatsugasako Formation can be classified into two groups in the scatter diagram of mean size versus sorting (Fig. 34). In short, the sandstones in Facies A and B of the Shirahama Member are comparatively coarse-grained and are inferior in sorting to the other sandstones in the Tatsugasako Formation. Such difference is also noticeable in the C-M diagram (Fig. 36). The C-M pattern of the sandstones in Facies A and B of the Shirahama Member is formed by segments PQ and OP, which represent the deposition by a mixture of suspension and rolling (PASSEGA and BYRAMJEE, 1969). On the other hand, the C-M pattern of the other sandstones is formed by segment QR representing the deposition by graded suspension. There is no remarkable difference in skewness and kurtosis, but the majority of the latter are relatively negative-skewed.

The sandstones of the Misaki Formation are moderately or moderately-well sorted except for a few specimens (Fig. 34). Four specimens from Facies 1 are less poorly sorted, and are unusual in lithology, showing a bimodal grain size distribution (Fig. 37). All of the sandstones of the formation are positive-skewed. Most of them are mesokurtic or leptokurtic.

3. Grain orientation

Grain orientation was measured on three sandstone beds in Facies C of the upper Tatsugasako Formation (Shirahama Member) in order to determine the relationship between flute mark direction and grain orientation. In each of the three samples, 11 thin sections parallel to the bedding plane were prepared. The orientation of apparent long axes of more than 150 elongate grains (having a ratio of long axis/short axis larger than 2) per one thin section was measured under the microscope. The measured values were classified into intervals of 10 degrees. The mean grain orientation and its dispersion were determined by the vector method proposed by CURRAY (1956) for statistical analysis of two-dimensional direction data. The results are shown in Fig. 38.

Although the degree of grain dispersion, as indicated by the vector magnitude values in terms of percent, is generally small, the mean grain orientation does not always agree with the flute mark direction. Many of the orientation deviate counterclockwise from the flute mark direction, as viewed from the stratigraphic top. This tendency is most remarkable in bed TH-12. Especially in the lower and middle parts of the bed, the mean grain orientation diverges at 45° to 90° counterclockwise from the flute mark direction. The vector magnitude is also smaller. It is worth noting that parallel lamination is well developed at 4 to 7cm distance up from the base (Fig. 38). In the upper part of the bed, the vector magnitude and the correspondence between flute mark and grain orientation are larger.

The data from beds TH-7 and TH-1 show a good mutual parallelism between the mean grain orientations at all levels and flute mark directions, except for a few thin sections. The vector magnitude is generally more than 20 percent. In some stratigraphic levels, however, small groups of grains lie perpendicular to the flute mark direction. It is noted that parallel lamination is present in the upper part of bed TH-7.

The above results indicate that the use of grain orientation in paleocurrent analysis is limited. Discrepancies between sole markings and grain orientation have also been reported on some ancient turbidites (e.g. BOUMA, 1962; SPOTTS, 1964). The grain fabric of detrital sediments is controlled by various factors (cf. POTTER and PETTIJOHN, 1963; DZULYNSKI and WALTON, 1965). The author has not been able to provide sufficient explanation for them. At least, the grain orientation should be considered from a viewpoint of internal sedimentary structures, because the fabric of sediments is largely affected by mechanism of transportation and deposition. In practice, the grain orientation in laminated parts diverges at right angle from the flute mark direction. From this, it may be inferred that the grains of the laminated parts were transported by tractive currents with particles' long axes perpendicular to the current.

C. PALEOCURRENT SYSTEM

Directional sedimentary structures such as flute marks, groove marks, ripple marks and cross lamination are frequently observed in the surveyed area. Such sedimentary structures provide useful information on the direction of transport as well as on the situation of provenance.

1. Hata Group

Fig. 39 shows the paleocurrent direction deduced from the flute marks and groove marks in the Tatsugasako and Kurusuno Formations. Taking account of the general strike of the bed, the paleocurrents are grouped roughly into two systems as follows. One is dominated by longitudinal currents suggesting transport from the southwest or from the south, accompanied with lateral currents mainly from the southeast. The other is characterized by longitudinal currents from the east or from the northeast, with lateral currents from the north-northwest. The former system is well developed in the Tsuganokawa Member of the Tatsugasako Formation and the Kurusuno Formation, while the latter in the Shirahama Member of the Tatsugasako Formation. It is noteworthy that longitudinal currents from the opposite direction occur in the different stratigraphic horizon.

Longitudinal currents from the east-northeast or from the east are said to be markedly developed in the Paleogene strata in eastern Shikoku and the Kii Peninsula (KUMON, 1983; TATEISHI, 1978). On the other hand, currents from the southwest have been rarely measured in other regions.

2. Misaki Formation

Ripple marks are well observed in the Misaki Formation, accompanied with flute marks. The thick-bedded sandstone also often exhibits large-scale cross lamination. Fig. 40 shows the paleocurrent direction deduced from ripple marks, flute marks and cross lamination. There is no marked difference in paleocurrent direction according to the stratigraphic horizon. In conclusion, the paleocurrents from the north or from the northwest predominate. The dominant direction of wave oscillation deduced from symmetrical ripples is also of N-S or NW-SE trend. This directional

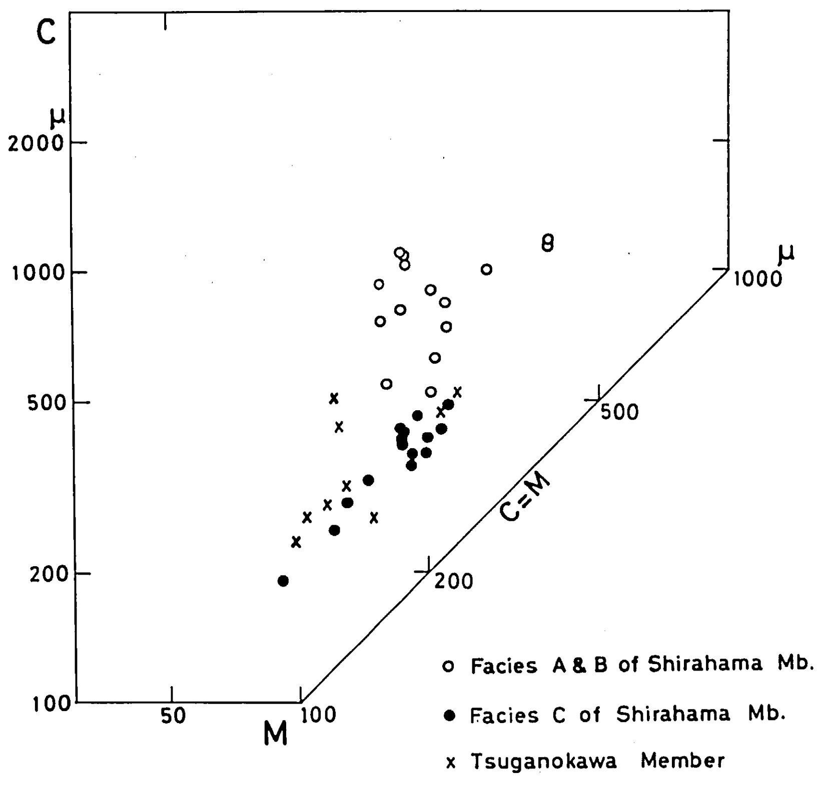


FIG. 36. C-M diagram of sandstones in the Tatsugasako Formation.
C: one-percentile in micron, M: median in micron.

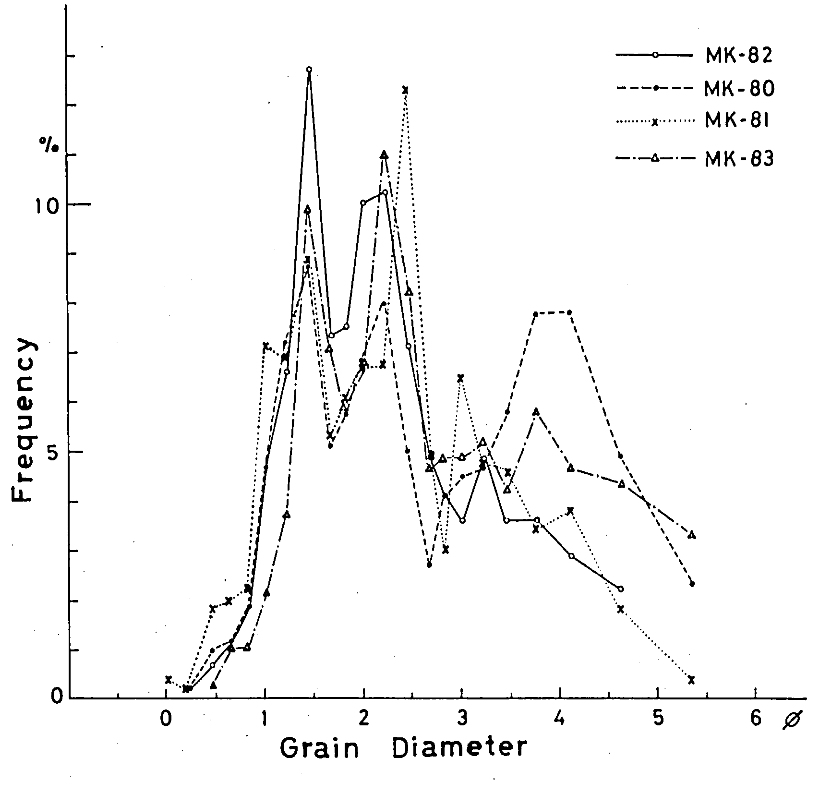


FIG. 37. Frequency curves of grain-size distribution for sandstones in Facies 1 of the Misaki Formation.

pattern is supported by the general trend of channel. Paleocurrents from the east or from the northeast are, though rare, also recognized. The paleocurrent system mentioned above may suggest that the land lay to the north and the coastline ran from east to west during the deposition of the Misaki Formation. Moreover, some cross-bedded sandstones show the presence of flows in opposite directions (h in Fig. 25). As will be discussed later, this bimodal pattern parallel to the inferred coastline may reflect the reversal of flow in tidal currents.

VI. Discussion and Concluding Remarks

A. Environmental Interpretation

1. Hata Group

It has been suggested in the foregoing that the clastic rocks in the Tatsugasako and Kurusuno Formations of the Hata Group have characteristics comparable to turbidite. Recently, various submarine fan models have been applied to the recognition of sedimentary environments and processes of ancient turbidite facies. The first extensive description was given by Mutti and Ricci-Lucchi (1972) and Walker and Mutti (1973), and after their works, several depositional models for both modern and ancient deposits have been proposed. These models are greatly applicable to the reconstruction of ancient sedimentary basins. Based on these studies, the interpretation on the sedimentary environments and processes of the Hata Group is given below.

a. Inner fan

Facies A2 is interbedded with shale facies (Fig. 5), and comprises characteristic pebbly sandstone containing lots of shale clasts. The sandstone exhibits planar stratification and rarely large-scale cross stratification. Abundant ill-sorted shale clasts in matrix-suported manner suggest the deposition from a debris flow. This facies is very similar to Facies A2 (organ-

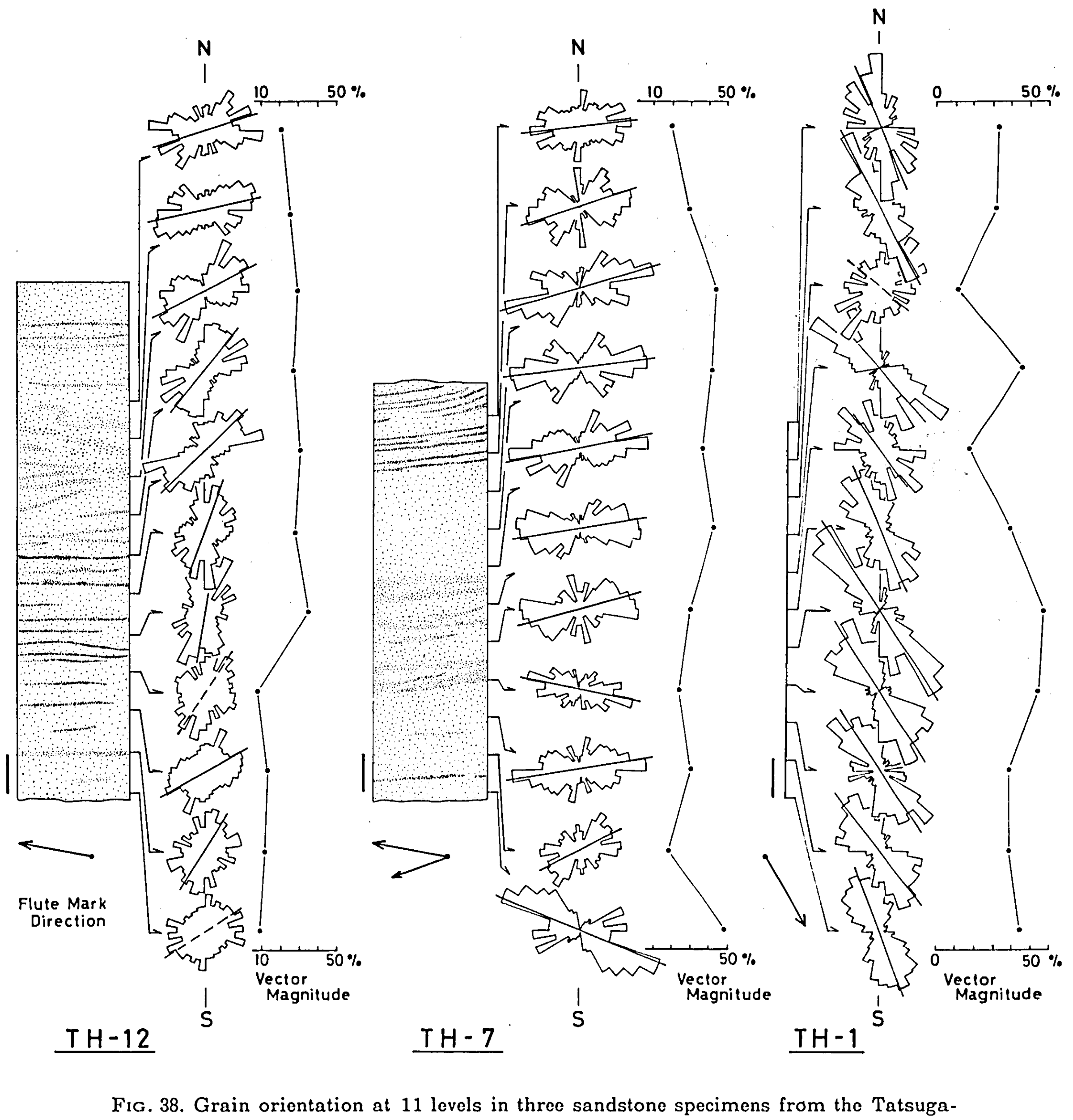


Fig. 38. Grain orientation at 11 levels in three sandstone specimens from the Tatsugasako Formation.
Bar indicates 1 cm.

ized conglomerates) of WALKER and MUTTI (1973), and appears to represent channel deposits in inner fan from the viewpoint of vertical succession. However, levee deposits, which tend to surround the coarse deposits within the channel in general (WALKER, 1978), are absent in the present facies. This might have probably resulted from the isolation of the fan due to the relative rise of the sea level. This interpretation may be supported by the stratigraphic position of Facies A2, which occurs in the uppermost part of a series of turbidite facies.

b. Mid-fan: Braided channels on suprafan lobe

Facies A1 consists of amalgamated, thick-bedded, pebbly to fine-grained sandstone, intercalated with shale and thinly alternating beds of sandstone and shale. The pebbly sandstone has an erosional base scouring the underlying shale, and grades upward into fine-grained sandstone. This facies is overlain by the shale of Facies D. The presence of water-escape structures in the sandstone suggests that sands were settled by rapid, mass deposition which trapped pore fluids and produced an unstable grain packing (HISCOTT and MIDDLETON, 1979). From these lithologic features, this facies is inferred to represented channel-fill deposits formed by sandy debris flows and or high-density turbidity currents.

