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Reconstruction of Fujikawa Trough in Mio-Pliocene Age and its Geotectonic Implication

By

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Contents

Abstract

The late Miocene to Pliocene Minobu Formation and its equivalents in the Southern Fossa Magna Region, central Japan, consist of turbidites and associated coarse clastic deposits. The thickness of the Minobu Formation and its equivalents attains up to 3 km. In those sediments, sixteen sedimentary facies are recognized, and they are grouped further into eight facies associations; Conglomeratic, Conglomeratic-sandy, Conglomerate-Sandstone, Sandy, Silty, Sandy-silty, Silty and Pebbly siltstone associations.

Among them, the first four associations are interpreted as channel fill sediments. While the second three associations are thought to be interchannel sediments. Interpretation of such facies associations as mentioned above is based on the following points; 1) comparative studies of sedimentary facies and facies association in the study area with those reported from modern and ancient turbidite basins, 2) morphologic analysis of sedimentary body of facies association and 3) dispersal pattern of sediments. The last of those associations is assumed from its characteristic sedimentary features to be slump deposits which flowed down along such steep slope as fault scarp.

Result of such interpretations leads further to the conclusion that sedimentary environments of the Minobu Formation and its equivalents is fillings of a trough which extends in N–S direction throughout the area. Furthermore, from sedimentological analysis of the trough fillings, feeder channel extending ENE-WSW direction, western boundary fault scarps and an axial channel of a few kilometres in width are revealed. Then it is named herein Fujikawa Trough. Petrography and dispersal pattern of clastic sediments indicate that the main source area was situated around the Kwanto mountainland, more than 40 kilometres away from Fujikawa Trough.

Comparison of Fujikawa Trough with modern trough and trench is made. Consequently, Suruga Trough seems to show the closest similarity by the following reasons of 1) similarity of internal topographic features such as western boundary fault scarps and an axial channel of a few kilometres wide, 2) similarity of the axial direction of trough and 3) similarity of the sedimentary ratio of fill sediments. Such geomorphologic similarity of both trough is important, and suggests that Fujikawa Trough was formed as a consequence of collision of Izu-Bonin Arc into Southwest Japan Arc in the same mannar as Suruga Trough is developing now.

1. INTRODUCTION

Fossa Magna Region is a large graben-like region located at junction of Southwest Japan and Izu-Bonin arcs, and offers a key towards clarification of geotectonic relationship between these two arcs (Fig. 1). Many surveys have been made since last century to establish the geologic development of the region (NAUMANN, 1887; HARADA, 1890; EHARA, 1953; MATSUDA, 1978; etc). In constract with geophysical interpretation, however, geological one of the region has not been developed further since the 1960's, owing to complex lithofacies changes and developments of folding and faulting.

It has been known that turbidites and associated coarse clastic deposits, more than 4000 m thick, are extensively developed in the southern part of the Fossa Magna Region (the Southern Fossa Magna Region). Sedimentological analysis of those sedimentary sequences, especially from a "tectono-sedimentologic viewpoint", is considered to be very important in clarifying the geologic development of this region. However, no such study has been carried out yet. Among the sedimetary sequences, the latest Miocene to early Pliocene Minobu Formation of the Fujikawa Group was selected for this study. Because this formation is well-exposed and most widely distributed. And many literally equivalent strata of the Minobu Formation, ranging from deep-sea to shallow marine environments, are recognized in the region.

In this paper, the author aims first to describe the complex lithofacies of the Minobu Formation and its equivalent strata from viewpoints of sedimentary facies and facies association of MUTTI & RICCI-LUCCHI (1972; 1975). The second aim is to reconstruct the sedimentary environments, especially focusing on paleotopography. The following points are taken into account; 1) the comparative studies of sedimentary facies and their preferred transition in each facies association of the Minobu Formation with those reported from modern and ancient turbidite basins, 2) a morphologic analysis of the sedimentary body as constituted by facies association, 3) the dispersal pattern of facies association and 4) the petrographic properties of the sediments. The third aim is to estimate the sedimentary and tectonic settings of the Minobu Formation and its equivalent strata by comparison with those of modern sedimentary and tectonic settings. Finally, a new tectono-sedimentological inter-

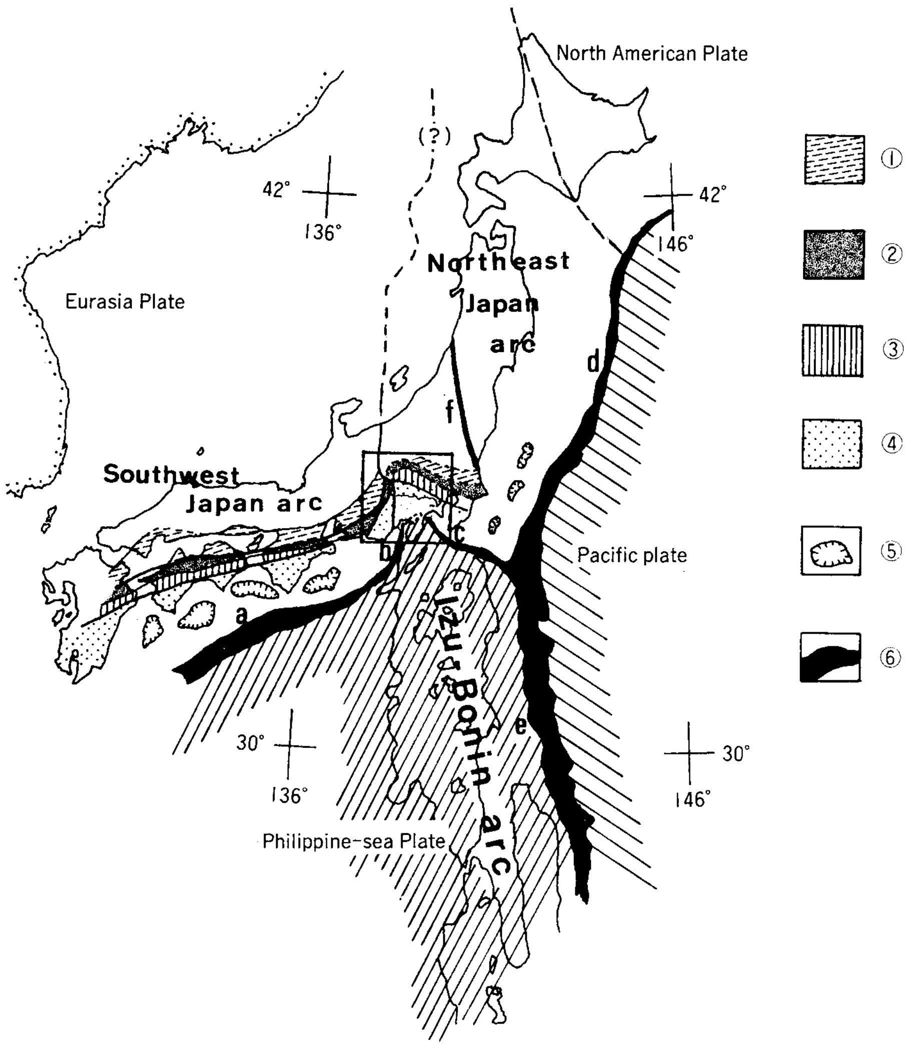


Fig. 1. Tectonic setting around the Southern Fossa Magna Region, showing the main geologic belts of Southwestern Japan Arc, and the modern fore-arc basins, trenchs and trough. a. Nankai Trough, b. Suruga Trough, c. Sagami Trough, d. Japan Trench, e. Izu-Mariana Trench, f. Tanakura Fault, 1. Ryoke Belt, 2. Sanbagawa Belt, 3. Chichibu Belt, 4. Shimanto Belt, 5. Fore-arc Basin, 6. Trench & Trough.

pretation is proposed for the development of the Neogene strata of this region from a model of plate collision.

2. GEOLOGICAL BACKGROUND OF THE WESTERN HALF OF THE SOUTHERN FOSSA MAGNA REGION

2-A. *Geologic setting of the Southern Fossa Magna Region*

As the most important geologic features in the Southern Fossa Magna Region and its surrounding region, it should be taken up that E–W zonal arrangement of main geologic belts of Southwest Japan Arc bends acutely to north here (Fig. 2). In those belts, the Ryoke, the Sanbagawa, the Chichibu and the Shimanto belts are

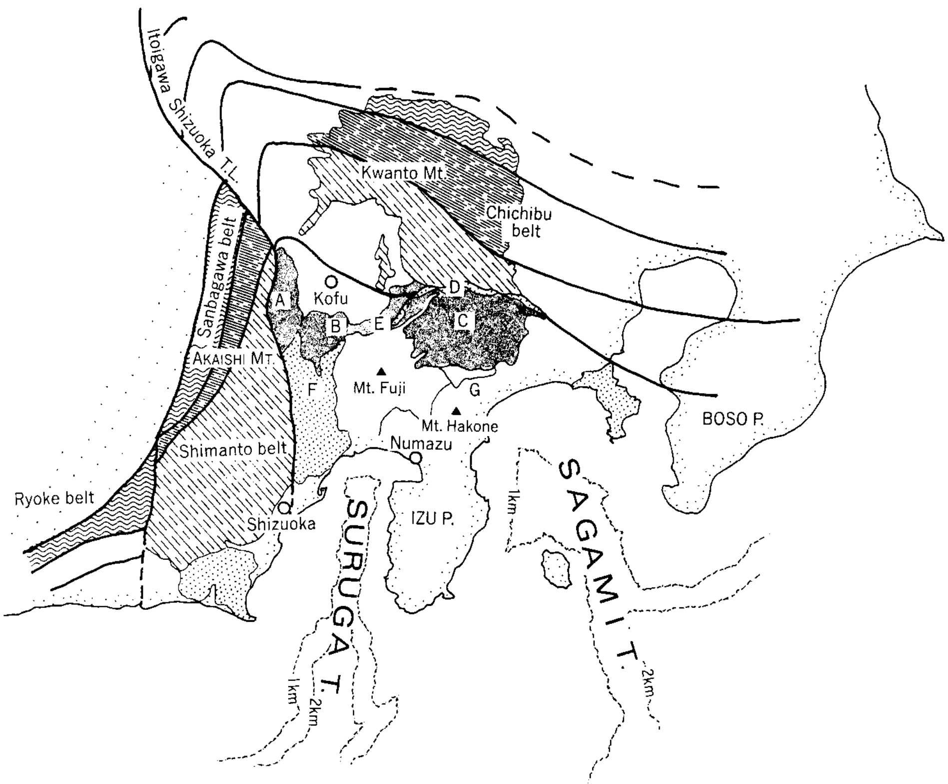


Fig. 2. Tectonic sketch and location map in and around the Southern Fossa Magna Region, showing bending morphology of geologic belts in the Southwest Japan arc, and of the modern troughs. A. Koma mountainland, B. Misaka mountainland, C. Tanzawa mountainland, D. Iwadono area, E. Nishikatsura area, F. Fujikawa area, G. Ashigara area.

included. In addition, it is also noticeable that the axes of modern Suruga and Sagami troughs bend along this bending trend.

Since NAUMANN (1887) and HARADA (1890), many geologists and geophysists have discussed the genesis of this interesting feature. With the introduction of plate tectonic models to this region, it has been speculated that the bending structure of the pre-Miocene sequence is caused by non-uniform compression from the southern side (HARA *et al.*, 1973; 1977; ICHIKAWA, 1980). And, it is believed that the curved line connecting Suruga and Sagami troughs through the Southern Fossa Magna Region is a modern plate boundary interpreted to have been constructed by the collision of Izu Peninsula to central Honshu (KAIZUKA, 1972; MATSUDA, 1978; and others). Now, it is believed that this region has been located on a collision boundary between Izu-Bonin Arc on Philippine-sea Plate and Southwest Japan Arc on Eurasian Plate (e.g. NIITSUMA, 1982, 1985). Accordingly, the late Miocene to Pliocene system in the Southern Fossa Magna Region should have recorded an unique geologic history of sedimentation and tectonism as the collision-accretion region between both arcs.

2-B. *Outline of geology and stratigraphy in the western half of the Southern Fossa Magna Region*

In the Southern Fossa Magna Region, the Neogene system is extensively developed (Fig. 3). Pre-Neogene basement rocks, however, are not exposed (Matsuda, 1984). The Neogene system in the western part of this region is classified into two groups; the middle Miocene Nishiyatsushiro Group and the late Miocene to Pliocene Fujikawa Group in ascending order (MATSUDA, 1961) (Table 1).

The Nishiyatsushiro Group is widely distributed in Tanzawa Mountains, Misaka Mountains and Aimata area in the central and northern part of the Southern Fossa Magna Region. The group is mainly composed of tholeiitic altered lava and hyaloclastic sediments. Some of them distributed in the western part of the region consist of alkaline volcanic rocks. Black mudstone is found interbedded with sandstone. It attains a thickness of 2800 m and is subdivided in ascending order into the Furusekigawa Formation and the Tokiwa Formation. The Nishiyatsushiro Group is comformably overlain by the Fujikawa Group (AKIYAMA, 1957; MATSUDA, 1958; FUJIKAWA COL. RES. GR. 1976; TOKUYAMA *et al.*, 1981).