Small-scale fining-upward sequences in this facies ranging in thickness from 2 to 10m correspond to the braided channel deposits on suprafan lobe suggested by NORMARK (1978) and WALKER (1978) for modern and ancient submarine fans. Such fining-upward sequences might have been caused by the filling and abandonment of a distributary channel (MUTTI and RICCI-LUCCHI, 1972; MUTTI, 1974).

Interbedded thin alternation up to 2m thick is interpreted as locally preserved overbank deposits (GHIBAUDO, 1980). Furthermore, interbedded Facies C or D ranging from several to 20m thick corresponds to inter-channel deposits.

c. Smooth suprafan or outer fan lobe

Facies B is characterized by non-channeled, thick-bedded sandstone, and is accompanied by flysch-type alternation of Facies C. Facies B passes upward and downward into Facies C. The sandstone of Facies B in the Shirahama Member of the Tatsugasako Formation differs in lithology from the majority of sandstones of this facies. The former is mainly medium to coarser-grained, while the latter is generally finer-grained and

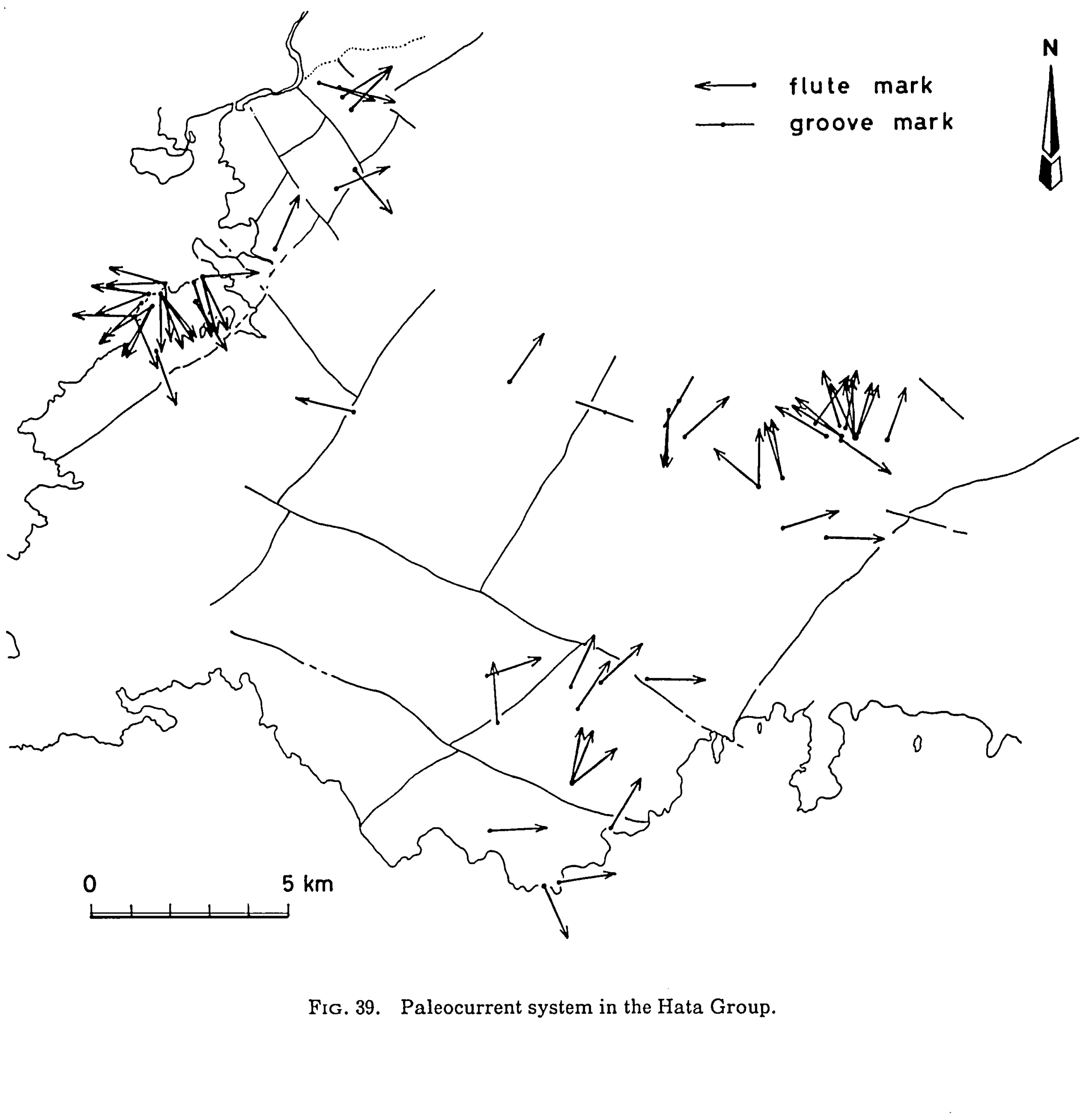


FIG. 39. Paleocurrent system in the Hata Group.

higher in mineralogical and textural maturity. These two are also differentiated in C-M diagram (Fig. 36) and paleocurrent pattern (Fig. 39) from each other.

The sedimentary process of thick-bedded sandstone in a deep-water has been discussed extensively, and is generally considered to be referred to the deposition by a kind of sedimentary gravity flows (MIDDLETON and HAMPTON, 1976): e.g. turbidity current and grain flow. However, the thick-bedded sandstone in Facies B scarcely have the characteristics of grain flow deposits designated by STAUFFER (1967). The angle of slope necessary for sustained grain flow is high. This may suggest that grain flow is a very localized process in the deep-water (RUPKE, 1978). Therefore, the thick-bedded sandstones cannot be taken for the product of deposition due to grain flow, because the sandstones occur widely in the Hata Group. This interpretation is supported by the presence of lots of scour marks and tool marks. Internally, the sandstone beds are not only poorly laminated, but commonly ungraded. These characteristic features of the sandstones resemble those of "proximal turbidites" proposed by WALKER (1967), though the sandstone is finer-grained than "proximal turbidites. Taking these respects into consideration, Facies B apparently resembles deposits of smooth suprafan lobe (WALKER , 1978) or proximal outer fan lobe in the Oligocene example of northern Apennines (GHIBAUDO , 1980). WALKER (1978, p.957)

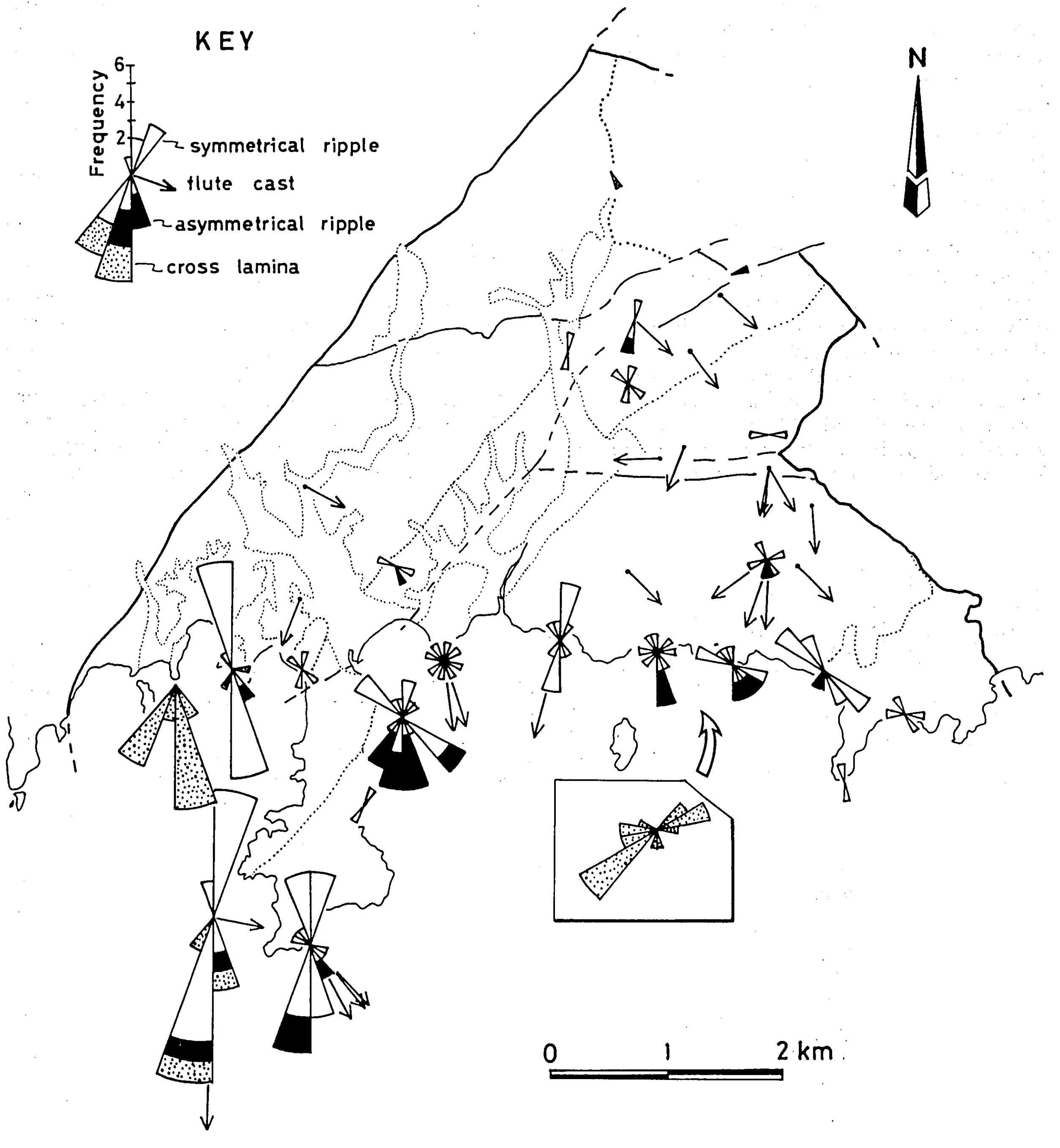


FIG. 40. Paleocurrent system in the Misaki Formation.Symmetrical ripples are plotted with bimodal directions.

mentioned that these two depositional sites are very difficult to distinguish from each other both physiographically and sedimentologically. It is questionable whether Facies B, with the exception of the Shirahama Member, is well-defined submarine fan deposits or not. This problem will be discussed later again.

d. Lobe fringe and basin plain

Facies C consists of thinly alternating beds of fine-grained sandstone and shale. Each of the sandstone beds has a sharp basal surface with scour marks or tool marks, and exhibits internally a base-missing BOUMA sequence. Therefore, Facies C is referred to the "distal turbidites" of WALKER (1967). It is also characterized by the occurrence of trace fossils such as *Nereites* and *Helminthoida* indicating deep-water condition.

MUTTI (1977) described five types of thin-bedded turbidites in the Eocene Hecho Group of the south-central Pyrenees, Spain. They are deposits of channel margin, inter-channel, central mouth, lobe fringe and basin plain. Most of Facies C in the Hata Group cannot be regarded as the first three types in terms of bedding features and associated deposits (D in Fig. 16, Figs. 17 & 18). Typical features of the lobe fringe deposits include cyclic vertical variations represented by changes in thickness of the sandstone bed and in sand/shale ratio (MUTTI, 1977). On the other hand, the basin plain deposits are characterized by the remarkable uniformity of bedding pattern both vertically and laterally (MUTTI, 1977). Judging from the above-stated criteria, Facies C in the Tsuganokawa Member and a part of the Shirahama Member (e.g. D & E in Fig. 16), as well as in a part of the Kurusuno Formation (e.g. H in Fig. 17) may correspond to the lobe fringe deposits, while the rest of the Shirahama Member and the Kurusuno Formation to the basin plain deposits. In addition to Facies C, Facies E (acidic tuff facies) in the Kurusuno Formation and most of Facies D are also regarded as the basin plain deposits.

As discussed above, the sequence of the inner fan to outer fan deposits is well preserved in the Shirahama Member of the Tatsugasako Formation. The Tsuganokawa Member of the Tatsugasako Formation and the Kurusuno Formation are lacking in the marked inner fan and mid-fan deposits. In these strata, the fan sediments may not have sufficiently developed as the result of the instability of slope due to tectonic oscillation. TOKUHASHI (1979) pointed out shortcomings of the existing submarine fan models. He mentioned that minutely investigated submarine fans are restricted to those at stable continental margins and nothing is known about an early stage of fan deposition. Basin geometry and tectonic setting are important factors which controll the facies distribution (CHAN and DOTT, 1983). Therefore, the depositional process in ancient active margins such as the Shimanto Belt should be considered from a wider viewpoint. From these the incomplete fan sedimentation of the Hata Group may be inferred. As the Tsuganokawa Member is of early Tertiary age, it may correspond to the deposits of "a preparatory stage" of fan sedimentation (TOKUHASHI, 1979) after active tectonic movement in latest Cretaceous to earliest Tertiary. On the other hand, judging from the thickness, distribution and paleocurrent direction, the Kurusuno Formation (especially the B Member) is interpreted as having been deposited in the elongate trough basin. The elongate trough geometry inhibited radial fan development (CHAN and DOTT, 1983). Additionally, gravity mass movements resulting from collapse of unstable slope may have interrupted the full fan sedi-

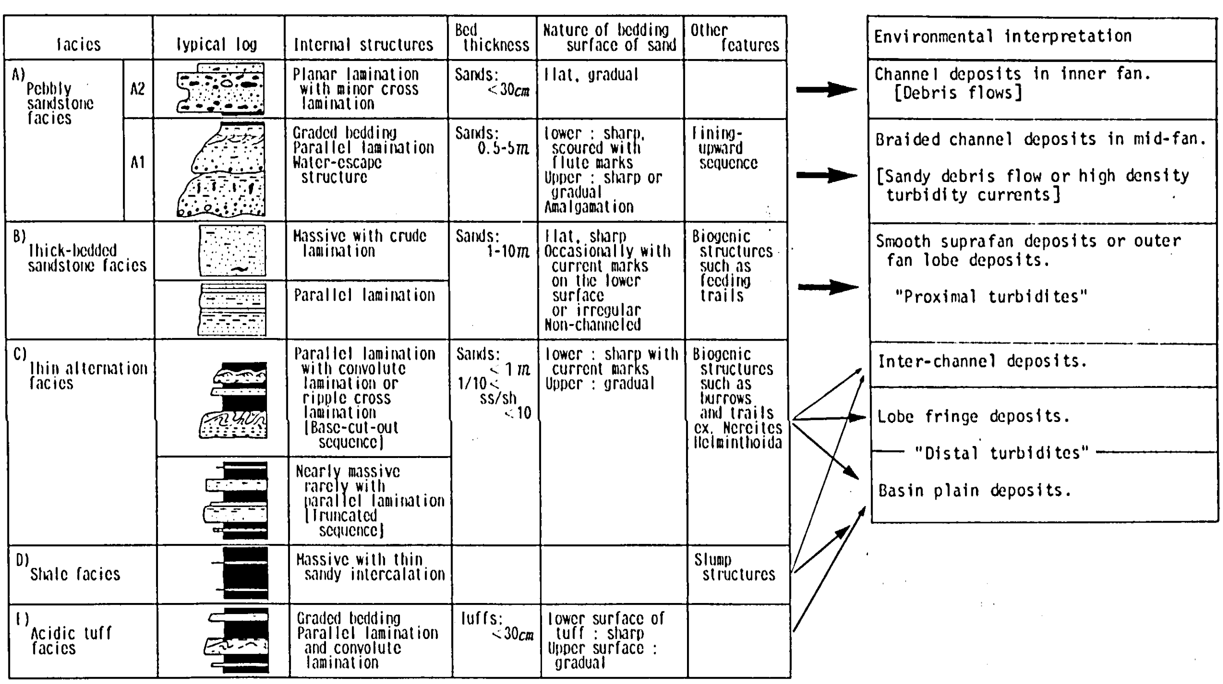


FIG. 41. Principal characteristics of the facies in the Tatsugasako and Kurusuno Formations and their environmental interpretation.

mentation and progradation. The principal charactertics and inferred depositional environments of each facies mentioned above are summarized in Fig. 41.

2. Shimizu Formation

The Shimizu Formation is considered to be an olistostrome as a whole. First, the author will guess the primary depositional environments based on the lithofacies of the main coherent beds (olistoliths), and then will refer to the secondary ones. The coherent beds are classified into three facies types: non-marine (?) type, shallow-water type and deep-water type.

a. Non-marine(?) type

Some coherent beds of the Shimizu Formation are characterized by the abundance in conglomerate. The conglomerate alternates with sandstone or mudstone, occasionally interbedded with pebbly mudstone. The non-marine(?) type consists mainly of Facies I, II and IV. Facies III and V are also partly included in this type. This type occurs in the lower half of each olistolith. It occasionally exhibits fining-upward cycles, each of which ranges from 1 to 10 m in thickness (Fig. 19), although the abrupt change from conglomerate to mudstone also takes place. The conglomerate does not show well-defined internal stratification and largely has muddy matrix. Plant remains or carbonaceous fragments are contained, but marine fossils have not been found. Fig. 42 shows the stratigraphic section of typical olistolith embracing a lot of conglomerate beds. The conglomerate and sandstone suddenly thin laterally.

From the above-mentioned features, it may be inferred that this facies type represents non-marine deposits (e.g. fluvial or deltaic deposits). Generally, fluvial deposits are characterized by fining-upward cycles (ALLEN 1964, 1970), while deltaic deposits exhibit coarsening-upward sequence. Although fining-upward cycles of small scale are present in this type, mudstone is more dominant as compared with the general fluvial deposits.

b. Shallow-water type

Facies III and IV partly belong to the shallow-water type. This type occupies the upper half of each main olistolith, overlying the conglomerate-dominated facies of the nonmarine(?) type (Fig. 10), and occasionally yields shallow-marine bivalves such as *Chlamys* sp. (s-1 in Fig. 14). BOUMA sequence is hardly applicable to the sandstone in this type. The sandstone has no characteristic sedimentary structures formed by marked current or wave effect. In these respects, this type is in striking contrast to the deep-water type, and is thought to be of low-energy, shallow-marine shelf environment.

c. Deep-water type

The deep-water type consists mostly of monotonous sequence of thinly alternating beds (Facies III), with some intercalations of pebbly mudstone (Facies V) (3 in Fig. 12, Q in Fig. 20). The alternating beds are associated with some slump folded units. No distinct thickening- or thinning-upward cycle is recognizable. The sandstone is fine- to very fine-grained, and shows features of the base-cut-out sequence or truncated sequence of BOUMA. The bed is, though thin, even and laterally well continuous. In short, Facies III of this type is similar to Facies C of the Hata Group in terms of internal sedimentary structure, grain size and bed-thickness of sandstone. In addition, it resembles Facies D of MUTTI and RICCI-LUCCHI (1972). The features described above suggest that this type corresponds to "distal turbidites" and possibly represents basin plain deposits.

In addition to the coherent beds mentioned above, the Shimizu Formation includes the following resedimented blocks and fossils, which are useful to infer the sedimentary environments:

1) Andesitic tuff breccia, andesite and basalt.
2) Acidic tuff.
3) Shallow-marine molluscs such as *Chlamys* sp., *Acila* sp.and oyster shells.
4) Larger foraminifers such as *Asterocyclina* sp.

In summary, it is concluded that many of the strata of the Shimizu Formation were originally deposited in shallow-marine (partially non-marine?) condition and subsequently transported into deep-water. At that time, they took the underlying strata as blocks in them. As a consequence, an olistostrome was formed.

3. Misaki Formation

The Misaki Formation consists mainly of shallow marine deposits, and represents a coarsening- and thickening-upward sequence as a whole. This largest-scale sedimentary cycle is considered to be attributed to progradation on the continental shelf (KATTO and TAIRA, 1979). Progressively decreasing depth of the sea is indicated by both physical and biogenic sedimentary structures observed in the formation.

It is generally known that four main currents, namely, semi-permanent currents, tidal currents, meteorological currents and density currents operate in the modern shallow marine environment (see JOHNSON, 1978). Especially, sedimentation on modern shelves is considered to be controlled either by tides or waves and storms (ANDERTON, 1976; etc.). In recent years, the importance of storm-induced process, which is effective in transporting sand in shelf environments, has come to be recognized.

Based on the sedimentological features described in the foregoing chapter, discussions on the sedimentary environments of the Misaki Formation are given below. And the principal characteristics of the facies and their environmental interpretation are summarized in Fig. 43.

a. Slope - basin plain

Many strata of the Lower Member are interpreted to have been deposited in slope to basin plain. Facies 2 is composed of mudstone with laminae of very fine-grained sandstone. It is poor in physical and biogenic sedimentary structures. This facies possibly shows the deposition under low-energy condition with no indication of marked current or wave effect. In general, offshore mudstone is characterized by intense bioturbation (HOWARD, 1972; REINECK and SINGH, 1975), but Facies 2 is lacking in this feature and does not contain carbonaceous fragments. Thus, the mudstone of Facies 2 possibly shows less oxygenated deep-water condition far off the land. Facies 2 grades upward into Facies 3, the latter of which contain some intercalated slump beds. These slump beds are attributed to gravitational movement on an unstable continental slope. Judging from the vertical transition from Facies 2 up into Facies 3, Facies 2 may be regarded as muddy basin plain or slope deposits.

Facies 1, which is exceptionally coarse facies in the Lower Member, occurs above the unconformity with a basal conglomerate. No doubt this facies is of marine origin, because it yields marine bivalves, foraminifers and radiolarians. The lateral extent of the facies is limited to about 1.2 km, and the change in thickness is fairly remarkable. Besides, the facies abuts locally on the basement rocks (Shimizu Formation) (KIMURA, 1985). From these facts, there is a possibility that Facies 1 represents channel deposits on slope to basin plain. These deposits may have been transported by a kind of debris flow. Ill sorting and bimodal grain-size distribution of the sandstone seem to be ascribed to the deposition by debris flow.

b. Offshore

Facies 3 and 4 in the Middle Member are composed of alternating beds of fine-grained sandstone and mudstone. Each of the sandstone beds is generally defined by sharp base and may have scour marks at contact with underlying bed. Some of them are similar to turbidite in appearance. Nevertheless, almost all of the sandstones are safely referred to the deposits by storm waves on the shelf rather than to turbidites in deep-water, because of the abundance in wave ripples and parallel lamination, the paucity of grading and the coexistence with bioturbated mudstone. Moreover, the presence of hummocky cross stratification strongly suggests the deposition by storm action (see next section). Sandstones of this kind have been called "storm-sand layers" by REINECK and SINGH (1972), "sublittoral sheet sandstones" by GOLDRING and BRIDGES (1973), and "storm lag deposits" by BRENNER and DAVIES (1973). These sandstones are believed to be deposited through suspension by retreating waves and ebb currents of storm surge (REINECK and SINGH, 1975; JOHNSON, 1978) and consequently may exhibit the internal structures similar to those of turbidite. The dominant parallel lamination is due to relatively high flow velocity, while ripple cross lamination and ripple marks seem to indicate lower flow velocity and oscillatory wave motion. The alternation of the sandstone of this kind and mudstone may suggest the alternation of storm and fair weather. In short, the Middle Member, which is mainly composed of Facies 3 and 4, is interpreted as offshore deposits on the storm-dominated open-shelf. Bioturbation, as well as the content of carbonaceous detritus, increases upward through the Middle Member. This may show the relative progradation.

Some of the thick-bedded sandstones in Facies 4 are dominated by tabular cross lamination with opposed flow directions (h in Fig. 25). The bidirectional currents are sub-parallel to the inferred shoreline, and then a set of oppositely dipping cross lamina can be explained as the product of ebb and flood tidal currents. The tabular cross-bedded sandstones are considered to represent sand ridges (bars or waves) in the offshore.

In the offshore facies, channel-like structures are occasionally recognized. Judging from the features mentioned in Section V-A-3, many of the structures are interpreted as slump scars rather than as erosional channels (LAIRD, 1968; CLARI and GHIBAUDO, 1979; ITO, 1985). Triggering mechanisms of slumps include many kinds of sedimentary and tectonic processes as discussed by many workers. For the generation of slump scars in the Misaki Formation, important factors were probably the impact of storm wave, earthquake and steepening due to tilting of the sea floor.

c. Shoreface

Shoreline sandstones are represented by Facies 5, which is interpreted as deposits of shoreface or offshore-shoreface transition by the following reasons.

The sandstone of Facies 5 is sometimes coarse-grained, and is characterized by the dominance of hummocky cross stratification, low-angle cross lamination and contorted bedding. The term of hummocky cross stratification was first introduced by HARMS et al. (1975), who attributed it to the oscillatory motion of storm waves. Then, hummocky cross stratification has been most commonly interpreted as an indicator of shallow marine environment affected by storm surge waves (BOURGEOIS, 1980; HUNTER and CLIFTON, 1982; DOTT and BOURGEOIS, 1982; MOUNT, 1982). In this connection, HARMS (1979) estimated that hummocky cross stratification may be formed in water 5 to 30m deep, while HUNTER and CLIFTON (1982) suggested a depth as shallow as 2m for an Eocene example in South Texas.

Each depositional unit characterized by hummocky cross stratification may represent individual storm event. The erosional base of a unit reflects onset of a major storm event, and hummocky cross stratification appears to result from scour and fill of the wave oscillation. The hummocky-bedded sandstone is succeeded by parallel-laminated and or ripple-laminated sandstone and mudstone, which were probably deposited during the waning storm period and fair weather period after the storm. In practice, some of the bedsets are lacking in this upper unit, and are often amalgamated with the overlying storm deposits. Amalgamation with successive beds provides evidence either of relatively frequent storm events or of storm events so vigorous that all fair weather deposits were scoured before the deposition of a new hummocky bed (DOTT and BOURGEOIS, 1982). An abundance of convoluted beds and contorted beds may suggest rapid deposition, and their intimate association with hummocky cross stratification strongly suggests that they were induced by storm wave impact or earthquake. Sand body greatly affected by storm wave may represent nearshore sand bar. This environmental interpretation is supported by much occurrence of Ophiomorpha, a good indicator of littoral to sublittoral shallow marine condition (KENNEDY and SELLWOOD, 1970; DIKE, 1972; HOWARD, 1972; FREY et al., 1978).

d. Upper shoreface - foreshore

Facies 5 gradually changes upward into Facies 6 (K in Fig.28), the latter of which is characterized by coarse-grained to pebbly sandstone exhibiting large-scale trough cross lamination and tabular cross lamination. Such cross laminations predominantly dip toward the sea (Fig. 40). The mode of occurrence of pebbles suggests that the pebbly sandstone is not simply lag deposits. The arrangement of pebbles along different lamina indicates that the pebbles were transported by bed load movement on the sand waves or dunes. The concentration of pebbles in the middle part of the sandstone bed probably indicates segregation in the wave breaker-zone. The less roundness than in Facies 5 suggests that the pebbles supplied by fluvial action were not much worn by waves on the beach.