The Fujikawa Group is mainly distributed in the western part of the Southern Fossa Magna Region. In contrast to the Nishiyatsushiro Group, it consists mainly of clastic sediments such as conglomerate, thick-bedded sandstone and siltstone. The calkalkaline andestic volcanic deposits are intercalated. Those volcanic deposits, however, are only weakly altered different from those of the pervasively altered Nishiyatsushiro Group. The Fujikawa Group, more than 6000 m thick, is sub-

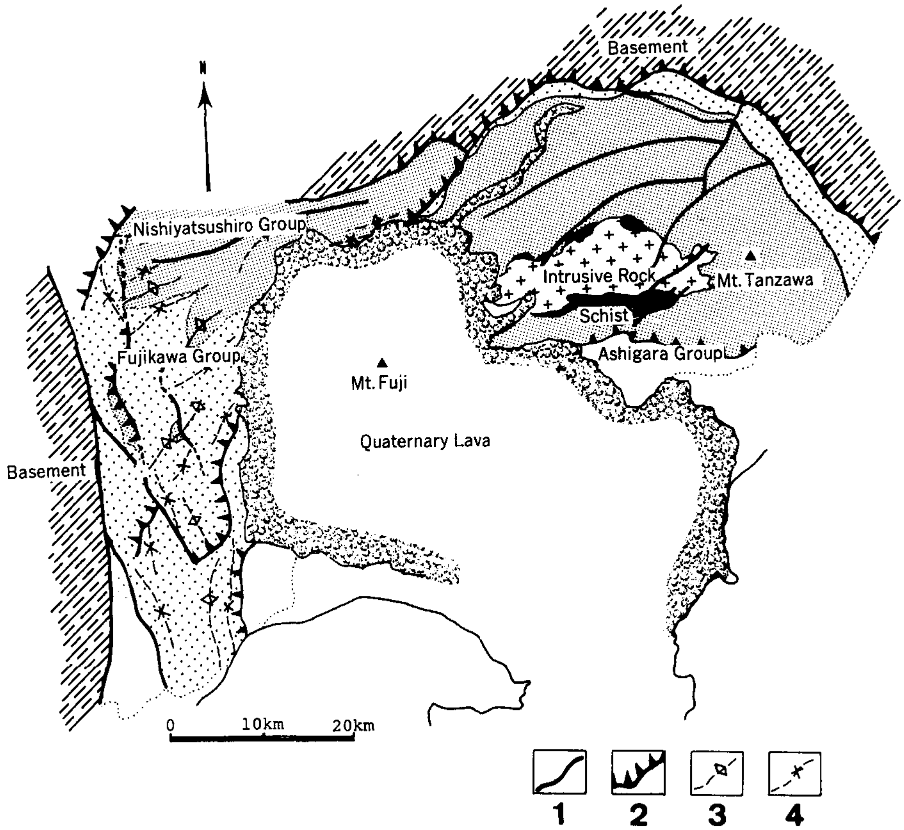


Fig. 3. Generalized geological and structural map of the Southern Fossa Magna Region, showing half-dome structure facing north around Tanzawa mountain, of the Miocene System. 1. Fault, 2. Thrust, 3. Anticline, 4. Syncline.

divided into three formations namely; the Shimobe, the Minobu and the Akebono formations in ascending order. The Fujikawa Group is unconformably overlain by the Kanbara Gravel of middle to late Pleistocene age (SURUGAWAN COL. RES. GR., 1981).

Based on the first or last occurrences of designated planktic foraminifer taxa, it appears that the Nishiyatsushiro Group ranges at least from N.10 to N.18 of BLOW's zone, corresponding to middle to late Miocene age (SHIMAZU *et al.*, 1971; CHIJI & KONDA, 1978). Moreover, KONDA (1980) suggested by the study of benthic foraminifer taxa that the paleobathymetry of the Nishiyatsushiro Group is nearly in upper bathyal zone.

In the Fujikawa Group, UJIIE & MURAKI (1976), CHIJI & KONDA (1978) and KANO *et al.* (1985) stated that the Fujikawa Group with an except of the Akebono

Table 1. Summary of stratigraphic succession and lithology in the western half of the Southern Fossa Magna Region.

Stratigraphy: Group	Stratigraphy: Formation	Lithology	Thickness	Blow's number	Geologic Time
KANBARA GRAVEL		Stratified gravels & sands	30 m +		*early to middle Pleistocene*
FUJIKAWA GROUP	Akebono Formation	thick-bedded conglomerate volcaniclastic deposits siltstone with sandstone	1200 m+	N 21	*Pliocene*
	Minobu Formation	siltstone interbedded with sandstone thick-bedded sandstone thick-bedded conglomerate pebbly mudstone volcaniclastic deposits	3100 m	N 19	
	Shimobe Formation	siltstone interbedded with sandstone thick-bedded tuffaceous sandstone volcaniclastic deposits	1900 m	N 18	*late Miocene*
NISHI-YATSUSHIRO GROUP	Tokiwa Formation	mudstone interbedded with tuff & tuffaceous sandstone	2000 m	N 17 N 16 N 15 N 14 N 13	*middle Miocene*
	Furusekigawa Formation	basalt lavas and pyroclastics tuffaceous mudststones and sandstones	800 m+	N 12 (N 10)	

Formation, can be correlated with N.18 up to N.21 of BLOW's zones, ranging in age from late Miocene to late Pliocene. Additionally, the most sequences of the Fujikawa Formation is deposited in upper bathyal environment or more deeper one (KANO *et al.*, 1985).

Based on KENNETT & SRINIVASANS'timetable (1983), the period between N.18 and N.21 that is corresponding to the geologic period of the Fujikawa Group except for the Akebono Formation is estimated as about 3 million years. This estimation gives a sedimentation rate for the Minobu and the Shimobe formations of the Fujikawa Group as approximately 150 cm/1000 year. This value of sedimentation rate is nearly equal to the higher one (cf. STOW *et al.*, 1984) for turbidites and associated coarse clastic deposits in the world.

2-C. *Geologic structure of the Southern Fossa Magna Region*

Neogene strata in the Southern Fossa Magna Region as a whole, excepting the Koma mountains, show a half-dome structure facing north (see Fig. 6 in SUGIYAMA, 1976) (Fig. 3). Thrust faults run not only along the boundary between the Neogene and pre-Neogene systems but also within the Neogene system, in which are of concordance with the half-dome structure. The diorite-gabbro complex intruding into the Neogene rocks (KUNO, 1957; YAZIMA, 1968; TAKITA, 1974), are also distributed in parallel wiih the half-dome structure. Study area belonging to the western half of the Southern Fossa Magna Region, is mostly situated on the west wing of the half-dome structure. This area corresponds to the conversional region of two structural trends of NE-SW and N-S directions (OTUKA, 1931). Folding structures of the ENE-WSW trend are developed in the eastern part of the study area, and gradually converge east- and southward to monoclinal structures of N-S strike, dipping west, which are parallel to the extension of "Fujikawa Tal" of MATSUDA (1958) (AKIYAMA, 1957; MATSUDA, 1961).

Such a strong deformation as repesented by bedding slip or slaty cleavage is not recognized in the study area. The plunge of folding is not steep and is less than 45 degrees. Accordingly, for the sedimentological investigation and reconstruction, the effect of structual deformation with an exception of probablely minor space shortening by folding and faulting are negligible, if it is present.

3. STRATIGRAPHY OF THE MINOBU FORMATION AND ITS EQUIVALENT STRATA

The Minobu Formation, the middle formation of the Fujikawa Group was first described in Minobu area by AKIYAMA (1957), and subsequently redefined by many workers (MATSUDA, 1958, 1961; FUJIKAWA COL. RES. GR., 1976; TOKUYAMA *et al.*, 1981; SOH, 1985). In this paper, the author follows his previous work (SOH, 1985) which is modified from Matsuda's works.

Equivalent strata of the Minobu Formation are distributed not only to the south of the type locality (Manzawa area), but also to the north (Akebono area), to the northeast (Nishikartsura area) and to the west (Aimata area).

Based on the similarity of predominated lithofacies, paleocurrent pattern and geologic structures, these areas can be grouped into three domains, that is, Nishikatsura domain, Fujikawa domain and Aimata domain (Fig. 4). Nishikatsura domain, comprising Minobu and Nishikatsura areas, stretches east-northeastward from Minobu area to Nishikatsura area 35 km away. Nishikatsura area is separated from Minobu area by Quarternary Fuji lava area of Aokigahara between. Resedimented conglomerate and thick-bedded turbidite are well-developed in this domain.

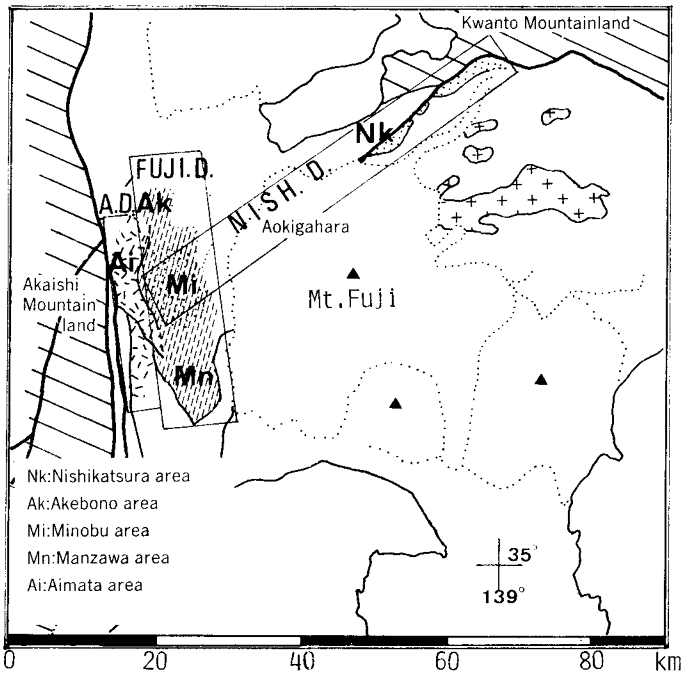


Fig. 4. Location map of the Minobu Formation and its equivalents. NISH.D.; Nishikatsura domain, FUJI.D; Fujikawa domain, A.D.; Aimata domain.

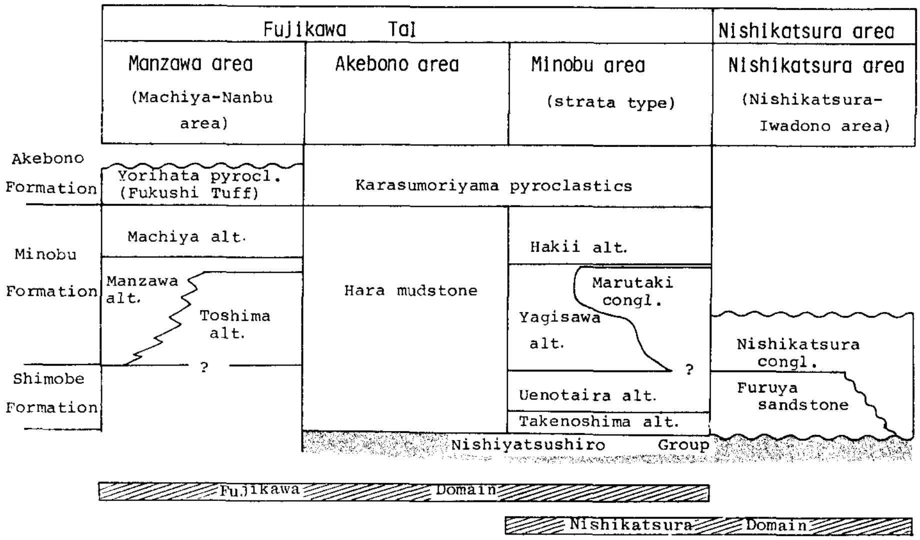
Fujikawa domain extends along Fuji River including Akebono, Minobu and Manzawa areas. It corresponds to the northeastern part of "Fujikawa Tal" of MATSUDA (1961). The sequence of this domain consists mainly of conglomerate, thick-bedded sandstone, siltstone interbedded with sandstone, with volcaniclastic intercalations and slump deposits. The boundaries of Akebono and Minobu, and of Minobu and Manzawa areas are drawn along axes of Tokiwa and Utsubuna anticlines, respectively (FUJIKAWA COL. RES. GR., 1976) (Fig. 5). It should be noted that Fujikawa and Nishikatsura domains overlap each other in Minobu area. Additionally, the westernmost Aimata domain stretches N-S and is characterized by hyaloclastic sediments and siltstone interbedded with tuffaceous sandstone. In this paper, the Aimata domain is only briefly mentioned.

Nishikatsura domain

Minobu area

The Minobu Formation in the type area consists of a complex sequence of resedimented conglomerate, thick-bedded sandstone, siltstone interbedded with sandstone, volcaniclastic sediments, and slump deposits. Three members have been

Table 2. Summary of stratigraphy of the Minobu Formation and its equivalent strata.



recognized namely the Yagisawa Mudstone, the Marutaki Conglomerate and the Hakii Alternation of mudstone and sandstone in ascending order (Table 2). As key volcaniclastic beds can be traced laterally from the Marutaki Conglomerate to the Yagisawa Mudstone (Soh, 1985), the Marutaki Conglomerate is confirmed to be in an equivalent stratigraphic position to part of the Yagisawa Mudstone. Succeedingly the Hakii Alternation comformably overlies both the Marutaki Conglomerate and the Yagisawa Mudstone.

Nishikatsura area

In Nishikatsura area, the Nishikatsura Group, equivalent to the lower part of the Fujikawa Group, unconformably overlies the Nishiyatsushiro Group. The Nishikatsura Group is divided in ascending order into the Furuya Sandstone and the Katsuragawa Conglomerate (Mikami, 1962; Watanabe, 1954; Fukuda & Shinoki, 1952; Mano *et al.*, 1977; Komatsu, 1984) (Table 2). Among them, the Katsuragawa Conglomerate corresponds to the Minobu Formation (Matsuda, 1961; 1972). The Katsuragawa Conglomerate is exposed continuously for more than 10 km along the Nishikatsura fault of Fukuda & Shinoki (1952) from Iwadono to Lake Kawaguchi (Fig. 6).

Fujikawa domain

Manzawa area

The Manzawa Formation of Matsuda (1961) in Manzawa area comprises four

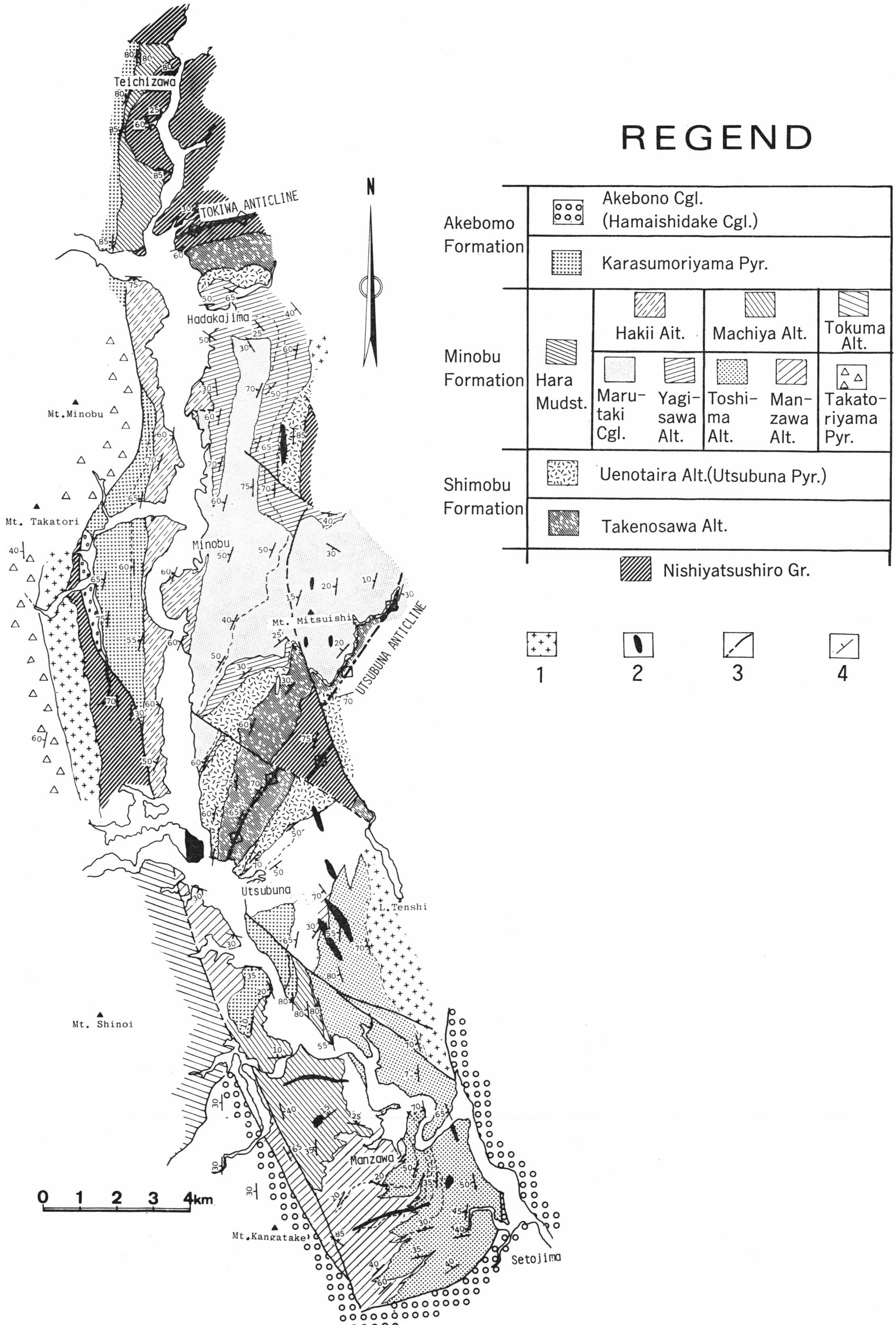


Fig. 5. Geological map of Fujikawa domain. The boundaries of Akebono and Minobu, and Minobu and Manzawa areas are drawn on the axes of the Tokiwa and Utsubuna Anti clines. 1. Intrusive rocks, 2. dyke rocks, 3. fault, 4. dip and strike.

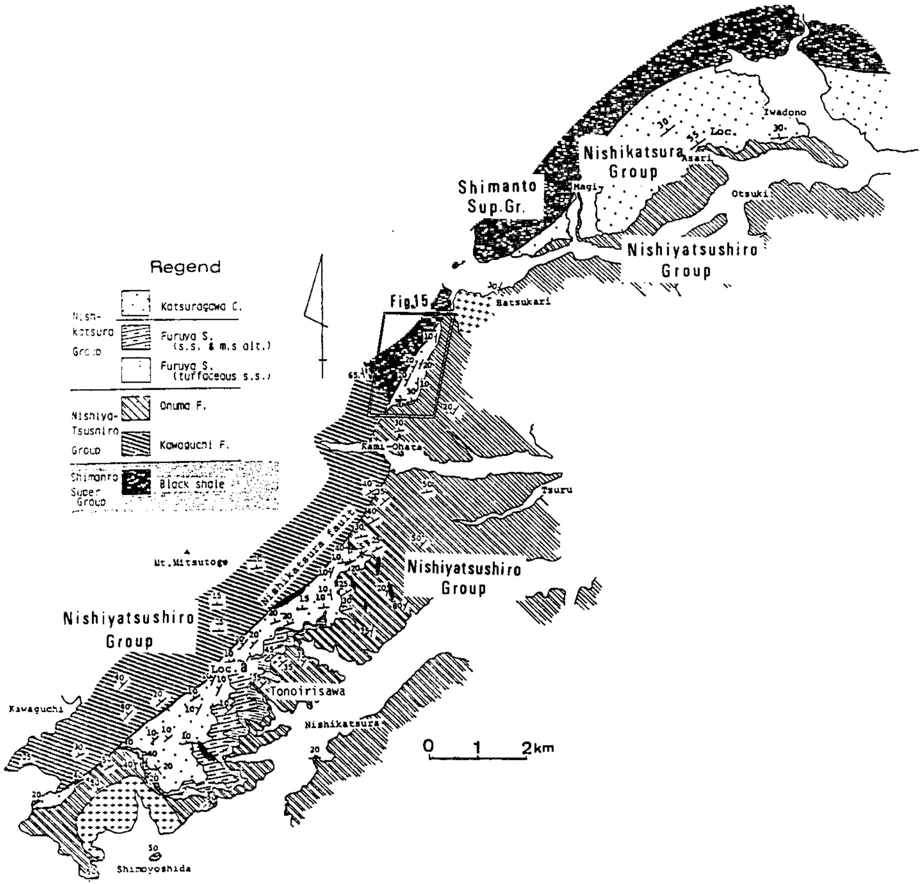


Fig. 6. Geological map of Nishikatsura area.

members; the Toshima Alternation, the Manzawa Alternation, the Machiya Alternation and the Fukushi Tuff in ascending order. The Manzawa Formation, however, is tentatively used here for the portion below the Fukushi Tuff (Fig. 5). This formation is considered to be equivalent to the Minobu Formation, because 1) some characteristic sequences of the underlying Shimobe Formation can be traced from Minobu area to Manzawa area bordering on Utsubuna Anticline, and 2) lithologically, the Fukushi Tuff (including the Yorihata Pyroclastics) are thought to correspond to the Karasumoriyama Pyroclastics, that is, the lowest member of the Akebono Formation in the Minobu and Akebono areas (FUJIKAWA COL. RES. GR., 1976). The thickness of the Manzawa Formation is up to 2500 m and is nearly equal to that of the Minobu Formation. The formation, however, is slightly different from the Minobu Formation in having more tuffaceous materials.

The Toshima Alternation is mainly distributed in the central part of Manzawa area (Fig. 5). As dacitic tuff and chaotic pebbly siltstone can be traced as key beds laterally from the Toshima Alternation to the Manzawa Alternation, most of the Toshima Alternation can be shown to be stratigraphically equivalent to the Manzawa Alternation. The Machiya Alternation overlies conformably both the Toshima Alternation and the Manzawa Alternation.

Intrusive rocks of gabbro-diolite complex and porphyrite, named Sanogawa Intrusive Rocks, are very common in the eastern part of this area, with a local contact metamorphism (YAZIMA, 1970).

Akebono area

In Akebono area, the Fujikawa Group is divided into the Hara Mudstone and the Akebono Formation in ascending order (AKIYAMA, 1957; MATSUDA, 1958; 1961). The Hara Mudstone is safely correlated with the Shimobe Formation and the Minobu Formation of Minobu area. Both sequences of the underlying Nishiyatsushiro Group and the overlying Akebono Formation, are traceable from Minobu area to Akebono area (AKIYAMA, 1957; MATSUDA, 1958; FUJIKAWA COL. RES. GR., 1976). In addition, this correlation is supported by the study of foraminiferal biostratigraphy by UJIIE & MURAKI (1976) in the Akebono area, and by CHIJI & KONDA (1978) in Minobu area. The Hara Mudstone consists mostly of massive siltstone with thin-bedded sandstone that decreases abruptly in thickness to the north.

Aimata domain

Aimata area

Aimata area is located on the western side of Fuji River and bounded to the east by Minobu area at the Minobu fault. According to MATSUDA (1961) and SHIMAZU *et al.* (1984), three formations are recognized in the Aimata area; the Gotenyama Formation of the Nishiyatsushiro Group, the Kuonji Mudstone and the Aimata Formation (the Takatoriyama Pyroclastics) of the Fujikawa Group in ascending order. MATSUDA (1961) and SHIMAZU *et al.* (1984) correlated the Aimata Formation with the Minobu Formation. This correlation is accepted in this paper, although a further study is required to confirm it.

The Aimata Formation, up to 2000 m thick, is composed mainly of hyaloclastic sediments such as andesitic and/or basaltic lava and tuff-breccia, intercalated with siltstone. The Aimata Formation is conspicuously different lithologically from the sequences of Fujikawa and Nishikatsura domains. I believe that the Aimata Formation is considered to have been deposited in a seamount environment basing on their characteristic sedimentary facies. Details on this interpretation, however, is out of duty of this paper.

4. SEDIMENTARY FACIES OF THE MINOBU FORMATION AND ITS EQUIVALENT STRATA

Based on lithologic and sedimentologic characteristics such as clast or grain size, sedimentary structures and bedding style, turbidites and associated coarse clastic deposits can be classified into several "Facies" consisting of a layer or group of layers. In the present study, descriptive classification of "Facies" is preferred rather than a genetic one deduced from the inferred depositional mechanism. In the Minobu Formation and its equivalent strata, sixteen facies are recognized, which can be grouped into five megafacies (Table 3).

1) Conglomerate and Pebbly Sandstone Megafacies

Facies A1: *thick-bedded disorganized conglomerate*

Facies A1 comprises poor-sorted, clast-supported conglomerate, containing clasts of cobble to granule sizes. Bed thickness ranges from 50 cm to 8 m (2 m average). It shows rapid lateral thickness change. Most beds have erosional, uneven-bases. Beds of this facies are massive (ungraded) or massive to normal-graded (in the sense of DAVIS & WALKER, 1975), occasionally inverse-graded to massive or more

Table 3. Classification of Sedimentary Facies.

1) Conglomerate and Pebbly Sandstone Megafacies	
Facies A1	: Thick-bedded disorganized conglomerate
Facies A2	: Thin-bedded poor-sorted conglomerate
Facies A3	: Well-sorted conglomerate
Facies A4	: Ungraded parallel-stratified conglomerate and sandstone
Facies A5	: Ungraded cross-stratified conglomerate and sandstone
Facies A6	: Massive pebbly sandstone
2) Sandstone Megafacies	
Facies B1	: Thick- to medium-bedded massive sandstone
Facies B2	: Coarse-grained parallel-stratified sandstone
Facies B3	: Cross-stratified sandstone
Facies B4	: Fine-grained parallel and thin-bedded sandstone
3) Alternations of Siltstone and Sandstone Megafacies	
Facies C1	: Sandstone interbedded with siltstone
Facies C2	: Siltstone interbedded with ripple cross-laminated sandstone
Facies C3	: Siltstone interbedded with thin-bedded coarse-grained sandstone
4) Chaotic deposits Megafacies	
Facies D1	: Pebbly siltstone
Facies D2	: Chaotic deposit with coherent folded/ contorted strata
5) Volcaniclastic Megafacies	
Facies E	: Volcaniclastic deposit

rarely inverse-graded to normal-graded. Clast organization such as preferred clast orientation and imbrication has not been observed.

Facies A2: *thin-bedded poor-sorted conglomerate*

Facies A2 comprises very poor-sorted, matrix- or clast-supported conglomerate. Although the conglomerate contains boulders to coarse pebbles, it is thin-bedded ranging from 5 cm to 40 cm thick. Most of the conglomerates show lenticular bedding with erosional base and well-stratified upper surface. Beds are massive and/or crude inverse- or normal-graded. Clast organization is not so developed. This facies is considered to represent channel lag sediments.