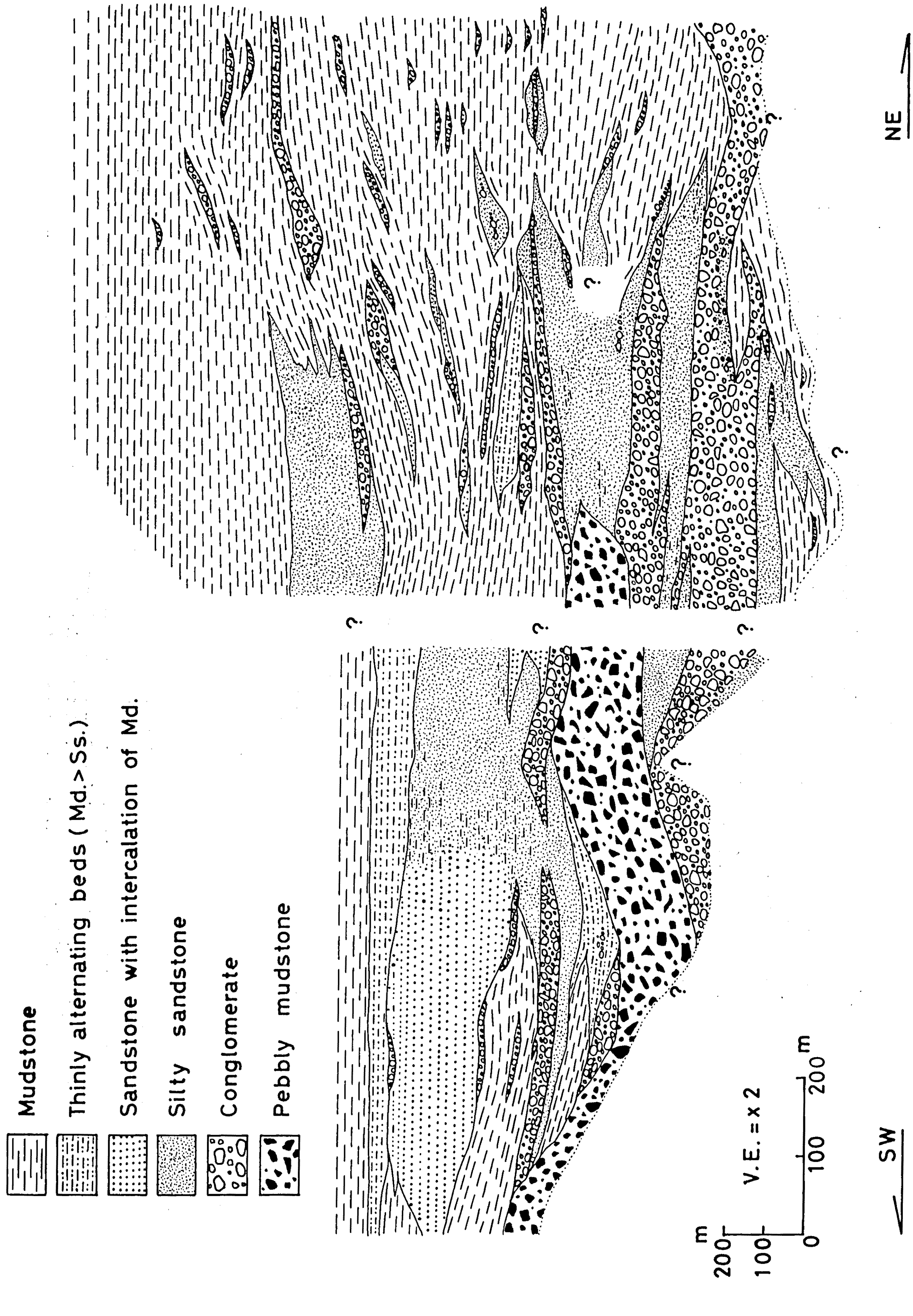


FIG. 42. Lithologic cross-profile showing the lateral variation of lithology of the coherent beds in the Shimizu Formation.

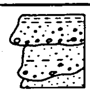
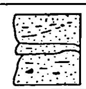
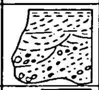
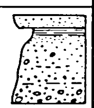
Facies	Typical log	Grain size	Internal structures	Biogenic structures	Bed thickness	Nature of bedding surface of sands	Other features	Environmental interpretation
9		Medium to coarse sand with pebble.	Massive or, rarely, grading and parallel lamination.	None.	Sands: 1-5 m or more.	Flat or undulous. Lower: usually erosional.	Mud clast. Carbonaceous detritus.	Fluvial deposits.
8		Fine sand occasionally with mudstone clast.	Massive or crude lamination with minor gently-inclined planar lamination.	None.	Sands: 2-10 m or more.	Low-angle discordance.	Carbonaceous detritus.	Beach sand. Washover fan deposits.
7		Clay to silt interbedded with very fine sand.	Massive with minor parallel lamination.	None.	Sands: <30 cm. Muds: 0.2-3 m.	Flat. Non-erosional.	Pseudo-pebble & -nodule. Abundant carbonaceous detritus.	Coastal marsh or lagoon deposits.
6		Fine to very coarse sand with pebble.	Large-scale trough and tabular cross laminations with minor planar lamination.	Rare.	Sands: >2 m.	Lower: channeled. Amalgamation.		Sand dunes or waves in upper shoreface to foreshore.
5		Fine to medium sand interbedded with clay to silt. Occasional pebble.	Low-angle cross lamination, HCS and parallel lamination with minor ripple cross lamination and trough cross lamination.	Burrow and bioturbation. ex. *Ophiomorpha*	Sands: 0.5-10 m or more.	Lower: erosional. Upper: flat, either erosional or gradual. Amalgamation.	Convolution Concretion. Streaks of coal. Mud clast.	Nearshore sand bars in shoreface, preserved especially during storms.
4		Fine sand interbedded with clay to silt.	Parallel lamination and ripple cross lamination with minor low-angle cross lamination, HCS and tabular cross lamination.	Trail and burrow. ex. *Nankaites* *Thalassinoides*	Sands: 10-100 cm. md < ss.	Lower: sharp occasionally with flutes. Upper: sharp or gradual with minor ripples.	Contorted bedding, ball and pillow structure. Oyster.	Offshore storm-sand layers interbedded with offshore mud. Offshore sand waves with tidal reworking.
3		Fine sand interbedded with clay to silt.	Parallel, wavy & flaser laminations with ripple cross lamination (partly climbing ripple lamination).	Burrow and trail (D-type). Intensive bioturbation.	Sands: 1-50 cm. md > ss.	Lower: sharp occasionally with flutes. Upper: sharp or gradual usually with ripples.	Slump fold.	Offshore mud with "distal" storm-sand layers. Inter-bar mud.
2		Silt to clay with minor very fine to fine sand.	Massive or parallel lamination with minor ripple cross lamination.	None.	Sands: 1-30 mm.	Flat, wavy or lenticular.		Slope to basin plain mud.
1		Pebble to silty sand interbedded with clay.	Massive or crude parallel lamination with minor cross lamination.	Burrow and trail.	Sands: 0.2-5 m.	Flat, usually non-erosional.	Molluscs, foraminifers & radiolarians.	Feeder channel deposits on slope to basin plain.

FIG. 43. Principal characteristics of the facies in the Misaki Formation and their environmental interpretation.

On the other hand, the parallel-laminated, fine-grained sandstone in Facies 6 may have been produced by swash-backwash wave process on the foreshore.

From the above-stated facts, it appears that Facies 6 is referable to the deposits in upper shoreface to foreshore. The seaward inclination of cross lamination may be interpreted as a result of rip currents (MAEJIMA, 1983) or ebb currents of storm surge.

e. Beach - supratidal complex

The upper half of the Upper Member consists of Facies 7, 8 and 9, which are alternately accumulated. They are probably referred to beach to supratidal (partly fluvial) deposits, though there is no conclusive evidence. No distinct eolian dune deposits are recognized in the beach facies of the Misaki Formation. This may be due to the collapse by frequent storm events. Biogenic structures are hardly recognizable throughout these facies.

Facies 7 is composed of massive or laminated, carbonaceous mudstone and siltstone containing pseudonodules of ore minerals. Such fine-grained sediments near the beach may represent lagoon or marsh sediments. The interbedded pebbly sandstones in Facies 7 (k in Fig. 28) may be regarded as washover fan deposits which were eroded from the beach by storm surge and were deposited on the lagoon or marsh.

Facies 8 consists of well-sorted, fine-grained sandstone, and has some characteristics similar to beach deposits. In modern beach deposits, seaward-inclined planar bedding with low-angle discordance is commonly known (CLIFTON et al., 1971; REINECK and SINGH, 1975). Unfortunately, it is difficult to identify the exact dip direction of lamination and discordance in the Misaki Formation.

Some sandstones of Facies 9 may be assigned to fluvial deposits. Locally concentrated pebbles near the basal surface, though the erosional base is not remarkable, are presumed to represent channel lags. The pebbly sandstone of Facies 9 often grades upward into the fine-grained sandstone, which is in turn overlain by mudstone (l in Fig. 28). Such small-scale fining-upward cycles (each cycle being less than 10m in thickness) are thought to have been caused by lateral migration of channels: filling and abandonment.

As mentioned above, the deposition of the Misaki Formation is well conformable to the shallow-marine depositional model. In conclusion, it is considered that the formation was probably deposited in an environment dominated by periodic storm-generated wave activity and subjected to tidal currents. The formation shows a progradational succession as a whole. Progradation may have repeated advance and retreat, because of subsidence or oversteepening due to tilting of the sea floor. The inferred sedimentary environments and processes of the Misaki Formation are schematically illustrated in Fig. 44.

B. DEPOSITIONAL HISTORY

The progress of geologic studies has brought about more attractive conception of sedimentation and tectonics on ancient active margins. In modern continental margins, the varied configurations of arc-trench system are believed to arise mainly from differences in structural evolution due to plate movement (e.g. DICKINSON and SEELY, 1979). Several memorable studies (KANMERA and SAKAI, 1975; TAIRA et al., 1980; etc.) have revealed that the Shimanto sedimentary sequence is comparable to the accretionary complex in the subduction zone. In this section, the author tries to reconstruct the depositional history, paying attention to these studies. The developmental process of the Tertiary basin in the surveyed area is divided into four stages mainly based on the stratigraphic and sedimentological results.

1. Eocene

In this stage, main depositional setting can be divided into three based on lithologic features: shelf, continental slope to forearc basin and trench inner slope to trench. The Hirata Formation, which occupies the northernmost region, is characterized by the occurrence of shallow-marine molluscs. Glauconite-bearing sandstones are also associated (KATTO, 1952; TAIRA et al., 1980). From these characteristics, the formation can be referred to shallow-marine shelf deposits. On the other hand, turbidites, which are well developed in the lower Tatsugasako and Kurusuno Formations, were accumulated in the continental slope to forearc basin. It is questionable whether these turbidites formed well-defined submarine fan or not. The sediments may have spilled or cascaded into deep-sea floor across a shelf edge rather than from a submarine canyon (CHAN and DOTT, 1983). The longitudinal paleocurrents are mainly from the southwest to the northeast and the lateral ones from the northwest to the southeast. With the most possibility, it is inferred that terrigenous materials were derived largely from the older sedimentary rocks of the Shimanto Supergroup on the north.

The Hiromi Formation consists of intensively sheared chaotic beds (sand-mud mixed facies), associated with greenstones and red shales. There is no doubt that the greenstones and red shales are of oceanic origin. Especially, the red shales are referred to pelagic sediments (SAITO and TANAKA, 1983). Their occurrence is suggestive of "melange" (TAIRA et al., 1980). The sandstones of the Hiromi Formation, which are regarded as blocks, can be clearly differentiated in mineral composition from those of the other formations of the Hata Group (see Figs. 29 & 30), having a mineral composition of the Cretaceous-type of some workers (TERAOKA, 1979; KUMON, 1983; etc.). Therefore, it may be inferred that the sandstone blocks in the Hiromi Formation were derived from the Cretaceous strata of the Shimanto Supergroup. Judging from the existence of pelagic sediments and pillow basalts, they are not likely to have been immediately derived from land, but from outer ridge such as trench slope break of DICKINSON (1973) and DICKINSON and SEELY (1979). It appears that the Hiromi Formation was formed as the result of mixing and deforming of terrigenous materials and oceanic materials in the vicinity of trench inner slope to trench.

2. Late Eocene — Early Oligocene

Entering into this stage, the sedimentation of the Hirata and Hiromi Formations seems to have been over. However, the Tatsugasako and Kurusuno Formations actively continued the deposition on the forearc basin. Judging from the paleocurrents and facies associations, the main depositional basins of the upper

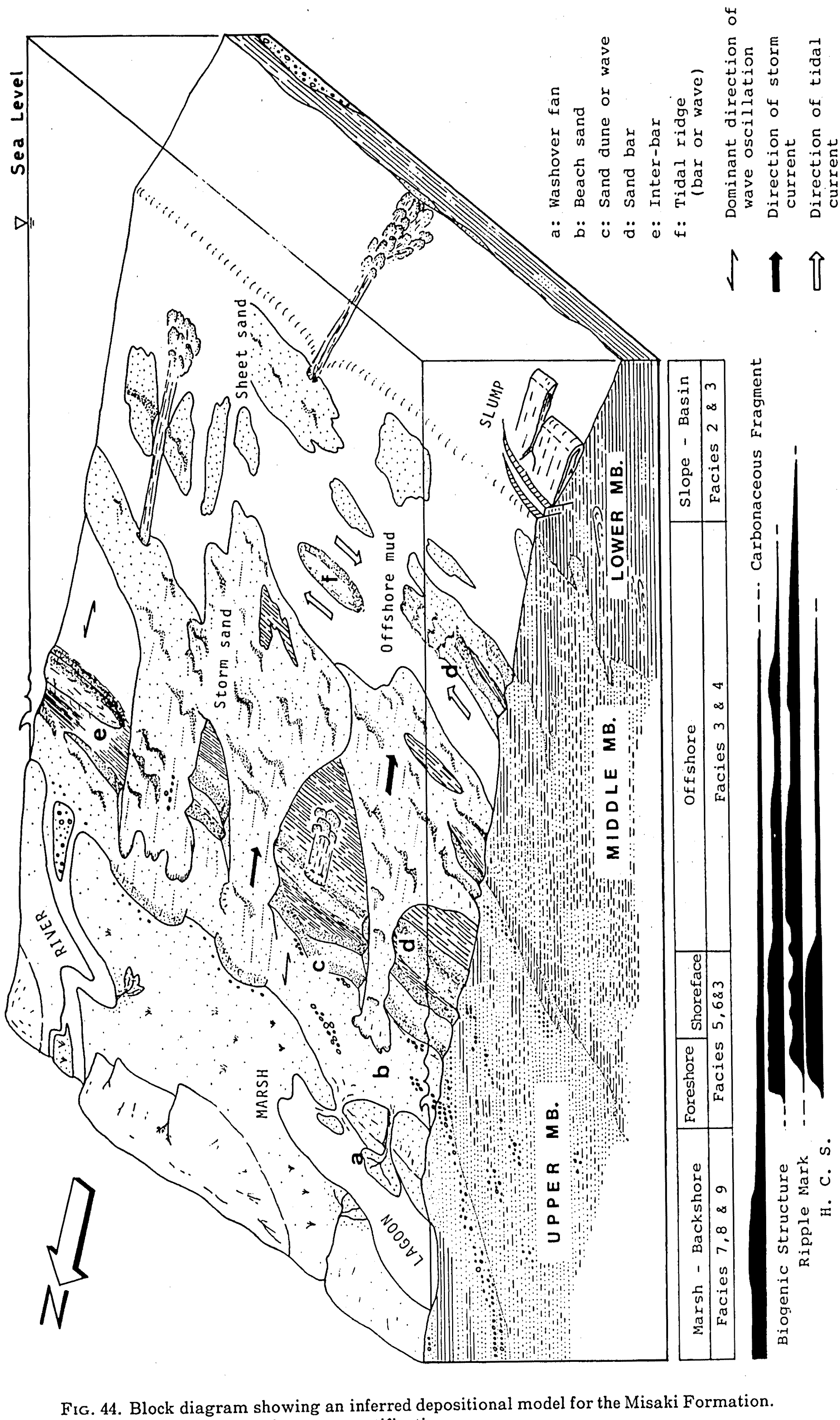


FIG. 44. Block diagram showing an inferred depositional model for the Misaki Formation. H.C.S. = hummocky cross stratification.

Tatsugasako and Kurusuno Formations were probably separated from each other by some outer ridge. In the northern region, the turbidite fan represented by the Shirahama Member of the Tatsugasako Formation was well developed from the continental slope to the inner forearc basin. The sandstones here are less-matured both texturally and mineralogically than those of the Kurusuno Formation. The Shirahama Member is, therefore, thought to have been deposited in a basin nearer to the source land. The lateral and longitudinal paleocurrents show that clastic materials were mainly transported from the northern region.

On the other hand, the turbidite sandstones of the Kurusuno Formation are finer-grained and better-matured. As discussed in the foregoing section, no well-defined submarine fan may have been formed in the sedimentary basin of the formation. The longitudinal paleocurrents are mainly from the southwest and the lateral ones from the southeast or south. It may be inferred that the above-mentioned outer ridge played a role of a barrier between the two depositional basins of the Tatsugasako and Kurusuno Formations. Taking juxtaposition of the formations into consideration, the Hiromi Formation may have been already accreted below the outer ridge in this stage. The chaotic beds interbedded in the turbidite facies of the Kurusuno Formation seem to be the product resulting from rock-fall or sliding in the vicinity of the outer ridge. The paleocurrents from the south suggest that the upheaval zone exsisted also on the south of the main depositional basin. This upheaval zone is possibly represented by outer ridge or trench slope break rather than by the Kuroshio Paleoland of KISHU SHIMANTO RESEARCH GROUP (1968, 1975), because clastic materials derived from the continental crust such as granitic rocks are lacking in the Kurusuno Formation.

3. Late Oligocene — Earliest Miocene

After the Hata Group had been deposited, the main depositional basin migrated southward. In the newly constructed basin, the original sediments of the Shimizu Formation were accumulated. They are mainly of shallow-water environment and partly of fluvial or deltaic environment. Distal turbidites under deep-water are also locally preserved. Morphology of the depositional basin and paleocurrent systems still remain unknown, because the sediments are scarcely left as autochthonous ones. As discussed by SAKAI (1985), the morphology of a forearc slope may have changed in this stage (ca. 30 Ma).

Subsequently, the original sediments of the Shimizu Formation were transferred into the deeper water by gravity mass movement. Thus, the olistostrome was formed. At that time, a part of the underlying strata (e.g. the Kurusuno Formation) was also emplaced in the olistostrome as olistoliths. The gravity mass movement may have been caused by change of condition of forearc slope due to abrupt change of plate boundary: switchover from transform boundary to convergent boundary (SAKAI, 1985). After forming the olistostrome in the outermost region, the sedimentation of the Shimanto Supergroup was finished. The Paleogene strata may have suffered major tectonic deformation in this stage. A system of NE-SW-trending folds characteristic of the Kurusuno Formation is not recognizable in the Miocene Misaki Formation.

4. late Early Miocene — Middle Miocene

In the late Early Miocene, the Misaki Formation, which is composed of shallow-marine sequence, began to be deposited, resting unconformably upon the Shimanto Supergroup. The Lower Member of the formation is composed of fine-grained deposits of the offshore to basin plain and the basal conglomerate is by no means remarkable. These facts strongly suggest that the unconformity was at least partially formed under the submarine environment. The sedimentary environments and processes of the Misaki Formation were fully discussed in the foregoing section. The sedimentary basin gradually became shallower by the progradational process on the shelf. Clastic materials were predominantly derived from the Shimanto Supergroup lying to the north. A very thick pile of the Misaki Formation (about 3,000 m thick) was accumulated rapidly during 4 to 5 m.y. or less. It can be stated that the uplift and erosion of the Paleogene Shimanto sequence caused sediment supply to fill the Miocene sedimentary basin. In addition, storm-wave energy was sufficient to produce sediment transport and deposition across the shelf. The depositional model is schematically illustrated in Fig. 45.

The sedimentary and tectonic gap comparable to that between the Shimizu Formation and the Misaki Formation has been recognized widely from Kyushu to the Kanto region. This gap in early Miocene time corresponds to the main phase of the "Takachiho disturbance" of SHUTO (1963), one of the remarkable geologic events in Tertiary time in Southwest Japan. In the final stage of the Shimanto "geosynclinal" deposition preceding the disturbance, an olistostrome was formed extensively in the outer margin of the Shimanto Belt (KANMERA, 1977; HISATOMI et al., 1980; SUGIYAMA, 1980; SAKAI, 1981; OGAWA, 1982). Furthermore, the Paleogene subduction complex is developed on the inner side of the olistostrome zone in Kyushu (SAKAI and KANMERA, 1980; SAKAI, 1985). SAKAI (1983, 1985) discussed the significance of such a series of events in connection with the developmental process of the Philippine Sea plate. The Philippine Sea had begun to spread at 30 Ma and had been opening until 17 Ma (KOBAYASHI and NAKADA, 1978; etc.). Such motion changed the plate boundary in the outer margin of Southwest Japan, and seems to have resulted in varying the slope morphology of forearc region. Different sedimentary units in the Shimanto Belt seem to have been formed in accordance with the plate motion.

In the investigated area, there are few sedimentary units corresponding to an accretionary wedge (only a part of the Hiromi Formation), and the imbricate structure, which is common in accretionary complex, is not so much developed. It appears that either extensive accretion did not occur during Paleogene time or the strata overlying the main accretionary complex widely crop out in southwestern Shikoku. This assumption is greatly supported by the absence of well-defined trench deposits. As respects the Miocene shallow-marine sequence, the Misaki Formation is poorer in fine facies in comparison with the Kumano and Tanabe Groups in the Kii Peninsula. Especially, it lacks the remarkable turbidite facies. In other words,

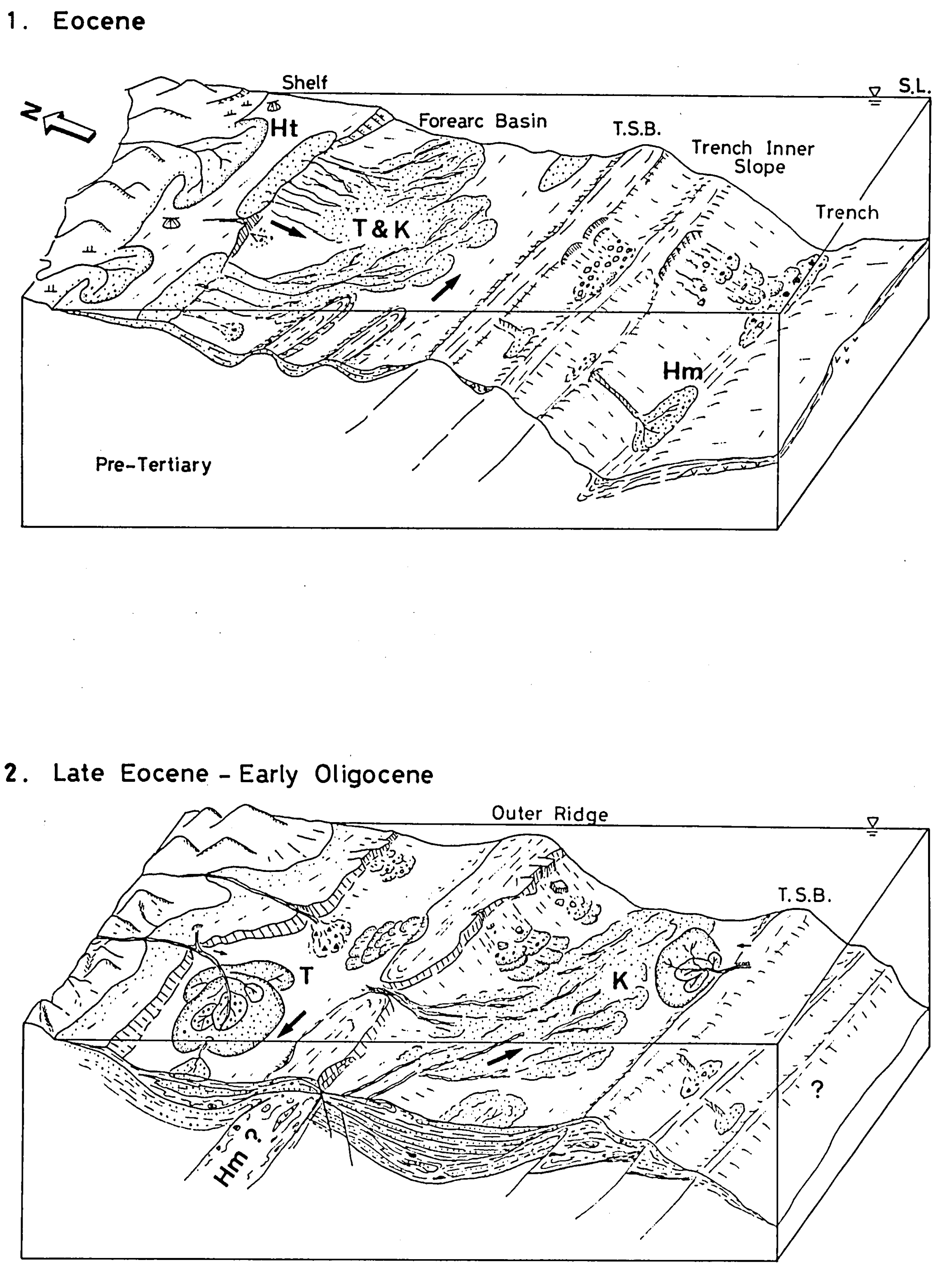
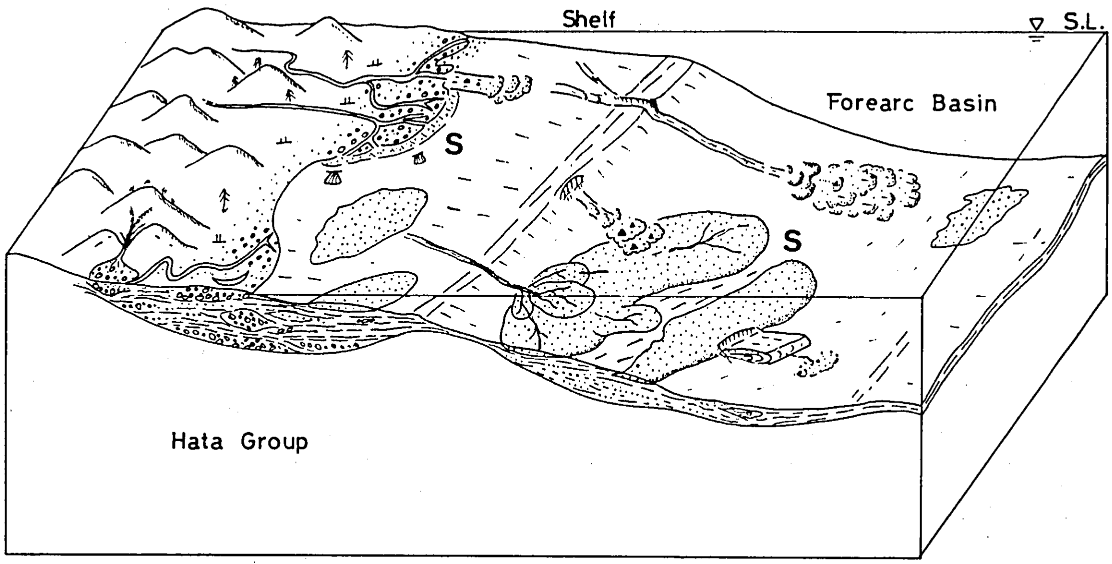
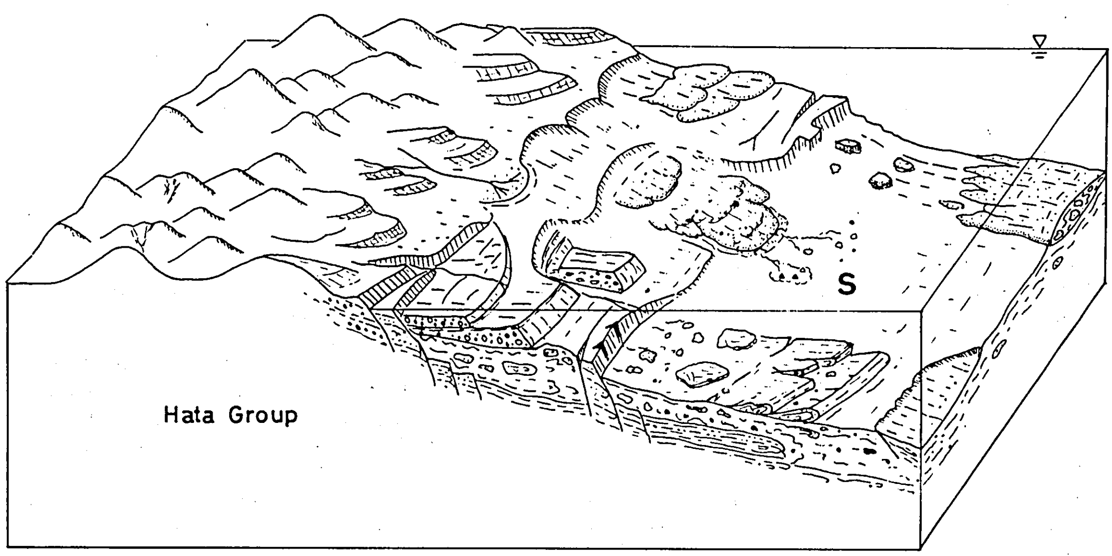


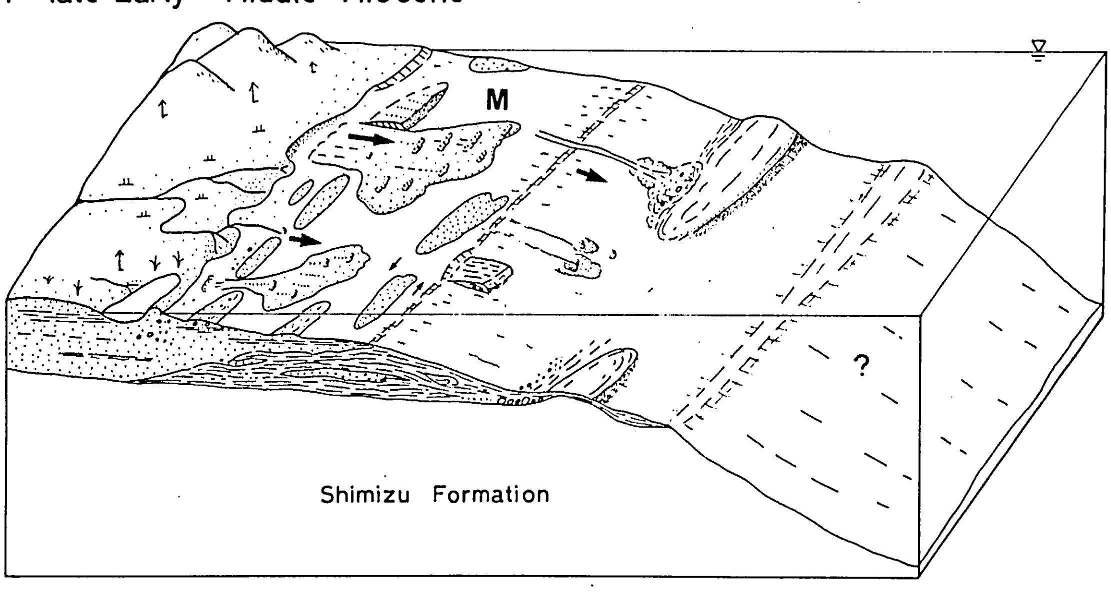
FIG. 45. Schematic block diagrams showing the depositional history in Tertiary time in and around the studied area.
T.S.B.=trench slope break, Ht=Hirata Fm., Hm=Hiromi Fm., T=Tatsugasako Fm., K=Kurusuno Fm.,S=Shimizu Fm., M=Misaki Fm. Arrows indicate the dominant direction of paleocurrents.