Facies A3: *well-sorted conglomerate*

Facies A3 is the second commonest facies in Conglomerate and Pebbly Sandstone Megafacies. It comprises matrix- or clast-supported and well-sorted conglomerate. Clasts are mostly coarse pebble to granule. The matrix consists of coarse- to medium-grained sand. Bed-thickness is 20 cm up to 6 m with average 80 cm. Most of the beds have sharp and erosional bases, and are either massive to normal-graded, or nomal-graded, or more rarely inverse- to normal-graded. Many of them show distinct clast imbrication. Inclination of clast is relatively high (20–35 degrees) in the lower part of the bed, but gradually decreases upward. Longest axes (A-axis) of clasts of this facies are aligned parallel to the paleocurrent direction. Flute marks are common on the sole of this facies.

Facies A4: *ungraded parallel-stratified conglomerate and sandstone*

Facies A4 comprises parallel-stratified alternations of ungraded conglomerate, ranging from 10 cm to 60 cm in bed thickness, and ungraded coarse-grained sandstone or pebbly sandstone, ranging from 5 cm to 1 m thick. Thickness of the alternation is 20 cm to 6 m, and 60 cm on an average. Bed boundaries are poorly defined, this facies often grades upward or downward into other facies. The conglomerate is matrix-supported and well-sorted. Clasts are mostly less than 6 cm across. A-axes of clasts are aligned parallel to bedding surface without any conspicuous clast imbrication.

Facies A5: *Ungraded cross-stratified conglomerate and sandstone*

Facies A5 comprises ungraded conglomerate and pebbly sandstone with trough-cross stratification. This facies is uncommon. Internal stratification surfaces are smooth, but the base of cross-stratified units scour underlaying beds. Most units are 10 cm to 60 cm thick. Inclination of cross stratification is up to 30 degrees. Conglomerate consists of well-sorted and matrix-supported. Most clasts are less than 3 cm across, and are aligned parallel to cross stratification. Clast imbrication seems to be absent.

Facies A6: *massive pebbly sandstone*

Facies A6 comprises poorly sorted, coarse- to very coarse-grained sandstone with clasts of granules and/or pebbles totalling less than 5%. Most clasts are concentrated on the bottom surface, but some of them are scattered throughout the sandstone bed. Abrupt normal grading is developed. Current ripples are often recognized in the uppermost part of the bed which are interpreted to have deposited from the entrained layer of MUTTI & RICCI-LUCCHI (1972). Inverse grading is rarely seen. Many rip-up clasts are contained in the upper part of the bed. At bed bases, various sole marks such as flute mark are recognized.

2) **Sandstone Megafacies**

Facies B1: *thick- to medium-bedded massive sandstone*

Facies B1 is the commonest facies of Sandstone Megafacies. It comprises coarse- to very coarse-grained sandstone. Some of sandstones have dish structures and/or crude coarse-tail gradings, but most of them are structureless. Bed-thicknesses of sandstones are 30 cm to 3 m (mostly 60 cm to 1 m). Base of sandstone bed shows gentle scouring. Amalgamation of beds is common. Most sandstone beds contain many rip-up clasts which tend to be arranged on a certain plane in the upper part of sandstone bed. Flute marks are frequently recognized on the sole surface.

Facies B2: *coarse-grained parallel-stratified sandstone*

Facies B2 comprises fine- to medium-grained sandstone characterized by the development of horizontal thick-stratification. Beds are 10 cm to 120 cm thick, 40 cm on an average. The base of the sandstone bed is not sharp and does not show scouring. Most sandstones are crudely normal-graded, or ungraded. This facies often grades into other facies below and above.

Facies B3: *cross-stratified sandstone*

Facies B3 consists of fine- to very coarse-grained sandstone characterized by development of trough-cross thick-laminations. Co-set thickness of cross laminations is 10 cm to 1 m (mostly 30 cm to 50 cm) occasionally up to 3 m. The bases of the co-set are erosional scouring into subjacent layers. In each cross-stratification, crudely normal grading is recognized. Inclinations of cross lamination are less than 20 degrees.

Facies B4: *fine-grained parallel and thin-laminated sandstone*

Facies B4 comprises parallel laminated alternations of fine- to medium-grained sand, and silt to very fine-grained sand. Some alternations show wavy laminations. Thickness of the sandstone is 2 cm to 1 m (mostly 10 cm to 15 cm). Bases of sandstone beds are flat and do not show any remarkable scourings. Basal boundary is generally poorly defined. Facies B4 often grades from Facies B1. No grain organization except for parallel lamination can be observed.

3) Alternations of Siltstone and Sandstone Megafacies

Facies C1: *sandstone interbedded with siltstone*

Facies C1 comprises rhythmic alternations of sandstone and siltstone referable to turbidite of classical definition (e.g. BOUMA, 1962; WALKER, 1967). Bed-thicknesses of the sandstone and siltstone are 10.2 cm and 5.1 cm on an average respectively, and the thickness ratio of sandstone and siltstone is 1.8 to 2.3, with 2.0 on an average. Sandstone is fine- to coarse-grained, and is normally graded. The base of sandstone beds are flat and sharp. Bouma sequences (Bauma, 1962), especially Tac and Tbc, are developed in the sandstone bed, but d division (upper parallel lamination) is not recognized. Various sole markings and trace fossils on the bottom surface are abundant. Most of sandstone change upward gradually into siltstone. Siltstone is massive and unicolor, and can not be subdivided into turbiditic and hemipelagic parts.

Facies C2: *siltstone interbedded with ripple cross-laminated sandstone*

Facies C2 is one of the commonest facies in the study area. The facies comprises monotonous siltstone interbedded with sandstone. Sandstone is mainly fine- to medium-grained, but sometimes coarse-grained. The average thicknesses of sandstone and siltstone beds are 2.8 cm and 13.3 cm, respectively, with a thickness ratio of approximately 0.2. Sandstone bed shows flaser bedding, current ripple lamination (BOUMA's c) and crudely normal-grading. Siltstone is poorly sorted, massive and unicolor.

Facies C3: *siltstone interbedded with thin-bedded coarse-grained sandstone*

Facies C3 comprises siltstone interbedded with coarse-grained, sometimes pebble-bearing sandstone. At a glance, the bedding of sandstone seems to be continuous laterally in a orderly way, but as carefully observed, most sandstone beds are irregular in thickness, and show lenticular beddings pinching out laterally over a short distance. Siltstone is massive and poorly sorted. This facies is accompanied with facies C2 in many cases. Based on the characteristics of intercalated sandstone bed, two subfacies are distinguished. Small size flute marks are often observed.

Subfacies C3–a: Subfacies C3–a contains medium- to very coarse-grained sandstone which is crude normal-graded or massive. It shows well-stratified surfaces both at the base and at the top, and lateral thinning of bed-thickness.

Subfacies C3–b: Subfacies C3–b comprises fine- to very coarse-grained sandstone with a few granules, which is normal-graded, rarely with current ripple lamination in the upper part of the bed. Base of the bed is to scour the underlying beds. The shape of sandstone beds is lenticular. The sandstone of this subfacies gradually changes upward into siltstone. Subfacies C3–b may be fill-sediments of minor channels.

4) Chaotic Deposit Megafacies

Facies D1: *pebbly siltstone*

Facies D1 consists of poorly sorted muddy siltstone containing angular clasts of andesite and basalt, 5 cm to 1.2 m in size. Many slump-folded blocks and/or rip-up clasts are frequently contained in it. Pebbly siltstone beds form lenticular sedimentary bodies with erosional base, a few tens to hundreds of metres across and 40 cm to 20 m thick. Normal grading is often observed.

Facies D2: *chaotic deposit with coherent folded/contorted strata*

Facies D2 is least developed in the study area. It comprises poorly sorted siltstone with transported blocks of contorted strata suffering coherent folding and deformation, and some pebbles. Beds of this facies are 40 cm to 5 m thick. Basal boundary is flat, and scouring of the subjacent layer is not recognized.

5) Volcaniclastic Sediments Megafacies

Facies E: *volcaniclastic deposit*

Facies E is composed of volcaniclastic materials, such as dacitic to andesitic tuff and tuff-breccia. Bed thickness is 2 cm to 2 m. Bed bases are flat and sharp. Most of the beds have normal grading, parallel stratification, and rip-up clasts of siltstone. Rill marks are observed on the sole of several beds.

5. FACIES ASSOCIATION

Facies association (Mutti & Ricci-Lucchi, 1972; 1975) is composed of a combination of facies, that make a preferred facies transition and form a characteristic sedimentary body of various scales and degree of organization. Facies association is considered to reflect the spacial expression of a depositional environment and process, and not directly corresponds to stratigraphic units such as a member and formation. Since Mutti & Ricci-Lucchi (1972), several attempts have been made to compare turbidites and associated coarse clastic deposits with those of reported modern and ancient turbidite basins, and have developed a concept of facies association for interpretion of turbidite paleoenvironments (Mutti & Ricci-Lucchi, 1975, Mutti, 1977, Walker, 1978, Underwood & Bachman, 1983, and others).

In the Minobu Formation and its equivalent strata, eight facies associations can be recognized, and they are grouped into coarse clastic association group, fine clastic association group and Pebbly Siltstone association (PMA). Coarse clastic association group is composed of Sandy association (SDA), Conglomeratic association

Table 4. List of Facies Association in the four different areas.

Fujikawa domain		Nishikatsura domain	
Manzawa area	Akebono area	Minobu area	Nishikatsura area
Conglomeratic-sandy ass. SCA Sandy-silty ass. SSA Silt ass. SMA	Sandy ass. SDA silty ass. SIA	Conglomeratic ass. GSA Sandy ass. SDA Silty ass. SIA	Conglomerate-sandstone ass. CPA
Pebbly mudstone association PMA			

(GSA), Conglomeratic-sandy association (SCA) and Conglomerate-sandstone association (CPA). Fine clastic association group consists of Silty association (SIA), Sandy-silty association (SSA) and Silt association (SMA). The Minobu Formation and its equivalents in the four different areas mentioned above, are each represented by the characteristic combination of these facies associations (Table 4).

Description of Facies Association

(1) Sandy association (SDA)

SDA can be recognized in the Hakii Alternation of Minobu area and the Hara Mudstone of Akebono area. SDA is exposed in many outcrops on the bank of Fuji River, for example at Loc. a and d in Fig. 7 and 8.

1-a: Facies component and facies transition

SDA consists of Facies B1, B2, B3, B4, C2 and C3 accompanied by Facies A1, A3 and A6. Vertical succession of these facies was observed in the fields and analysed by the modified markov chain analysis (POWER & EASTERLING, 1982). Examples of the measured data of facies transition are shown in Fig. 9. Results of the analysis on the preferred sequence is shown in Fig. 10.

Characteristic features of SDA are summarized as follows. 1) The preferred facies transition is interpreted as a fining upward sequence (Fig. 9), that is, Facies A1, A3, A6 and B1 with erosional bases tending to change into Facies C2 and C3 through Facies B3, B2 and B4. 2) The thickness of fining upward sequence ranges from 2 m to 8 m. 3) Coarse-grained sedimentary facies such as A3, B1, B2 and B3 are predominant in the sequence, and fine-grained sedimentary facies such as Facies C2 and Facies C3 occupies only a few per cent of the total volume.

1-b: Geometry and internal structure

One of the important features of SDA for the analysis of the sedimentary process is the morphology of the sedimentary body. In a N-S transverse section (Fig. 7), normal to paleocurrent direction, SDA forms a lenticular sedimentary body several tens of meters to a few hundred meters wide and several meters to a few tens of meters thick without exception.

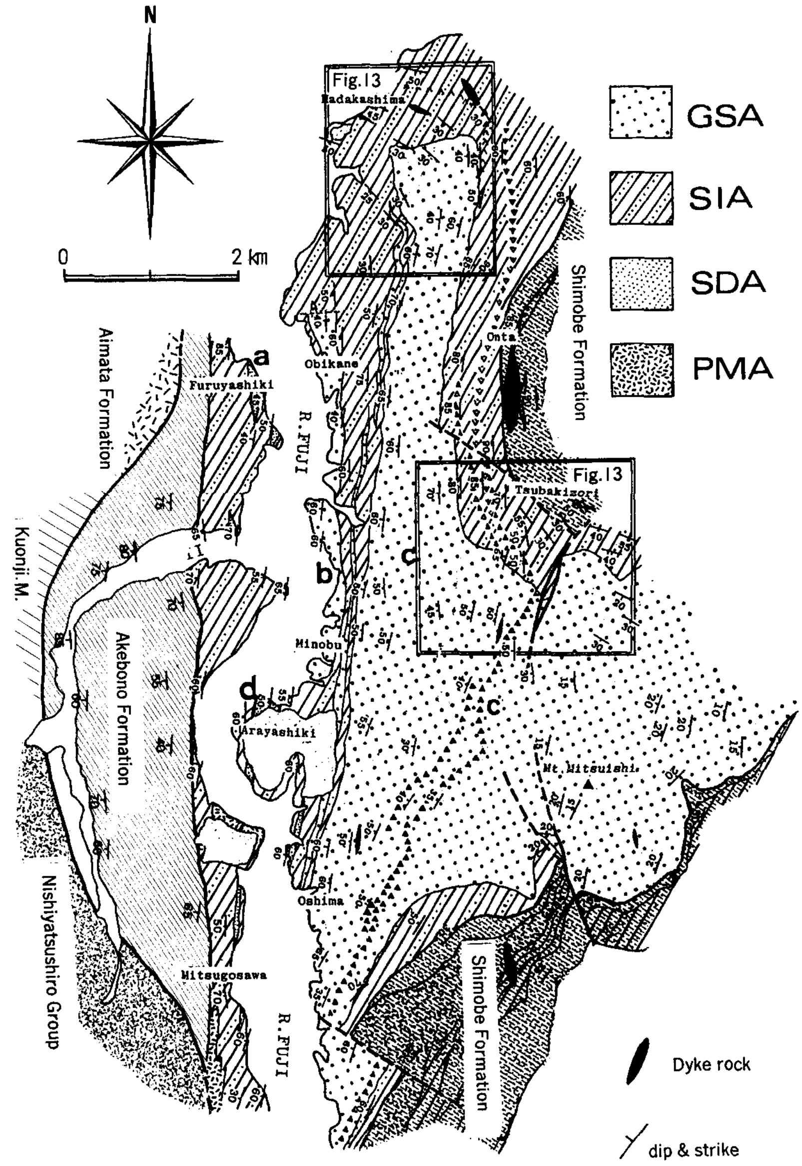


Fig. 7. Facies association map of Minobu area.

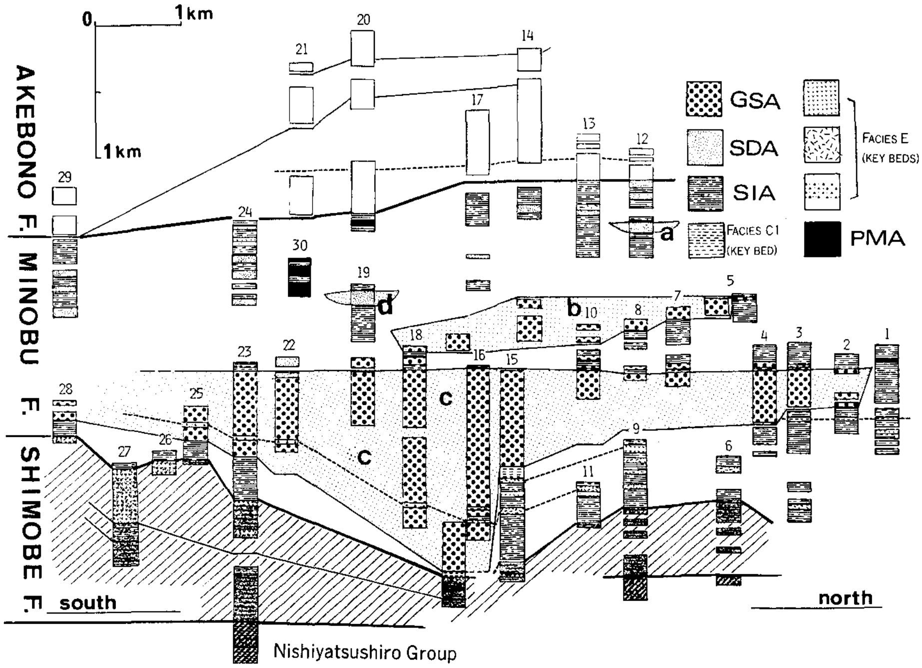


Fig. 8. Morphology of GSA and SDA, in the profile normal to paleocurrent direction. Solid and broken lines indicate the boundaries of facies association and key beds respectively. For location of each column, see Fig. 23.

Furuyashiki Sedimentary Body, named for one of the SDA, is well-exposed at the cliff to the west of Furuyashiki (Loc. a in Figs. 7 and 8). In the Cliff, N-S trending profiles of the southern part of the overlying Furuyashiki Sedimentary Body and the surrounding SIA are exhibited. Dip and strike of beddings within the body and of the surrounding SIA can be observed to be parallel each other. However it should be noticeable that the boundary surface shown as line a-a' in Plate 2-1, which is conspicuous and sharp, is gently oblique to the bedding plane, constituting a "concave-up arch". When tilting correction of the bedding plane is made, this boundary surface dips northwest at a little less than 20 degrees. Paleocurrent direction measured within the body is of concordance with strike of the original boundary surface. Beds within the body thin rapidly toward the boundary surface abutting and onlapping at this boundary. Thus, the basal surface is considered to represent a part of erosional wall. Upper boundary of SDA can be observed at several outcrops. In an outcrop, east of Furuyashiki (see, Plate 2-3), upper boundary of Furuyashiki Sedimentary Body is observed to be nearly flat and gradational to the overlying SIA in contrast to that of the basal boundary. Detailed mapping work between inter-outcrops indicates that the upper boundary is in parallel with the bedding plane of adjacent SIA and bedding within the sedimentary body.

On the other hand, an E-W profile of sedimentary body of SDA, that is parallel to paleocurrent direction, can be observed at the cliff north of Arayashiki. The boundary of Arayashiki the sedimentary body and the underlying beds (a-a′ in plate 2-2) shows a conspicuous surface nearly concordant and parallel to bedding planes. Beds within the sedimentary body are continuous and uniform in thickness and sedimentary structures, in contrast to those of the N-S profile described above. Based on these two profiles, different in relation to paleocurrent direction, they can give a three-dimensional morphology of sedimentary body of SDA. Details of the morphology are discussed later.

Internal structure of Furuyashiki Sedimentary Body is characterized by a series of superimposed thinning and fining upward sequences with scoured bases often incised a few meters deep. Individual beds within the sedimentary body are variable in thickness, and are laterally discontinuous.

These features of its morphology and internal structure are commonly recognized in many other sedimentary bodies of SDA, for examples, Arayashiki and Kitahara Sedimentary bodies.

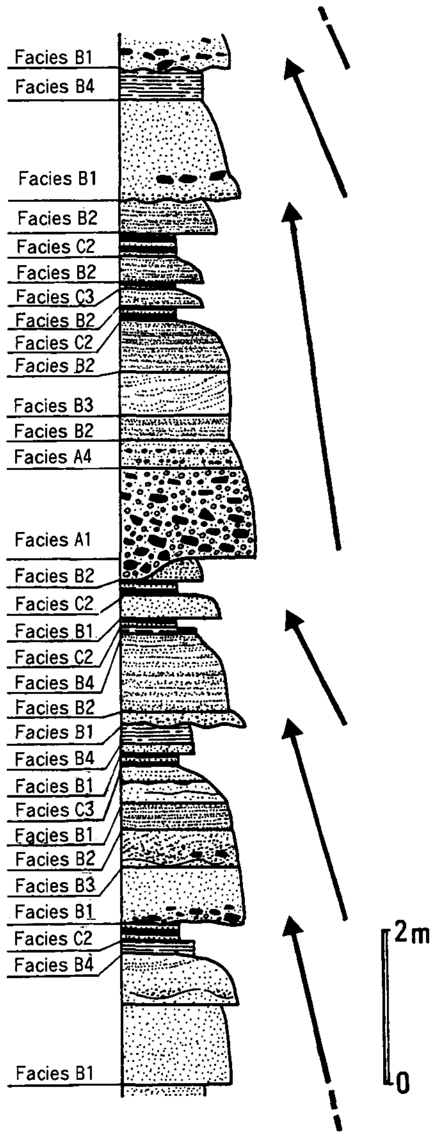


Fig. 9. An measured section of Kitahara Sedimentary Body, showing sedimentary facies and cycles in the sandy association (SDA). Arrows indicate fining-upward sequences.

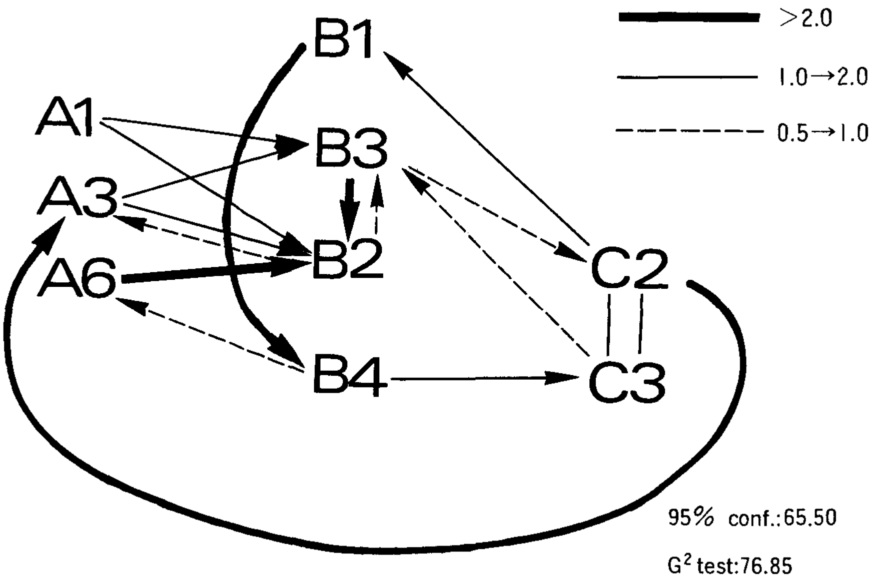


Fig. 10. Transitional pattern of sedimentary facies in the sandy association (SDA). after Powers & Easterling (1982).

(2) Conglomeratic association (GSA)

GSA is exposed in Minobu area only, along the highland area on eastside of Fuji River from Hadakazima to Nanbu, which correspond to most of the Marutaiki Conglomerate as a stratigraphic unit. Good outcrops of GSA can be observed along Kuwagara Stream.

2–a: Facies components and facies transition

GSA consists mainly of Facies A1, A3, A6, B1, B2, B3, B4, C3 and C2 intercalated with A5 and E1. Facies D1 can not be observed. Facies described above are complexly interbedded one another, so that, the modified Markov chain analysis (POWER & EASTERLING, 1982) is made for determining preferred facies transition. According to this analysis, the following relationships of facies transition can be suggested (Figs. 11 & 12). 1) GSA has a preferred facies sequence changing upward from Facies A1, A3, A6 and B1 (with erosional bases) into Facies C2 and C3 through Facies A4, B3, B2 and B4 (Fig. 12). 2) Preferred sequences of GSA are also interpreted as fining upward sequences, although they are more complex and irregular than those of SDA.

2–b: Geometry and internal structure

GSA forms a conspicuously sedimentary body like SDA, but larger than the

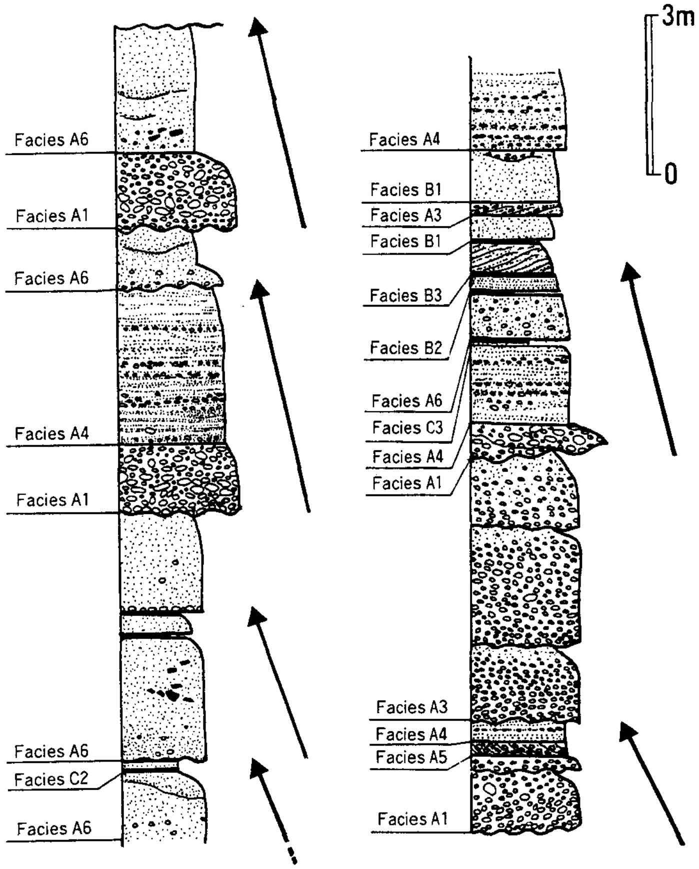


Fig. 11. An measured section showing sedimentary facies and cycles in GSA. Arrows indicate fining-upward sequences.

latter being 3 km to 13 km across in the N-S section and 20 m to 2000 m thick. Marutaki Sedimentary Body, shown as c in Fig. 7 and 8, is the largest and most widely distributed in the east of Marutaki. It offers a good example for investigating detailed morphology and internal structures of the sedimentary body of GSA.