3. Late Oligocene - Earliest Miocene





4. late Early - Middle Miocene



deep-water facies is poorly developed in the Misaki Formation. In farther west region, the Miocene Iorigawa Formation in Kyushu is mostly composed of conglomerate and includes no obvious marine deposits (HASHIMOTO and MIYAHISA, 1959). These facts show peculiarity of individual region in sedimentation and geotectonics. Further detailed study will lead to a better understanding of the geologic development.

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TABLE 3. QUANTITATIVE DATA ON MAJOR MINERAL COMPOSITION OF SANDSTONES (IN).

Formation	Specimen	Quartz	Feldspar			Rock Fragments			Matrix
			K-f.	Pl.	Total	Ig.	Oth.	Total	
Hiromi Formation	FR- 1	21.6	4.7	31.8	36.6	7.1	8.4	15.5	26.5
	HT- 3	16.6	10.1	21.7	31.8	6.9	5.7	12.6	39.0
	HT- 4	29.6	12.0	20.8	32.8	4.5	5.3	9.8	27.7
	HT- 5	20.8	6.1	28.5	34.6	2.7	5.9	8.6	36.0
	HT- 6	25.5	17.3	21.0	38.3	1.9	8.0	9.9	26.4
	HT- 7	38.1	13.0	16.2	29.2	4.2	19.8	23.6	9.1
	HT- 9	18.1	10.9	27.3	38.2	2.2	3.9	6.1	37.6
	HT-10	29.5	6.8	7.8	14.6	10.4	5.3	15.7	40.2
	HT-11	34.7	15.7	10.6	26.3	13.9	9.6	23.5	20.4
	HT-12	19.4	14.1	15.1	29.2	3.1	5.2	8.3	43.2
	HT-14	19.4	8.5	26.0	35.4	3.7	5.1	8.8	37.4
	IY- 1	26.2	9.5	33.4	42.8	8.2	8.3	16.5	14.5
	IY- 3	20.9	8.2	25.4	33.6	7.1	6.4	13.5	32.1
	IY- 4	23.2	10.0	22.9	32.9	4.7	4.6	9.3	34.6
	IY- 9	26.6	10.6	22.4	33.0	8.2	7.0	15.2	25.3
	IY-11	22.0	12.1	29.3	41.4	7.9	3.9	11.8	24.8
	IY-21	31.4	4.3	27.9	32.2	2.8	8.4	11.2	25.3
	IY-23	31.1	24.3	21.1	45.4	4.1	4.2	8.3	15.2
	IY-24	33.3	6.5	21.7	28.8	7.6	5.8	13.4	25.2
	IY-25	50.2	6.8	24.0	30.8	3.4	6.4	9.8	9.2
	IY-26	40.3	8.1	21.4	29.5	2.5	4.5	7.0	23.3
	IY-27	19.2	5.7	11.8	17.5	6.4	7.5	13.9	49.4
	IY-28	30.1	15.6	15.1	30.7	4.0	6.3	10.3	28.9
	IY-29	27.5	9.5	17.1	26.6	4.1	6.6	10.7	35.2
	KR- 2	18.3	19.8	17.5	37.3	4.0	4.0	8.0	36.5
	KR- 3	31.3	17.2	11.3	28.5	3.4	10.4	13.8	26.5
	KR- 4	17.3	4.1	32.2	36.3	6.1	8.3	14.4	32.1
	TG-12	25.6	0.1	34.6	34.7	+	1.7	1.7	38.0
	TG-13	54.2	5.1	17.0	22.5	1.1	5.0	6.1	17.3
	TG-14	50.3	-	17.2	17.2	3.6	6.4	10.0	22.5
	TG-19	13.0	5.6	25.8	31.5	4.2	5.0	9.2	46.4
	(Ave.)	27.9	9.7	21.8	31.6	4.9	6.5	11.5	29.1

Formation	Specimen	Quartz	Feldspar			Rock Fragments			Matrix
			K-f.	Pl.	Total	Ig.	Oth.	Total	
Tatsugasako Formation	AR- 1	40.6	11.0	17.6	28.6	3.2	4.1	7.3	23.5
	AR- 6	42.7	5.7	20.6	26.4	1.4	4.7	6.1	24.8
	AR-12	40.3	-	26.8	26.8	3.3	11.2	14.5	18.5
	AR-15	29.5	0.4	27.5	27.8	1.8	9.2	11.0	31.7
	AR-16	31.9	3.6	20.5	24.1	3.8	15.0	18.8	25.2
	AR-17	39.6	0.4	21.9	22.3	0.2	4.8	5.0	33.1
	AR-18	28.4	8.8	18.9	27.7	0.4	2.0	2.4	41.6
	AR-19	30.9	10.7	19.4	30.1	0.6	8.4	9.0	30.0
	HT-15	35.5	10.8	22.2	33.0	4.3	7.6	11.9	19.6
	HT-16	38.1	6.8	21.6	28.5	2.3	8.1	10.4	23.1
	IY-22	36.7	15.4	12.0	27.3	5.3	9.0	14.3	21.6
	KT- 2	38.8	9.0	19.3	28.3	0.7	2.9	3.6	29.4
	MI- 2	42.1	13.5	18.8	32.3	0.8	7.9	8.7	16.9
	MI- 4	40.5	2.0	22.5	24.5	0.4	5.6	6.0	28.9
	OM- 3	28.9	9.3	27.7	36.5	4.8	3.1	7.9	26.7
	OM- 7	20.7	9.5	18.3	27.7	8.0	11.5	19.5	32.1
	SK- 2	25.8	13.9	33.5	47.4	3.1	4.6	7.7	19.1
	SK- 3	30.1	9.4	31.8	41.2	5.0	6.6	11.6	17.1
	SK-10	25.0	11.6	30.1	41.7	4.7	4.8	9.5	23.8
	TA- 2	40.9	1.3	18.1	19.4	0.6	5.1	5.7	34.0
	TA- 3	25.6	2.7	21.2	23.9	1.4	7.3	8.7	41.8
	TA- 5	31.0	2.0	24.5	26.5	0.6	7.7	8.3	34.3
	TG- 1	26.4	4.7	27.6	32.3	0.8	5.0	5.8	35.6
	TG- 3	31.6	4.5	27.4	31.8	0.7	2.9	3.6	33.1
	TG- 5	35.1	-	23.9	23.9	0.5	5.0	5.5	35.6
	TG- 8	46.2	1.0	23.0	24.0	1.6	13.3	14.9	14.9
	TG- 9	39.9	0.2	24.3	24.5	0.3	4.9	5.2	30.5
	TG-20	28.3	13.9	14.6	28.6	0.6	15.8	16.4	26.8
	TG-22	40.4	11.8	10.6	22.4	1.1	5.3	6.4	30.9
	TG-24	36.2	10.9	25.2	36.1	2.0	7.7	9.7	18.0
	TH- 2	27.1	2.3	22.1	24.4	0.5	5.4	5.9	42.6
	TH- 3	29.0	17.2	29.3	46.5	1.8	3.1	4.9	19.6
	TH- 5	16.5	15.5	16.7	32.2	5.0	32.2	37.2	14.2
	TH- 6	37.4	9.2	19.8	29.0	1.4	4.2	5.6	28.0

Formation	Specimen	Quartz	Feldspar			Rock Fragments			Matrix
			K-f.	Pl.	Total	Ig.	Oth.	Total	
Tatsugasako Fm.	TH- 7	52.0	4.2	7.0	11.1	0.5	4.3	4.8	32.1
	TH-13	46.3	8.5	19.4	27.8	1.1	3.5	4.6	21.3
	TH-16	30.3	0.1	33.5	33.6	1.3	3.6	4.9	31.3
	YZ- 1	44.9	4.4	21.7	26.1	0.5	6.3	6.8	22.2
	YZ- 2	36.3	2.9	25.2	28.1	1.0	3.7	4.7	30.9
	YZ- 5	33.9	3.6	26.4	29.9	0.4	2.2	2.2	33.6
	YZ- 7	29.5	7.1	24.6	31.6	1.2	8.4	9.6	29.4
	(Ave.)	34.4	6.8	22.3	29.2	1.9	7.0	8.9	27.5
Kurusuno Formation	DA- 1	38.5	4.4	32.9	37.3	0.4	3.0	3.4	20.8
	DA- 2	43.7	1.9	19.9	21.8	0.3	6.2	6.5	28.0
	DA- 3	37.5	8.9	24.5	33.4	0.4	2.8	3.2	25.9
	DA- 5	38.5	6.8	23.6	30.4	0.1	2.2	2.3	28.8
	DA- 6	34.0	7.1	30.9	38.0	0.1	2.4	2.5	25.5
	DA- 8	40.6	5.5	23.8	29.3	-	4.2	4.2	25.9
	DA-12	39.1	9.2	24.4	33.6	-	3.1	3.1	24.2
	DA-13	39.9	8.7	27.7	35.9	0.5	2.8	3.3	20.9
	DA-14	47.9	6.6	16.5	23.1	0.2	3.1	3.3	25.7
	DA-15	30.9	6.9	26.7	33.6	0.5	7.1	7.6	28.3
	DA-16	45.2	6.3	15.7	22.0	0.2	3.8	4.0	28.8
	FI- 4	41.5	2.2	21.7	23.9	0.3	4.9	5.2	29.4
	FI- 7	41.4	13.1	20.8	33.9	0.6	3.2	3.8	20.9
	FI- 9	39.9	6.5	34.4	40.9	0.3	2.3	2.6	16.6
	FI-10	32.3	4.5	30.4	34.9	1.3	7.8	9.1	23.7
	FI-11	42.1	6.1	22.1	28.2	0.1	3.7	3.8	25.9
	FI-12	37.4	6.5	27.7	34.2	0.4	3.3	3.7	24.7
	FI-13	39.3	9.4	31.4	40.8	0.3	3.4	3.7	16.2
	FI-15	48.5	4.4	18.8	23.2	0.3	5.2	5.5	22.8
	FI-17	30.7	1.9	28.6	30.5	0.2	6.6	6.8	32.0
	FI-19	43.1	-	21.5	21.5	0.1	2.4	2.5	32.9
	FI-20	34.0	6.6	29.5	36.1	0.2	3.1	3.3	26.6
	HM- 9	39.9	11.9	28.0	39.9	0.2	5.1	5.3	14.9
	HM-10	47.9	9.0	22.8	31.8	0.9	2.8	3.7	16.6
	IH- 1	38.3	6.0	26.7	32.7	0.4	4.1	4.5	24.5

Formation	Specimen	Quartz	Feldspar			Rock Fragments			Matrix
			K-f.	Pl.	Total	Ig.	Oth.	Total	
Kurusuno Formation	IH- 4	38.3	9.3	24.9	34.2	-	4.2	4.2	23.3
	IH- 8	33.7	7.4	31.1	38.5	0.1	3.1	3.2	24.6
	IH- 9	40.0	5.6	22.8	28.4	-	2.8	2.8	28.8
	IH-10	36.5	1.4	35.9	37.3	-	3.2	3.2	23.0
	IH-13	41.4	7.5	24.6	32.1	-	7.0	7.0	19.5
	IH-14	38.1	2.3	24.3	26.6	-	3.4	3.4	31.9
	IH-15	34.7	4.8	31.9	36.7	-	3.2	3.2	25.4
	IH-16	43.6	10.3	21.9	32.2	-	2.7	2.7	21.5
	IH-17	28.4	4.3	27.6	31.9	-	3.8	3.8	35.9
	KK- 1	43.4	5.1	20.1	25.2	0.2	2.4	2.6	28.8
	KK- 2	42.7	-	34.8	34.8	-	1.2	1.2	21.3
	KK- 3	49.3	3.9	23.1	27.0	0.5	2.0	2.5	21.2
	KK- 4	47.8	5.4	25.3	30.0	-	1.3	1.3	20.2
	KK- 5	41.9	8.3	23.7	32.0	0.4	0.8	1.2	24.9
	KK- 6	50.5	3.3	26.0	29.3	0.1	0.1	0.2	20.0
	KK- 8	42.2	0.5	27.5	28.0	-	0.2	0.2	29.6
	KK- 9	43.8	-	29.1	29.1	-	0.6	0.6	26.5
	KK-11	42.8	4.3	22.5	26.8	0.2	1.4	1.6	28.8
	KK-13	48.9	3.4	18.2	21.6	-	2.0	2.0	27.5
	KK-15	52.3	4.1	14.6	18.7	0.4	3.4	3.8	25.2
	KK-19	48.8	3.7	21.2	24.9	-	3.6	3.6	22.7
	KK-20	47.4	5.3	18.9	24.6	0.1	3.7	3.8	24.2
	KK-30	52.9	5.1	10.0	15.1	0.3	5.0	5.3	26.7
	KK-36	42.0	5.3	22.3	27.6	0.1	2.1	2.2	28.2
	KK-39	43.5	7.2	21.9	29.1	0.1	3.0	3.1	24.3
	KK-40	46.1	6.0	19.5	25.5	0.4	5.1	5.5	22.9
	KK-41	47.8	8.3	21.9	30.2	0.3	4.6	4.9	17.1
	KK-42	36.2	2.1	20.9	23.0	1.0	9.5	10.5	30.3
	KK-43	38.6	8.5	24.1	32.6	0.3	1.3	1.6	27.2
	KK-44	42.7	4.7	16.2	20.9	0.1	2.4	2.5	33.9
	KK-45	44.3	4.0	23.6	27.6	-	3.0	3.0	25.1
	KK-46	45.5	3.7	23.5	27.2	0.2	3.3	3.5	23.8
	KK-47	45.5	7.2	18.8	26.0	0.5	4.6	5.1	23.4
	KK-48	53.7	-	17.9	17.9	0.5	6.1	6.6	21.8

TABLE 3. (CONTINUED)