Outline of the N-S profile, normal to paleocurrent direction, of Marutaki Sedimentary Body looks like a section of "baseball-type cap" placed upside down (Fig. 8). Unfortunately, lowest base of the sedimentary body is not exposed, but basal boundary of the northern marginal part, that is the wing of "cap", is well-exposed (Loc. b. and c. in Fig. 13). In those outcrops, the base of the sedimentary body, usually sharp and conspicuous one, seems to be in parallel with the underlying bedding surface. However, the base of the sedimentary body should be interpreted

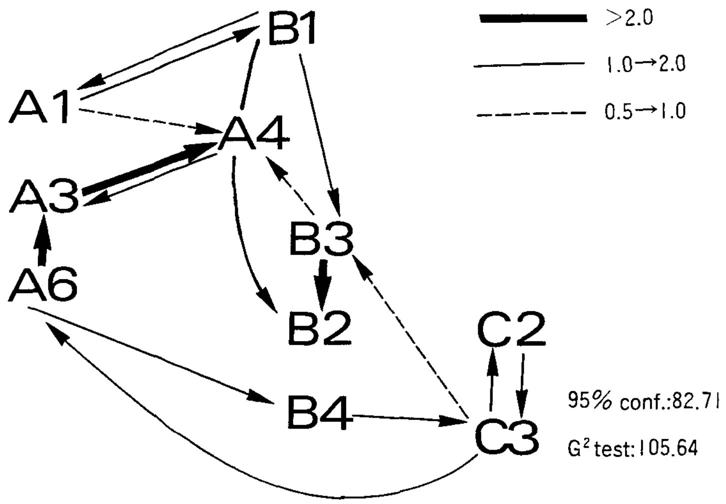


Fig. 12. Transitional pattern of sedimentary facies in GSA. after Powers & Easterling (1982).

to scour the underlying SIA. This is because it is slightly oblique to the bedding plane of the underlying SIA, when tracing the several outcrops laterally (Fig. 8). Additionally, according to the detailed facies map (Fig. 13-A), the disruption of the key bed in the underlying SIA is recognized to the north of Onta, indicating the erosion of the underlying SIA.

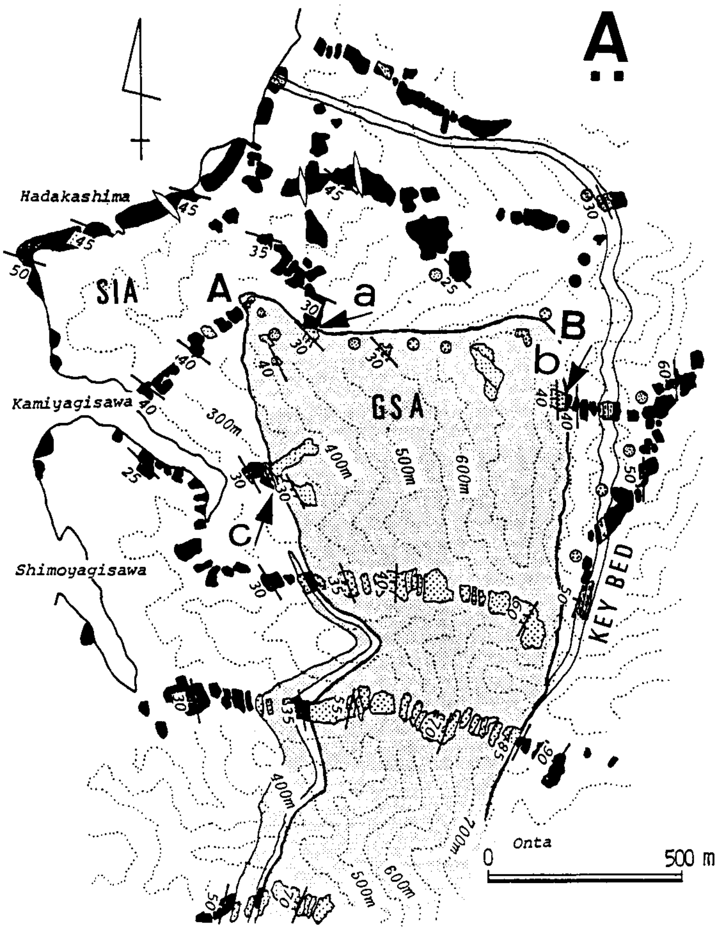
At the northern wing of the sedimentary body, the boundary surface between the sedimentary body and the laterally juxtaposed SIA, clearly discord with the bedding plane of both GSA and SIA. Judging from the detailed facies map at the north-western tip of "cap" in Hadakashima area, the dip and strike of the boundary surface (as shown A-B line in Fig. 13-A) is estimated to be approximately N80W 65S. In contrast, these bedding planes display approximately N40W30SW.

In addition, the same characteristic phenomenon is recognized at the northern part of the "cap" in Okuzure (Fig. 13-B). Judging from the topographic map in which the locations of outcrops are plotted (Fig. 13-B), the basal boundary of Marutaki Sedimentary Body at Okuzure is conspicuously oblique to the bedding planes of GSA and SIA, and scours to the underlying SIA. The boundary contacts around Okuzure are also observed to be sedimentary, and not to be faulted (Loc. e in Fig. 13-B). Such erosional structure of the basal boundary to the underlying SIA, and the obliqueness of the boundary surface to the bedding planes are strongly influenced by the original topography reconstructed as a bottom of large-scale "groove structure" on the sea-floor, and a wall of "groove structue" with a ralative high angle, relatively.

Basal boundary of the southern half of the sedimentary body, however, is not so clear because of dense vegetation and limited outcrops.

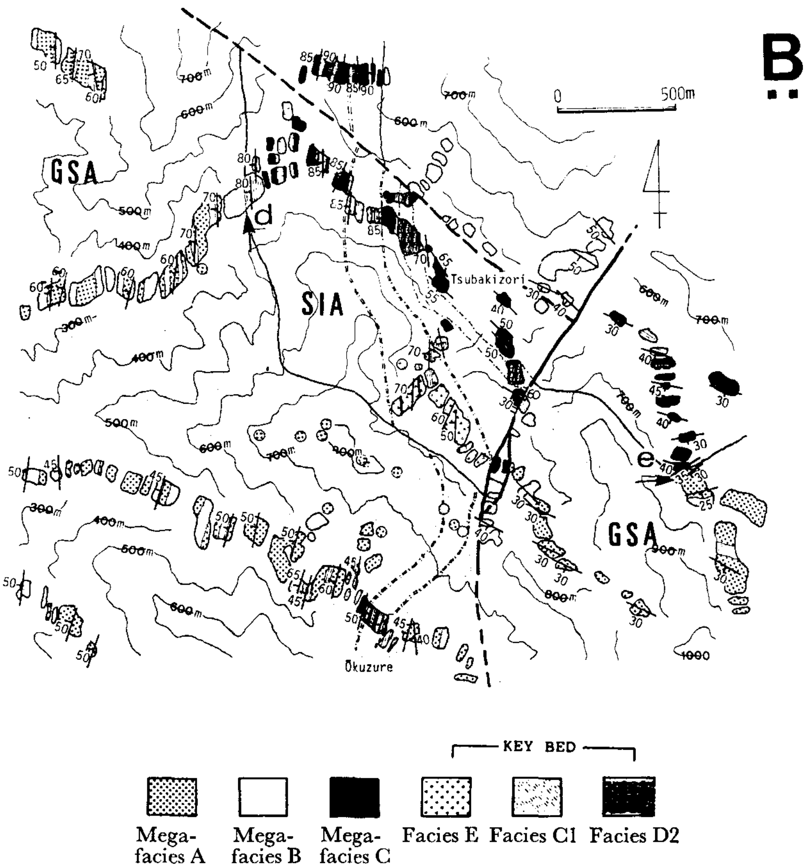
The upper boundary of Marutaki Sedimentary Body can be traced for 15 km in N-S direction. It is of structural concordance with the overlying beds of SIA (Fig. 7), and a gradational transition to the latter can be observed in many outcrops such as Loc. c in Fig. 13-A.

As a whole, the distribution of Marutaki Sedimentary Body extends along NNE-SSW parallel with the direction of paleocurrent measurements of the sedimentary body (MATSUDA, 1958).



A: Hadakashima area, on tip of the "cap" of Marutaki Body. Heavy line is the boundary of the conglomeratic (dotted part) and silty associations. Thin lines indicate a key bed.

Fig. 13.



B: Okuzure area, on the northern part of Marutaki body. Boundary of conglomeratic and silty associations is oblique to the dip and strike of beddings and key bed. 1. dyke rocks, 2. floating block, 3. dip and strike. a, b, c, d, e, means localities of the outcrops showing the contact of two associations.

Fig. 13. Topographic maps with location of outcrops in the northern part of Marutaki Sedimentary Body.

Internal structure of Marutaki Sedimentary Body is seems to be represented by a series of superimposed fining upward sequences with basal scouring up to a few meters deep. Most beds within the sedimentary body are laterally discontinuous.

Basically identical characteristic features are recognized in Obikane Sedimentary Body of GSA which has similar facies components to those of Marutaki Sedimentary Body of GSA. These characteristics are thought to be common features of the sedimentary bodies of GSA.

(3) Silty association (SIA)

SIA is widely exposed along Fuji River from Minobu to Akebono areas, and composes the most part of the Yagisawa Mudstone, the Hakii Aternation and the Hara Mudstone. SIA is partially heterotopic but contemporaneous with GSA and SDA.

3–a: Facies component and facies transition

SIA is composed mainly of Facies C2 intercalated with Facies C3, and sometimes contains Facies C1, E1 and D2 (Plate 3-1). Positive preferred facies transition in this association can not be recognized. Distinct sedimentary cycles such as a thinning or thickening upward sequences are also not observed.

3–b: Distributional pattern

SIA does not form any sedimentary body of a definite shape, but is extensively developed surrounding GSA and SDA (Figs. 7 and 8). Broadly speaking, SIA is monotonous throughout the study area. However, local variations of the dominated sedimentary facies, and of thickness ratio of sandstone and siltstone of the same sedimentary facies are recognized. For examples, in Tsubakizori near the boundary of Marutaki Sedimentary Body, Facies C1 is better developed than facies C2 and C3. Additionally, the thickness of sandstones in Facies C3 tends to decrease around Teuchizawa, and to increase around Mitsugozawa.

(4) Conglomerate-sandstone association (CPA)

CPA is distributed in Nishikatsura area. Details of the sedimentary features of CPA can be observed in Tonoirisawa Stream (Loc. a in Fig. 6). The Katsuragawa Conglomerate corresponds to this facies association.

4–a: Facies component and facies transition

CPA consists of Facies A1 and A3 with intercalation of facies A2, A4, A5, A6, B2 and B3 (Fig. 14 & Plate 1-3, 1-4, 1-5, 1-6). Positive preferred facies transition can not be obtained from the statistical analysis. It appears that the association is monotonous laterally as well as vertically. However, in some vertical sequence of CPA, crude finning upward sequence, that is Facies A1, A2 and A3 with erosional base tending to shift gradually Facies B2 and B3 through Facies A4, are recognized.

4–b: Geometry and internal structure

CPA is continuously distributed as a narrow belt along Nishikatsura Fault, extending in an ENE-WSW direction for 20 km, from Iwadono to Lake Kawaguchi. Longitudinal profile of the distribution is parallel to the paleocurrent direction measured from CPA.

Two different kinds of the boundary between CPA and the underlying strata are observed. Around Tonoirisawa (Loc. a in Fig. 6), the underlying Furuya Sandstone changes gradually into CPA with an increasing the intercalation of conglomerate beds. However, the boundary is sharp in outcrops forming a base of channel structure (Plate 1-1). The boundary surface is mapped approximately parallel to the bedding planes of both CPA and the underlying Furuya Sandstone. On the other hand, in the area from Kamiohata to Asari (Fig. 6), the boundary is oblique to bedding plane of the underlying strata. Many angular clasts of the underlying Nishiyatsushiro Group, are observed on the uneven boundary surface (e.g. outcrops south to Asari) indicating the erosion to the underlyings. Judging from a geologic map (Fig. 15), such erosional surface can be traced from Asari to Kami-Ohata. Original strike of the erosional surface, when making bedding correction, is parallel with the paleocurrent direction measured within CAP, that is, in parallel with the elongation of the distribution of CPA.

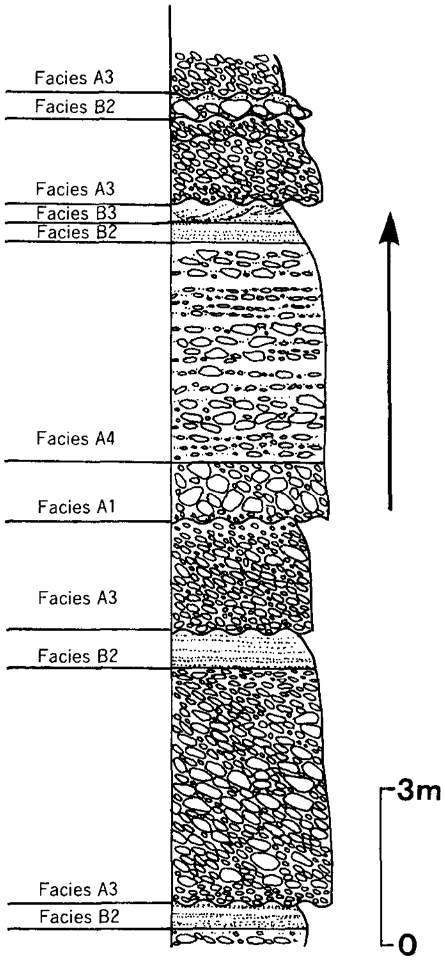


Fig. 14. An example of the measured section of CPA. At Hishakuruzawa.

Upper boundary of CPA can not be observed in Nishikatsura area due to cutting by Nishikatsura Fault.

As to the internal structure, CPA seems to be structureless with the exception of minor channel structures (Plate 1-1). Beds of CPA show to be rather continuous in thickness than that of GSA mentioned above.

(5) Conglomeratic-sandy association (SCA)

SCA is widely distributed in Manzawa area (Fig. 16), which corresponds to the Toshima Alternation and the most part of coarse-grained sediments within the Utubuna Alternation and the Manzawa Alternation. Good exposure is found on the right bank of Fuji River west of Hashinoue.

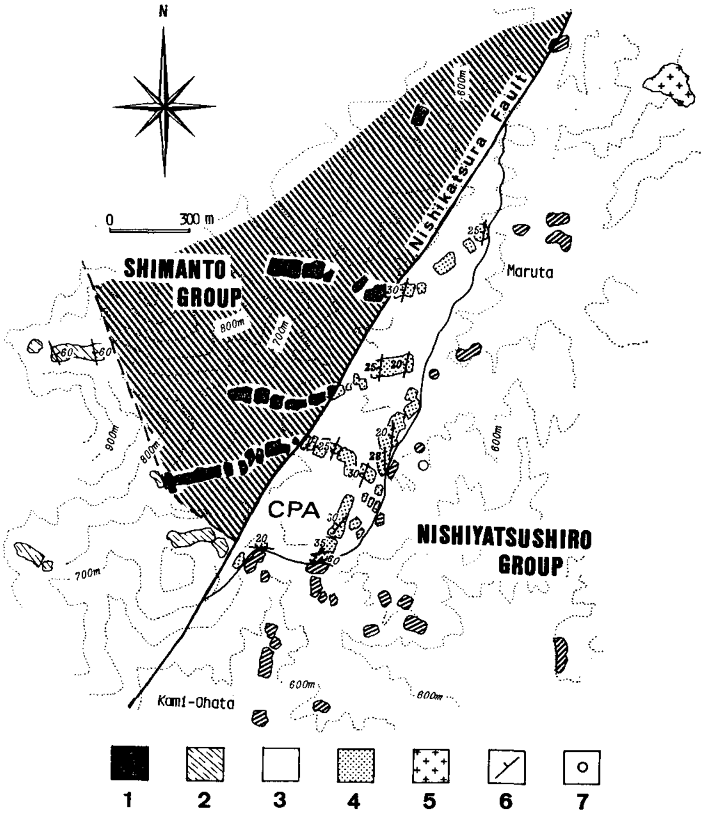


Fig. 15. Topographic map with location of outcrops in Maruta, see Fig. 6 for map location. Note that CPA directly about to the underlying Nishiyatsushiro Group. 1. black shale of "Shimanto Group", 2. alternations of sandstone and mudstone (Kawaguchi Formation, Nishiyatsushiro group), 3. altered pyroclastics (Onuma Formation, Nishiyatsushiro group), 4. Conglomerate-sandstone association (CPA), 5. intrusive rocks (porphyrite), 6. dip and strike, 7. floating block.

5-a: Facies component and facies transition

SCA is composed of Facies A3, A6, B1, B2, C2 and C3 interbedded with Facies A1, A2, A4, B3, B4, C1 and E1. Facies D2 is also frequently contained within them (Fig. 17). Result of the modified Markov chain analysis indicates that the association has positive preferred facies transitions, which are principally regarded as fining-upward sequences (Fig. 18). An example of measured data of facies transition, is shown in Fig. 17. SCA is more complicated and variable laterally than GSA due to frequent intercalations of both chaotic deposits and fine clastic sediments classified as Facies D1, D2 C2 and C1. Noteworthy is that the distribution of Facies A1, A2 and A6 tends to be confined to the central part northwest of

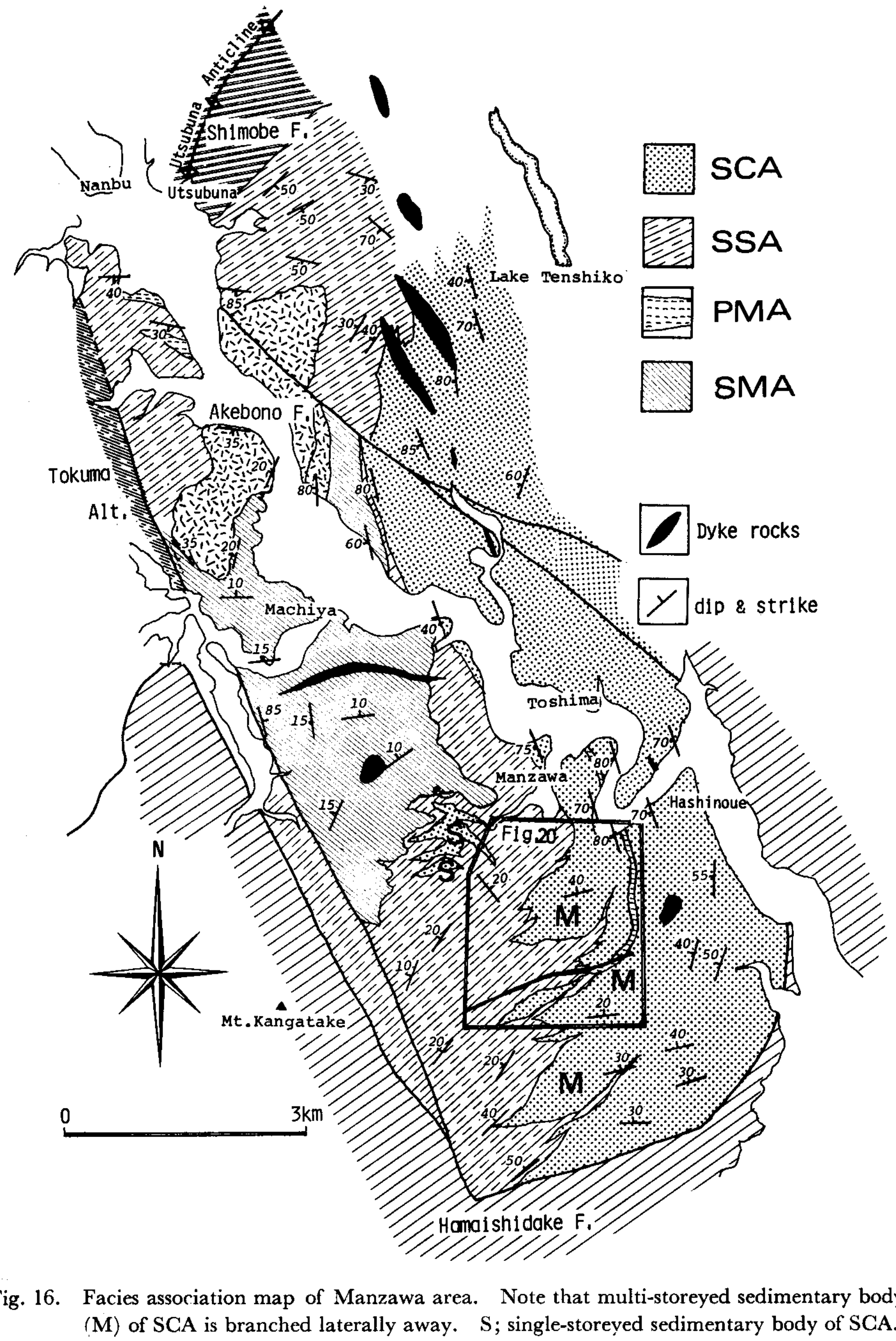


Fig. 16. Facies association map of Manzawa area. Note that multi-storeyed sedimentary body (M) of SCA is branched laterally away. S; single-storeyed sedimentary body of SCA.

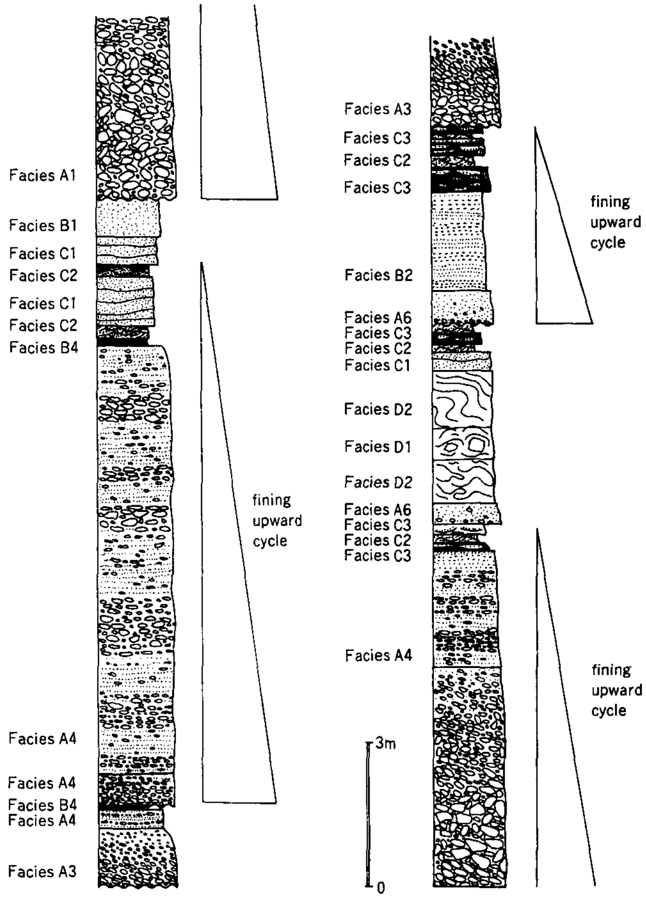


Fig. 17. An example of the measured section of SCA, showing fining-upward sedimentary cycles.

Hashinoue.

Many thinning-upward sedimentary cycles of 20 m up to 100 m thick are observed in SCA (Fig. 19). Alternations of Siltstone and Sandstone Megafacies, a few metres to 30 m thick, are frequently contained in the upper part of the sedimentary cycles. Most sequences of this cycle, however, comprise Conglomerate and Pebbly Sandstone Megafacies and Sandstone Megafacies only. Facies D1, D2 and E are minor compornent, occasionally intercalated in the upper part of the cycles.

5–b: Geometry and internal structure

SCA forms a lenticular sedimentary body in the profile normal to the paleocurrent direction measured within SCA. In morphology, two different types are recognized in the sedimentary body of SCA. The first one is single-storeied

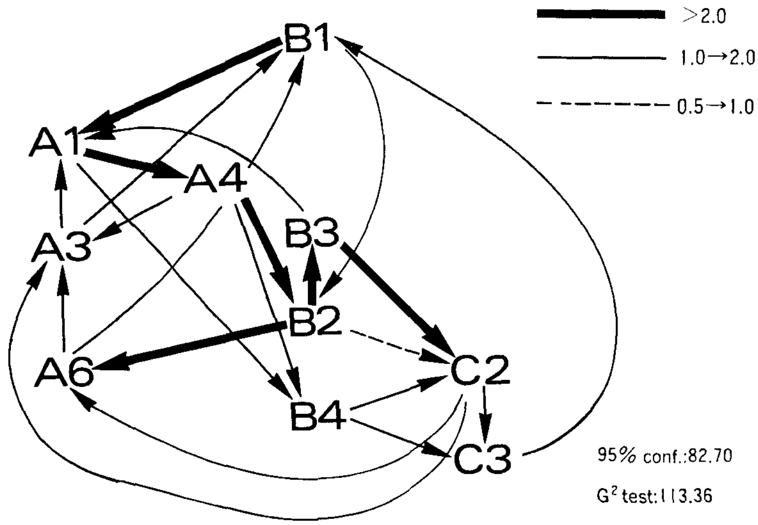


Fig. 18. Transitional pattern of sedimentary facies of SCA, showing fining-upward sequence.

sedimentary body, which is developed western part of Manzawa area (S in Fig. 16). Sedimentary bodies of the single storeyed type are less than several tens of meters wide and ten to twenty of meters thick. Geometric characteristics of this sedimentary body is similar to that of SDA.