	Specimen	Quartz	Feldspar			Rock Fragments			Matrix
			K-f.	Pl.	Total	Ig.	Oth.	Total	
Kurusuno Formation	KK-49	37.3	3.2	26.9	30.1	0.5	4.8	5.3	27.3
	KK-50	45.3	5.7	19.5	25.2	0.3	5.2	5.5	24.0
	KK-53	49.6	5.6	18.8	24.4	0.4	4.7	5.1	20.9
	KK-55	42.2	2.6	29.1	31.7	0.1	3.4	3.5	22.6
	KK-57	43.4	7.5	28.9	36.4	-	2.4	2.4	17.8
	MK- 1	28.6	2.0	33.5	35.5	-	3.0	3.0	29.9
	MK- 2	49.6	10.0	19.0	29.0	0.1	3.4	3.4	17.9
	MK- 6	51.6	12.3	14.8	27.1	0.6	2.1	2.7	18.6
	MK- 7	45.4	1.0	24.7	25.7	0.1	1.8	1.9	27.0
	MK- 8	45.8	0.1	32.4	32.5	-	0.6	0.6	21.1
	MK-16	48.6	-	24.3	24.3	0.4	1.7	2.1	25.0
	MK-17	47.5	7.4	23.4	30.8	0.6	1.6	2.2	19.5
	MK-18	46.5	-	26.0	26.0	0.7	2.6	3.3	24.2
	MK-19	43.6	6.8	20.1	26.9	-	3.5	3.5	26.0
	MK-23	40.8	10.8	24.8	34.8	0.5	1.6	2.1	22.3
	MK-55	46.0	0.3	22.8	23.1	-	0.4	0.4	30.5
	NT- 7	38.1	1.5	23.3	24.8	-	1.4	1.4	35.7
	NT- 9	31.1	2.8	22.9	25.7	0.8	10.8	11.0	32.2
	NT-10	40.7	1.0	24.8	25.8	0.1	2.3	2.4	31.1
	SG- 1	46.5	5.8	14.7	20.5	-	3.2	3.2	29.8
	SG- 3	54.2	4.7	11.2	15.9	0.1	9.1	9.2	20.8
	SG- 8	50.6	3.1	14.2	17.3	0.2	3.8	4.0	28.1
	SG-10	50.8	3.7	16.4	20.1	0.2	4.6	4.8	24.3
	SG-12	49.3	1.1	17.3	18.4	0.3	3.8	4.1	28.2
	SG-15	45.6	5.1	15.1	20.2	0.1	5.4	5.5	28.7
	SG-19	48.8	6.4	21.8	28.2	0.1	5.9	6.0	17.0
	SG-29	45.3	0.6	23.8	24.4	-	2.1	2.1	28.2
	SG-32	44.4	1.2	22.5	23.7	0.1	2.7	2.8	29.8
	SG-36	39.2	0.1	29.6	29.7	-	1.3	1.3	29.8
	SG-37	54.0	11.8	19.0	30.8	0.2	2.2	2.4	12.8
	SG-39	40.4	2.5	28.1	30.6	0.1	3.0	3.1	25.9
	SG-40	44.9	7.1	24.0	31.1	0.5	4.1	4.6	19.4
	SG-41	42.7	0.7	34.6	35.3	-	1.4	1.4	20.6
	SG-42	38.5	0.1	31.0	31.1	-	2.8	2.8	27.6

	Specimen	Quartz	Feldspar			Rock Fragments			Matrix
			K-f.	Pl.	Total	Ig.	Oth.	Total	
Kurusuno Fm.	ST-34	41.4	3.9	29.0	32.9	0.1	1.4	1.5	24.2
	ST-35	40.4	4.4	23.6	28.0	0.2	2.7	2.9	28.7
	ST-36	51.3	-	26.9	26.9	0.1	3.0	3.1	18.7
	ST-37	36.4	12.0	28.6	40.6	0.5	2.3	2.8	20.2
	ST-38	48.6	2.9	23.3	26.2	0.3	2.3	2.6	22.6
	ST-39	42.7	2.7	19.9	22.6	-	3.0	3.0	31.7
	ST-41	42.0	7.3	24.7	32.0	0.1	4.9	5.0	21.0
	ST-42	49.9	4.6	23.5	28.1	-	5.8	5.8	16.2
	(Ave.)	43.2	4.7	24.1	28.8	0.2	3.4	3.6	24.4
Shimizu Formation	AZ- 6	31.1	2.8	34.6	37.4	-	2.4	2.4	29.1
	AZ- 7	40.6	0.1	31.2	31.3	-	3.0	3.0	25.1
	AZ- 9	35.5	1.1	34.5	35.6	0.2	4.7	4.9	24.0
	AZ-11	33.8	0.7	37.6	38.3	-	4.5	4.5	23.4
	AZ-12	36.2	8.1	31.0	39.1	0.8	6.4	7.2	17.5
	AZ-13	32.8	10.3	36.0	46.3	0.4	5.2	5.6	15.3
	AZ-15	28.0	2.1	39.7	41.8	0.3	5.3	5.6	24.6
	AZ-16	33.6	10.8	23.1	33.9	0.1	5.7	5.8	26.7
	AZ-19	39.0	3.0	34.0	37.0	0.5	4.9	5.4	18.6
	AZ-21	35.7	5.3	23.0	28.3	0.5	12.4	12.9	23.1
	AZ-22	47.5	4.4	21.8	26.2	0.7	10.5	11.2	15.1
	AZ-26	45.9	2.7	17.2	19.9	1.2	24.1	25.3	8.9
	AZ-27	39.5	5.1	25.3	30.4	0.1	2.4	2.5	27.6
	AZ-28	33.7	5.5	18.2	23.7	-	14.9	14.9	27.7
	AZ-38	38.0	4.7	34.1	38.8	-	1.8	1.8	21.4
	AZ-40	34.4	7.8	22.4	30.2	0.5	13.1	13.6	21.8
	AZ-41	38.6	1.8	23.1	24.9	0.2	10.8	11.0	25.5
	AZ-42	32.0	5.3	20.7	26.0	-	7.1	7.1	34.9
	(Ave.)	36.4	4.5	28.2	32.7	0.3	7.7	8.0	22.9
	cg-A*	33.8	7.6	19.3	26.9	3.3	14.3	17.6	21.7
	cg-B*	20.4	9.0	30.2	39.2	0.1	3.3	3.4	37.0
	cg-C*	52.4	0.5	16.7	17.2	2.5	18.1	20.6	9.8

* clast in conglomerate

	Specimen	Quartz	Feldspar			Rock Fragments			Matrix
			K-f.	Pl.	Total	Ig.	Oth.	Total	
Kurusuno Formation	SG-43	41.9	3.8	22.8	26.6	0.1	2.8	2.9	28.6
	SG-44	45.0	11.1	22.5	33.6	0.1	3.6	3.7	17.7
	SG-45	42.6	3.5	25.0	28.5	0.3	2.1	2.4	26.5
	SG-46	48.5	3.1	29.3	32.4	0.1	3.9	4.0	15.1
	SG-47	38.3	6.1	32.3	38.4	0.9	7.8	8.7	14.6
	SG-48	42.7	12.5	23.3	35.8	0.1	3.4	3.5	18.0
	SG-49	47.4	5.6	23.3	28.9	0.1	1.7	1.8	21.9
	SG-50	38.5	6.5	35.2	41.7	0.2	2.6	2.8	17.0
	SG-51	36.4	4.7	34.4	39.1	-	0.7	0.7	23.8
	SG-52	40.2	5.3	31.6	36.9	-	1.7	1.7	21.2
	SG-54	39.1	5.5	35.3	40.8	0.3	1.3	1.6	18.5
	SG-55	46.4	-	32.1	32.1	0.3	3.6	3.9	17.6
	SG-56	40.6	4.4	34.5	38.9	-	3.2	3.2	17.3
	SG-57	49.0	0.6	35.1	35.7	0.1	3.0	3.1	12.2
	SG-58	47.7	3.6	25.7	29.3	0.3	3.1	3.4	19.6
	SG-59	51.8	11.9	19.9	31.8	1.4	4.1	5.5	10.9
	SG-60	44.5	-	27.6	27.6	-	4.5	4.5	23.4
	SG-67	35.7	1.9	27.7	29.6	-	3.9	3.9	30.8
	SG-73	52.0	1.1	11.7	12.8	-	1.5	1.5	33.7
	SG-75	41.6	4.6	27.5	31.5	-	1.2	1.2	25.7
	SG-79	34.3	4.0	35.5	39.5	-	2.4	2.4	23.8
	SG-82	41.3	3.8	30.1	33.9	-	2.5	2.5	22.3
	ST- 1	43.6	3.8	14.4	18.2	0.1	3.9	4.0	34.2
	ST- 2	44.4	6.2	22.8	29.0	0.1	5.9	6.0	20.6
	ST- 3	46.6	6.7	27.2	33.9	-	2.7	2.7	16.8
	ST- 4	40.0	3.0	21.1	24.1	-	2.7	2.7	33.2
	ST- 5	45.5	6.6	21.1	27.7	0.1	4.8	4.9	21.9
	ST- 6	43.9	2.2	23.2	25.4	0.2	3.4	3.6	27.1
	ST- 7	45.2	0.5	12.9	13.4	-	3.7	3.7	37.7
	ST- 8	39.5	0.9	20.8	21.7	-	3.1	3.1	35.7
	ST- 9	45.7	4.2	21.7	25.9	-	3.4	3.4	25.0
	ST-10	54.6	-	9.0	9.0	-	5.6	5.6	30.8
	ST-11	42.9	-	24.2	24.2	0.2	4.1	4.3	28.6
	ST-33	52.8	-	12.6	12.6	-	3.3	3.3	31.4

	Specimen	Quartz	Feldspar			Rock Fragments			Matrix
			K-f.	Pl.	Total	Ig.	Oth.	Total	
Misaki Formation	Mk-12	35.2	6.7	24.6	31.3	0.7	6.3	7.0	26.5
	MK-13	31.0	2.5	25.6	28.1	-	2.4	2.4	38.5
	MK-29	42.3	1.8	34.9	36.7	0.2	2.8	3.0	18.0
	MK-30	35.6	4.9	25.8	30.7	-	7.8	7.8	25.9
	MK-32	23.7	2.4	23.9	26.3	-	3.1	3.1	46.9
	MK-33	49.9	+	16.4	16.4	0.3	4.9	5.2	28.5
	MK-34	43.6	2.9	18.3	21.2	0.2	1.9	2.1	33.1
	MK-35	33.2	0.3	23.0	23.3	-	2.3	2.3	41.2
	MK-36	51.8	3.7	20.8	24.5	0.3	3.1	3.4	20.3
	MK-37	40.6	1.6	20.8	22.4	-	4.8	4.8	32.1
	MK-38	39.2	3.2	35.4	38.7	0.1	3.1	3.2	18.9
	MK-43	34.4	3.2	24.1	27.3	0.2	2.7	2.9	35.4
	MK-44	47.5	-	25.3	25.3	0.2	7.2	7.4	19.8
	MK-45	40.8	-	31.1	31.1	0.1	3.8	3.9	24.2
	MK-49	31.2	1.7	33.8	35.5	0.2	3.7	3.9	29.4
	MK-53	30.2	3.1	22.3	25.4	0.5	3.5	4.0	40.4
	(Ave.)	38.1	2.4	25.2	27.6	0.2	4.0	4.2	29.9

K-f.: potash feldspar +: traceable
Pl. : plagioclase -: untraceable
Ig. : igneous rock fragments
Oth.: other rock fragments (Ave.): average

TABLE 4. QUANTITATIVE DATA ON SIZE PARAMETERS AND THEIR EVALUATIONS OF SANDSTONES.

Formation	Specimen	C	Md	Me	So	Sk	Ku
Hiroi Fm.	IY- 2	-0.57	1.68	1.63	0.83(M)	-0.08(S)	1.00(M)
	IY- 4	0.80	2.55	2.62	0.82(M)	0.14(P)	1.04(M)
	IY- 5	-0.10	1.70	1.74	0.85(M)	0.04(S)	0.92(M)
	IY- 9	0.20	1.70	1.78	0.77(M)	0.20(P)	1.02(M)
	IY-11	0.95	2.50	2.53	0.66(MW)	0.03(S)	1.05(M)
	IY-26	0.15	2.07	2.04	0.96(M)	-0.04(S)	0.83(P)
	IY-27	-0.55	2.75	2.80	1.24(P)	0.05(S)	0.99(M)
	IY-28	1.55	2.42	2.50	0.50(W)	0.30(P)	1.10(M)
	IY-29	1.65	2.80	2.83	0.64(MW)	0.12(P)	0.98(M)
Tatsugasako Formation	AR-15	1.20	3.02	3.02	0.88(M)	0.02(S)	0.85(P)
	IY-22	1.07	2.24	2.25	0.58(MW)	0.11(P)	1.11(M)
	MI- 2	0.95	2.10	2.13	0.58(MW)	0.11(P)	1.14(L)
	SU- 2	1.20	2.42	2.44	0.53(MW)	0.07(S)	0.92(M)
	TA- 3	0.96	3.05	3.04	0.71(MW)	-0.01(S)	1.10(M)
	TG- 2	2.10	3.35	3.33	0.54(MW)	-0.02(S)	1.16(L)
	TG- 3	1.81	3.10	3.14	0.59(MW)	0.10(S)	1.27(L)
	TG- 9	1.90	3.27	3.27	0.58(MW)	-0.05(S)	1.12(L)
	TG-24	1.90	2.75	2.74	0.45(W)	0.04(S)	1.11(M)
	YZ- 5	1.65	2.97	3.00	0.60(MW)	0.06(S)	1.00(M)
	SK- 2	0.94	2.30	2.38	0.59(MW)	0.25(P)	1.01(M)
	SK- 3	0.25	2.20	2.19	0.72(M)	-0.03(S)	0.98(M)
	SK- 7a	-0.10	2.50	2.46	0.77(M)	-0.14(N)	1.31(L)
	SK- 7b	0.10	2.72	2.68	0.78(M)	-0.13(N)	1.09(M)
	SK- 7c	-0.05	2.50	2.42	0.90(M)	-0.15(N)	1.08(M)
	SK- 7d	0.30	2.55	2.44	0.95(M)	-0.16(N)	1.12(L)
	SK- 7e	0.38	2.70	2.63	0.90(M)	-0.15(N)	1.14(L)
	SK- 7f	-0.12	2.55	2.51	0.84(M)	-0.08(S)	1.02(M)
	SK-10	0.66	2.26	2.30	0.73(M)	0.07(S)	0.92(M)
	TH- 1	1.80	2.95	3.02	0.55(MW)	0.18(P)	0.98(M)
	TH- 2	0.85	2.65	2.63	0.70(MW)	-0.03(S)	1.08(M)
	TH- 3	-0,25	1.40	1.54	0.98(M)	0.19(P)	0.93(M)
	TH- 4	0.15	2.30	2.29	0.92(M)	-0.05(S)	1.20(L)

Formation	Specimen	C	Md	Me	So	Sk	Ku
Tatsugasako Formation	TH- 5	-0.20	1.40	1.49	0.79(M)	0.18(P)	0.98(M)
	TH- 6	0.43	2.20	2.18	0.85(M)	-0.01(S)	0.83(P)
	TH- 7	2.40	3.45	3.49	0.42(W)	0.11(P)	1.04(M)
	TH-12a	1.00	2.18	2.23	0.54(MW)	0.14(P)	0.97(M)
	TH-12b	1.25	2.50	2.45	0.52(MW)	-0.13(N)	1.01(M)
	TH-12c	1.40	2.45	2.47	0.46(W)	0.06(S)	0.98(M)
	TH-12d	1.23	2.23	2.28	0.49(W)	0.11(P)	0.96(M)
	TH-12e	1.50	2.47	2.48	0.52(MW)	0.06(S)	0.97(M)
	TH-12f	1.40	2.35	2.37	0.50(MW)	0.09(S)	0.92(M)
	TH-12g	1.30	2.32	2.36	0.51(MW)	0.15(P)	1.01(M)
	TH-12h	1.10	2.40	2.43	0.47(W)	0.07(S)	0.88(P)
	TH-12i	1.30	2.53	2.51	0.50(MW)	-0.03(S)	0.90(M)
	TH-12j	1.23	2.52	2.53	0.55(MW)	0.05(S)	0.95(M)
	TH-12k	1.32	2.53	2.52	0.54(MW)	-0.01(S)	0.88(P)
	TH-12v	1.63	2.80	2.77	0.54(MW)	-0.03(S)	0.92(M)
	TH-13	0.00	1.85	1.93	0.84(M)	0.14(P)	1.02(M)
	TH-16	2.00	3.05	3.06	0.48(W)	0.06(S)	1.09(M)
Kurusumo Fm.	KK-12	(1.43)	3.04	3.10	0.83(M)	0.14(P)	0.86(P)
	KK-24	1.01	2.98	2.95	0.96(M)	-0.02(S)	1.03(M)
	SG-80	1.01	3.07	3.05	0.90(M)	-0.04(S)	0.99(M)
	ST-37	0.63	2.20	2.25	0.67(MW)	0.11(P)	1.19(L)
Shimizu Fm.	AZ-59	2.57	3.77	3.87	0.69(MW)	0.21(P)	0.92(M)
	AZ-93	2.08	3.31	3.34	0.65(MW)	0.09(S)	1.11(M)
	Az-93p	1.80	3.08	3.12	0.69(MW)	0.11(P)	1.08(M)
	AZ-93v	2.07	3.32	3.34	0.65(MW)	0.11(P)	1.09(M)
	MK-84	0.80	3.05	2.99	0.83(M)	-0.11(N)	1.02(M)
	MK-89	-0.32	2.60	2.56	1.10(P)	-0.01(S)	0.94(M)
Misaki Fm.	MK-11	2.35	3.54	3.59	0.53(MW)	0.14(P)	1.07(M)
	MK-14	1.27	2.20	2.29	0.53(MW)	0.23(P)	1.10(M)
	MK-15	0.63	2.20	2.25	0.67(MW)	0.11(P)	1.19(L)
	MK-39	1.24	2.54	2.60	0.69(MW)	0.17(P)	1.06(M)

Formation	Specimen	C	Md	Me	So	Sk	Ku
Misaki Formation	MK-41	1.00	2.22	2.32	0.83(M)	0.25(P)	1.10(M)
	MK-43	2.07	3.20	3.22	0.62(MW)	0.16(P)	0.74(P)
	MK-50	1.74	3.08	3.14	0.74(M)	0.16(P)	1.11(M)
	MK-54	0.82	2.35	2.48	0.77(M)	0.27(P)	1.12(L)
	MK-75	2.30	3.42	3.46	0.51(MW)	0.11(P)	1.13(L)
	MK-80	0.45	2.20	2.38	1.14(P)	0.22(P)	0.73(P)
	MK-81	0.32	2.10	2.11	0.98(M)	0.07(S)	0.85(P)
	MK-82	0.47	1.95	2.12	0.89(M)	0.24(P)	0.96(M)
	MK-83	0.62	2.25	2.41	1.04(P)	0.26(P)	0.91(M)
	MK-86	1.91	3.14	3.25	0.79(M)	0.21(P)	0.98(M)
	MK-88a	(2.00)	3.30	3.32	0.56(MW)	0.08(S)	1.00(M)
	MK-88b	2.12	3.15	3.18	0.54(MW)	0.11(P)	1.26(L)
	MK-90	2.08	3.07	3.26	0.76(M)	0.37(VP)	1.01(M)
	MK-92	2.15	3.27	3.35	0.52(MW)	0.23(P)	1.07(M)
	MK-93a	2.33	3.30	3.33	0.55(MW)	0.13(P)	1.05(M)
	MK-93b	2.33	3.35	3.38	0.57(MW)	0.11(P)	0.97(M)
	Mk-93c	1.82	3.24	3.26	0.65(MW)	0.08(S)	1.14(L)
	MK-93d	2.08	3.31	3.34	0.65(MW)	0.09(S)	1.11(M)
	To-1	(2.35)	3.73	3.79	0.63(MW)	0.14(P)	0.77(P)
	To-m	(2.10)	3.62	3.73	0.76(M)	0.12(P)	0.83(M)

C: one percentile (parenthesized values were obtained by the extrapolation from the cumulative frequency curves),
Md: median diameter, Me: mean diameter, So: sorting index (W: well sorted, MW: moderately well sorted, M: moderately sorted, P: poorly sorted), Sk: skewness (N: negative, S: symmetrical, P: positive, VP: very positive),
Ku: kurtosis (P: platykurtic, M: mesokurtic, L: leptokurtic)

Explanation of Plate 1

1. Pebbly sandstone containing abundant clasts of shale (Facies A2) in the Shirahama Member of the Tatsugasako Formation. The scale is 1m long.
2. Pebbly sandstone (Facies A1) in the Shirahama Member of the Tatsugasako Formation.
3. Thick-bedded, fine-grained sandstone (Facies B) in the Tsuganokawa Member of the Tatsugasako Formation. Stratigraphic top to left.
4. Thinly alternating beds of sandstone and shale (Facies C) in the Shirahama Member of the Tatsugasako Formation. Stratigraphic top to left. The scale is 1m long.
5. Flysch-type alternation (Facies C) in the Shirahama Member of the Tatsugasako Formation. This sandstone shows the base-cut-out sequence of BOUMA. Stratigraphic top to left.
6. Thinly alternating beds of acidic tuff and shale (Facies E) in the B Member of the Kurusuno Formation. Maximum thickness of the acidic tuff bed is about 30cm. Stratigraphic top to left.
7. Thinly alternating beds of sandstone and shale (Facies C: "distal turbidites") in the B Member of the Kurusuno Formation. Stratigraphic top to left. The scale is 1m long.
8. Flute marks on underside of thick-bedded sandstone (Facies B) in the B Member of the Kurusuno Formation. Current from right to left. The scale is 0.5m long.

Explanation of Plate 2

1. Pebbly mudstone in the Shimizu Formation. Maximum diameter of the clast is about 1 m.
2. Mudstone with sandy intercalations (Facies 2) in the Lower Member of the Misaki Formation. Stratigraphic top to left.
3. Storm-sand layers alternating with bioturbated mudstone and siltstone (Facies 3 and 4) in the Middle Member of the Misaki Formation. The sandstone in the middle shows hummocky cross stratification. Hammer gives scale.
4. Strongly bioturbated sandstone and mudstone (Facies 4) in the Middle Member of the Misaki Formation.
5. Hummocky cross-stratified sandstone overlain by parallel-laminated sandstone (Facies 5) in the Upper Member of the Misaki Formation. Stratigraphic top to left. Hammer gives scale.
6. Convolute lamination within the thick-bedded sandstone (Facies 5) in the Upper Member of the Misaki Formation. Stratigraphic top to left. Thickness of the convoluted part is about 1.3 m.
7. *Ophiomorpha* sp. within the thick-bedded sandstone (Facies 5) in the Upper Member of the Misaki Formation.
8. Tabular cross-laminated, coarse-grained sandstone (Facies 6) in the Upper Member of the Misaki Formation.

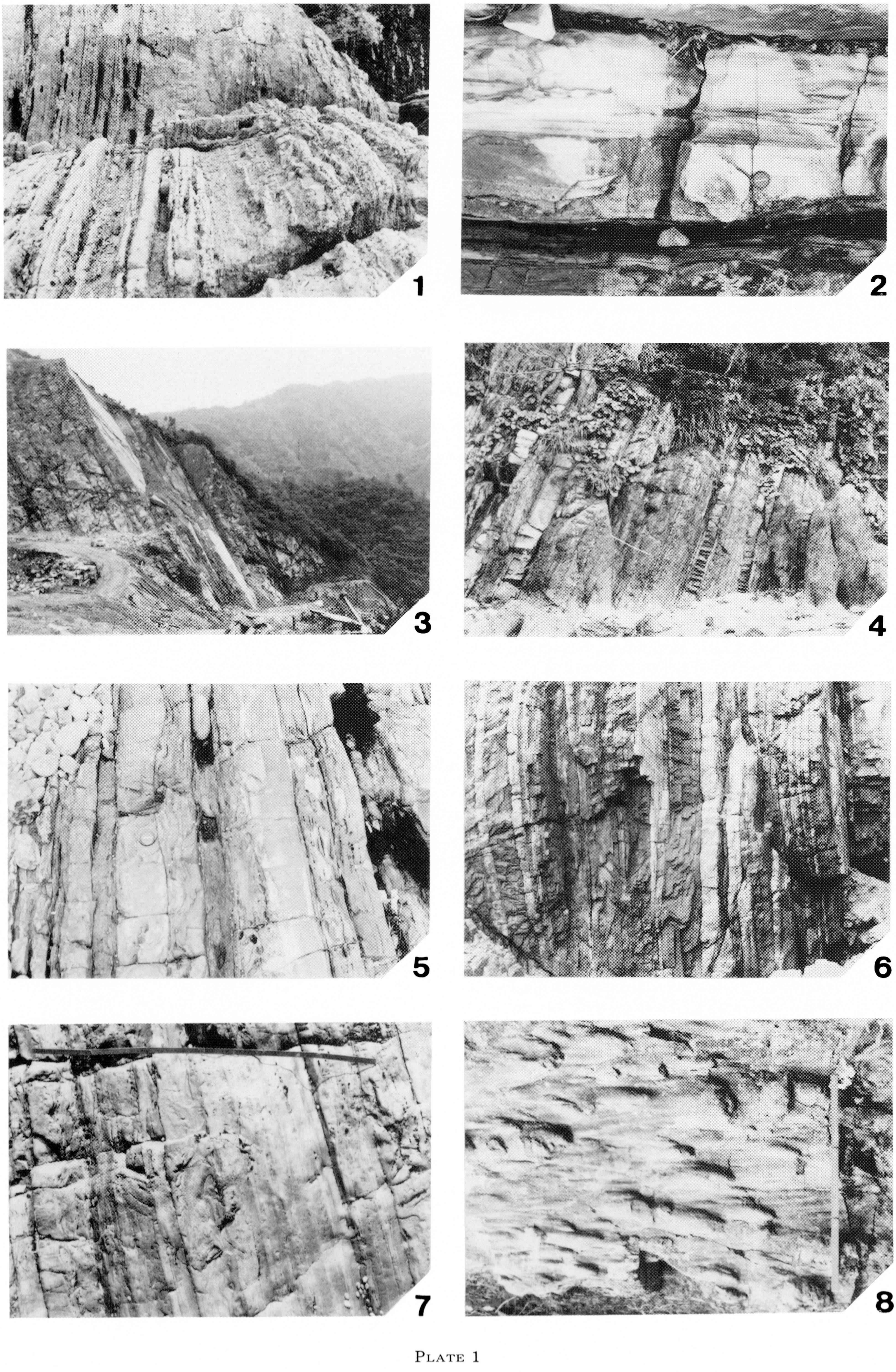

PLATE 1

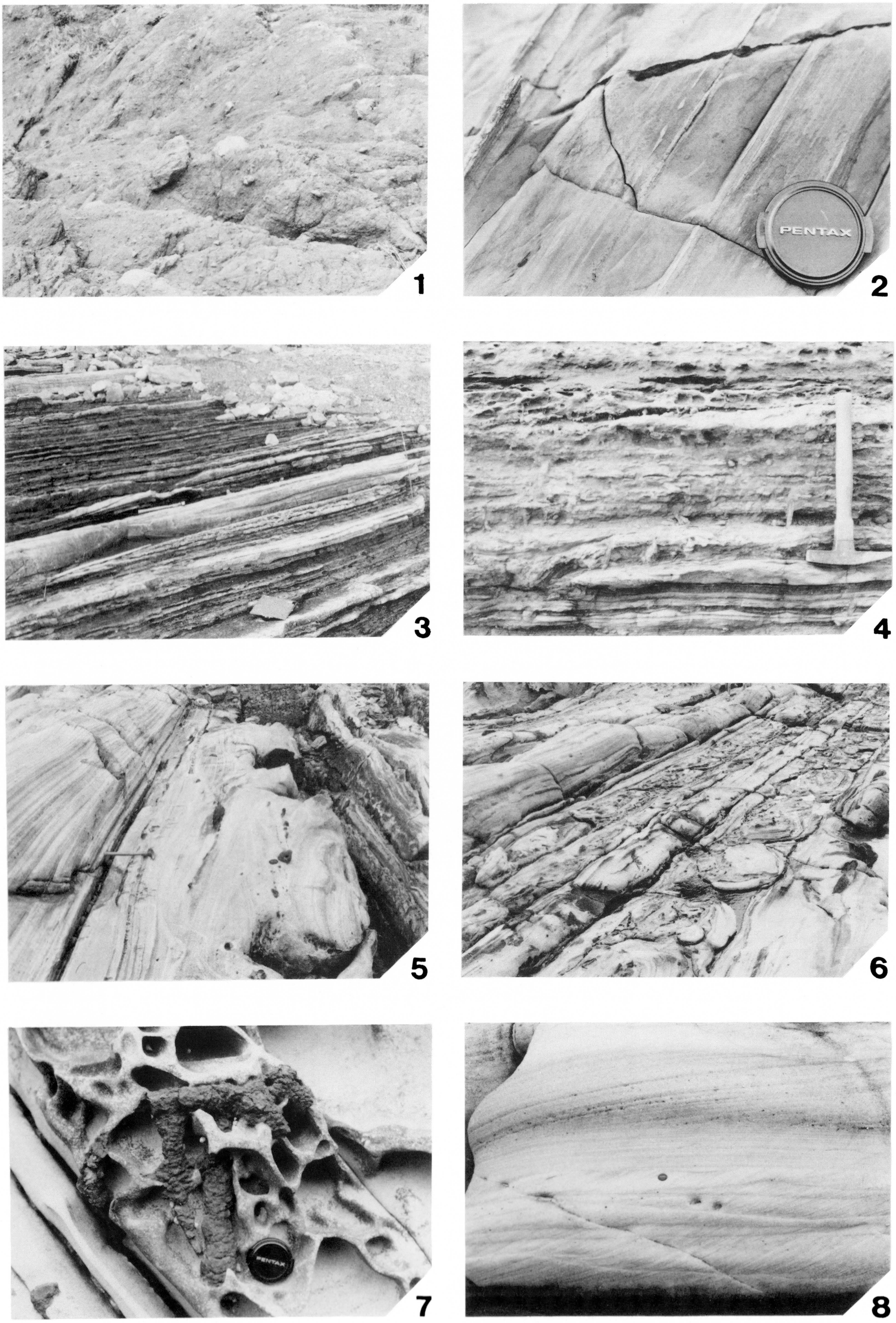

PLATE 2