The second type is the multi-storeyed sedimentary body consisting of a pile of many smaller scale sedimentary bodies. The sedimentary body of this type, distributed around Hashinoue, is 5–7 km wide and more than 2000 m thick only (M in Fig. 16). It is characterized in having lateral branches, that is, SCA oftenly interfingers with SSA laterally, and is completely replaced by the latter over a few kilometers (Figs. 16 & 20). As to internal structure, many thinning-upward sedimentary cycles of 20 m up to 100 m thick are observed. The basal boundary of the branched body can be traced laterally to the basal surface of the large-scale thinning-upward sedimentary cycle. Channel structures of various sizes are developed in SCA. Emphasis is that the mutual relationship of sedimetary body of SCA and the juxtaposed SSA is quite similar to that of Furuyashiki Sedimentary Body of SDA and the surrounding SIA mentioned above. For example at Loc. A in Fig. 20, the basal boundary surface of the branched body of SCA is conspicuously sharp and gently curved. It is clear that the surface discords with the bedding planes of the sedimentary body and underlying SSA, indicating the erosion of the underlying SSA. Beds within the sedimentary body thin out towards boundary surfaces onlapping the boundary plane. Strike of the original surfaces of the boundary is NNW-SSE parallel to predominant paleocurrent direction of this area. Upper boundary of the sedimentary body is of structual concordance with the overlying SSA not only

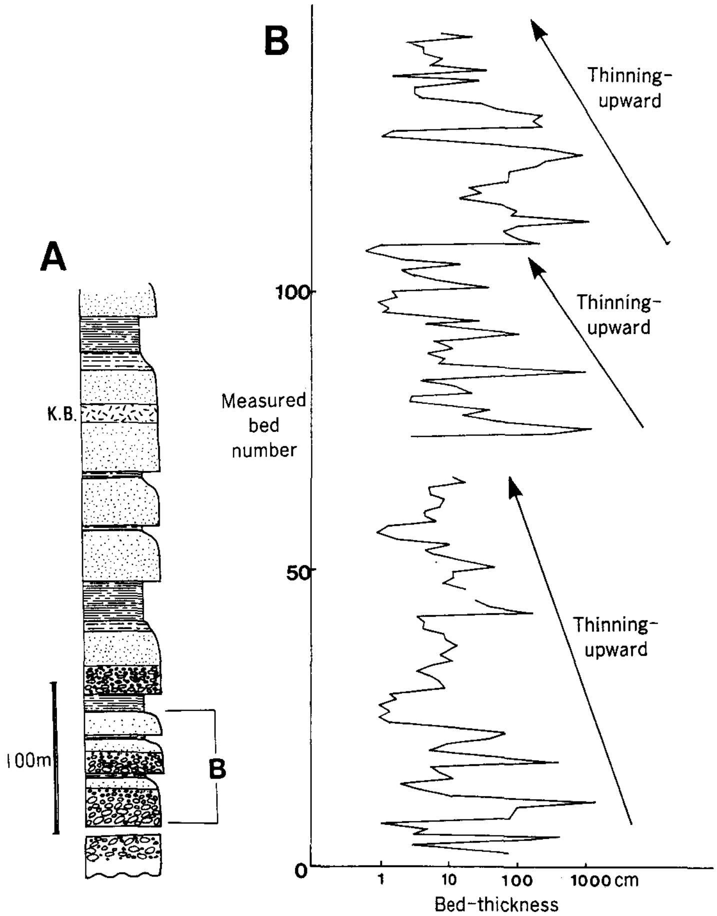


Fig. 19. Generalized section of SCA, showing developments of thinning-upward cycles through the section. A: measured section at Hashinoue. K.B; keybeds of Facies E. B: Bed-thicness of B portion in A, arrows shows thinning-upward cycles.

in outcrops, but also in mappable order (Figs. 16 & 20). Beds constituting the sedimentary body are laterally discontinuous, and are variable in thickness in contrast with continuous and uniform beds of SSA.

(6) Sandy-silty association (SSA)

SSA composed of most of the Utubuna Alternation and the Manzawa Alternation in Manzawa area. It borders with SCA in the highlands in the west of Kobayama (southwestern part) and in the mountains east of Utsubuna (northeastern part) in distribution. However, outcrops in the latter area are limited, because of wide distribution of the Sanogawa intrusive rocks. Several key beds can be traced throughout SCA to SSA (Fig. 20).

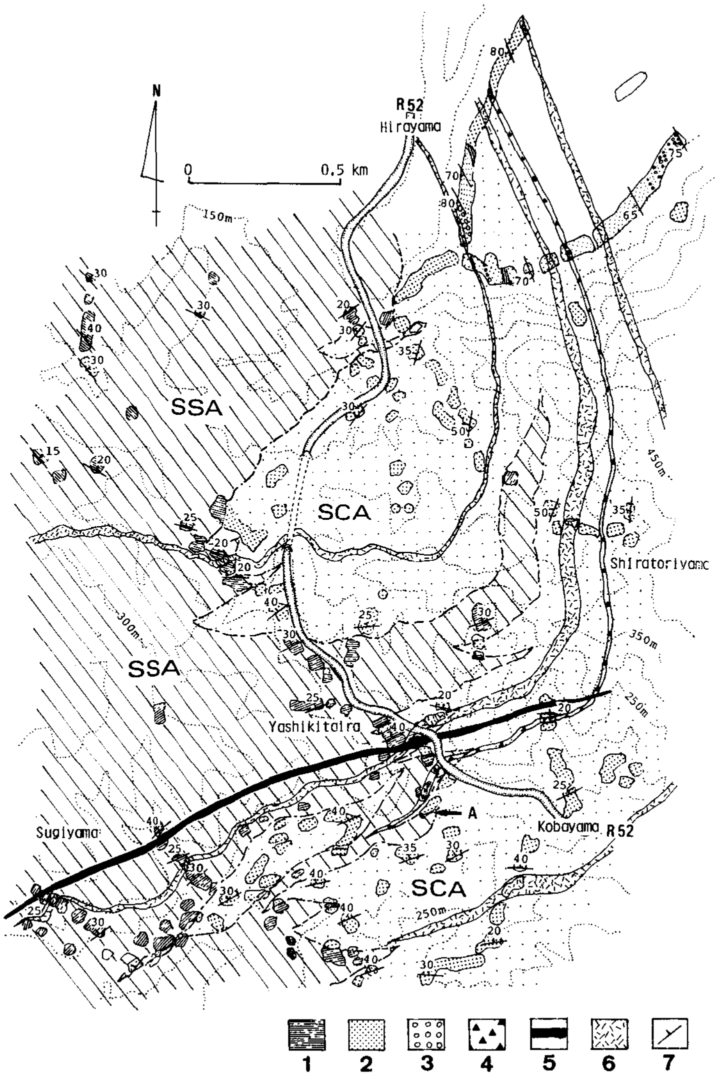


Fig. 20. Topographic map with locations of outcrop around Yashikitaira, showing the relationship of the branched SCA (dotted part) and SSA (hatched part). Note that several key beds can be traceed from SCA to SSA. 1. SSA, 2. Sandstone Megafacies of SCA, 3. Conglomerate and Pebbly sandstone Megafacies of SCA, 4. PMA, 5. dyke rocks, 6. volcaniclastics (key beds), 7. dip and strike of bedding.

6–a: Facies components and facies transition

SSA consists mainly of Facies C3, C1 intercalated with Facies C2 and E, and occasionally Facies D2. Subfacies C3–b is most predominant. Facies C2 is not well-developed comparing with SIA and SMA. Conspicuous preferred facies transition of SSA is not recognized by field observations and by statistical analysis.

6–b: Distributional pattern and internal structure

SSA is widely distributed surrounding the sedimentary body of SCA, and partly interfingers with the latter as already noticed (Fig. 16). Noteworthy is that, in SSA, lateral changes of sedimentary facies are recognized. The predominant sedimentary facies of SSA tends to change from Facies C1 to Facies C2 and C3–b laterally far away from the margin of the sedimentary body of SCA. Additionally, thickness and grain-size of sandstone beds in the same facies also decreases to the same direction.

(7) Silt association (SMA)

SMA is developed in lowland in and around Machiya. It consists mainly of two facies, Facies C2 and E with intercalation of Facies C3. The association, which corresponds to the Machiya Alternation as a stratigraphic unit, seems to be monotonous. No special facies transition are recognized either laterally or vertically, but thickness of siltstone beds in SMA tends to increase upward. Its distribution, however, is confined (Fig. 16). SMA reaches a few hundred meters in thickness.

(8) Pebbly siltstone association (PMA)

PMA comprises Facies D1 (Fig. 21), and is scattered in Fujikawa domain stretching for 30 km from Akebono area to Manzawa area (Fig. 22). Comparing with the other facies associations, it has many particular characteristics in its distributional pattern, internal structure, geometry and dispersal pattarn.

PMA is distributed fairly continuous in N-S direction, in contrast with its limited distribution in an E-W profile. For example, the distribution of PMA in Manzawa area is restricted in the western part and is thinning out eastward.

Pebbly siltstone bed is regarded as the product of infilling of channel structure. Pebbly siltstone beds, well-observed at many locations (Fig. 22), are mostly not persistent more than 50 meters, and form lenticular bodies (Plate 4-4). Most bases of the beds are sharp, irregular and erosional (Plate 4-5). In contrast, top of the bed gradually merges into the overlying SIA or SSA.

At the west of Minobu, some of PMA show the normal grading (Fig. 21). In the beds, the heavy clasts, mostly of massive andesite and basalt, tend to gradually decrease upward in size (maximum size of the clast 1.2 m in diameter, Plate 4-2).

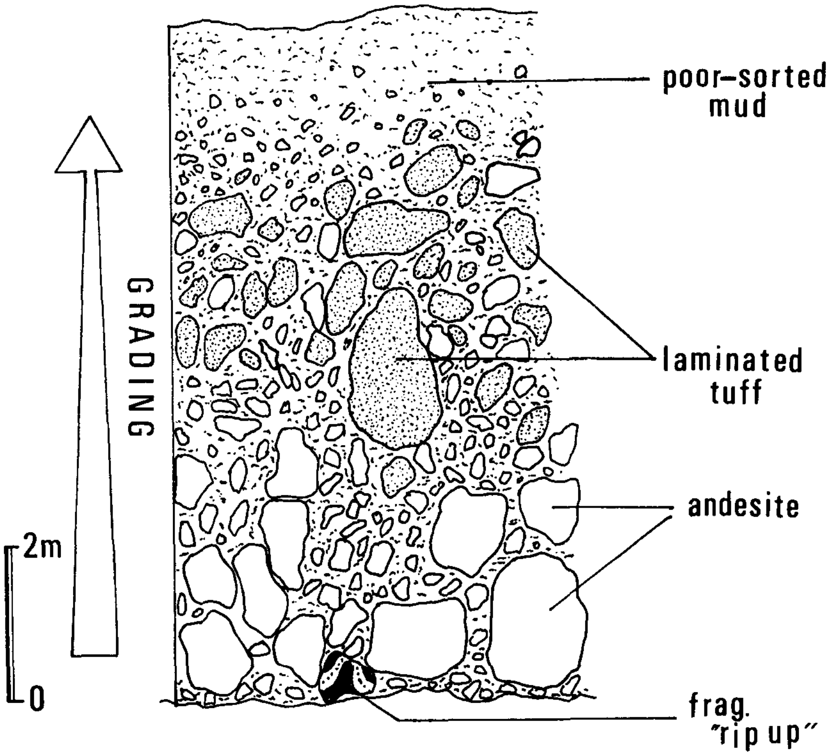


Fig. 21. An example of PMA showing internal sedimentary structure.

In the middle to upper part of the pebbly siltstone bed, the clasts composed of porous and laminated tuff predominate. The uppermost consists of poor-sorted siltstone with some andesite fragments. Any modification structure such as ripple-laminations do not observed in the bed. Thus, such different organization of clasts with in a bedis caused by the difference of clast density between the heavy massive andesite and the lighit porous tuff, and not by different flows.

6. DISPERSAL PATTERN OF SEDIMENTS

In the Minobu Formation and its equivalent strata of the western half of the Southern Fossa Magna Region, three main paleocurrent directions are recognized. The first paleocurrent direction is west-southwestward transport. SDA, GSA, SIA (Minobu and Akebono areas) and PCA (Nishikatsura area) are mostly transported by sediment gravity flow in this direction. The second is south-southeastward transport, developed in SCA and SSA (Manzawa area). The last one is observed in PMA (Akebono to Manzawa areas) and a part of SMA, which shows

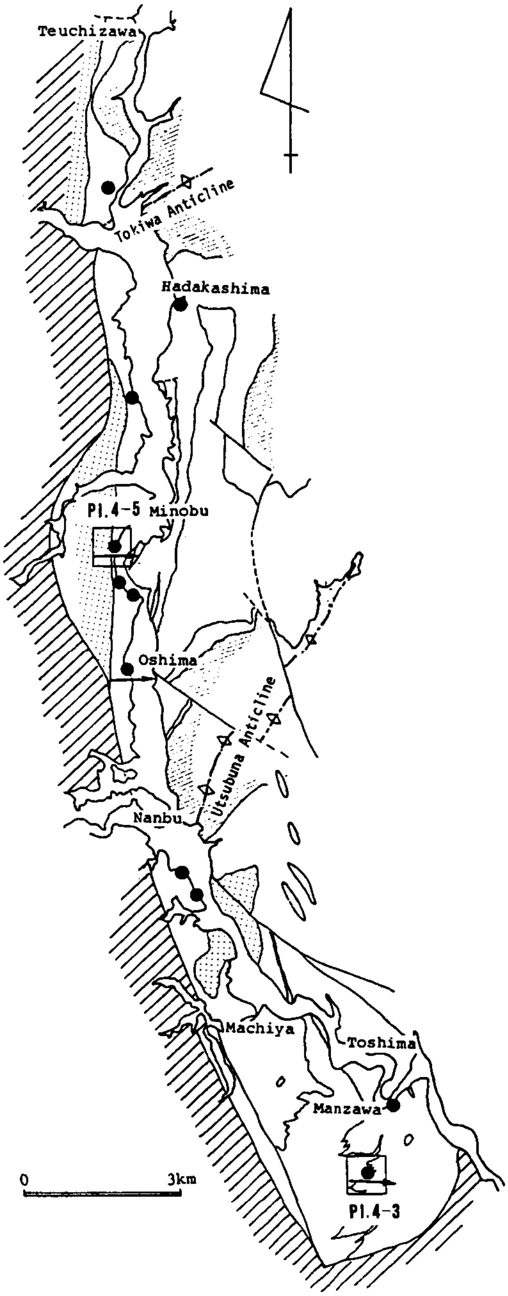


Fig. 22. Locality map of PMA. Outcrops of PMA are shown as closed circles. Arrows indicate the direction of transporting of PMA.

eastward transport that is quite different from the first paleocurrent direction.

West-southwestward Paleocurrent Direction

SDA, GSA and SIA (Minobu and Akebono areas)

In the Fujikawa Tal, the west-southwestward paleocurrent direction is

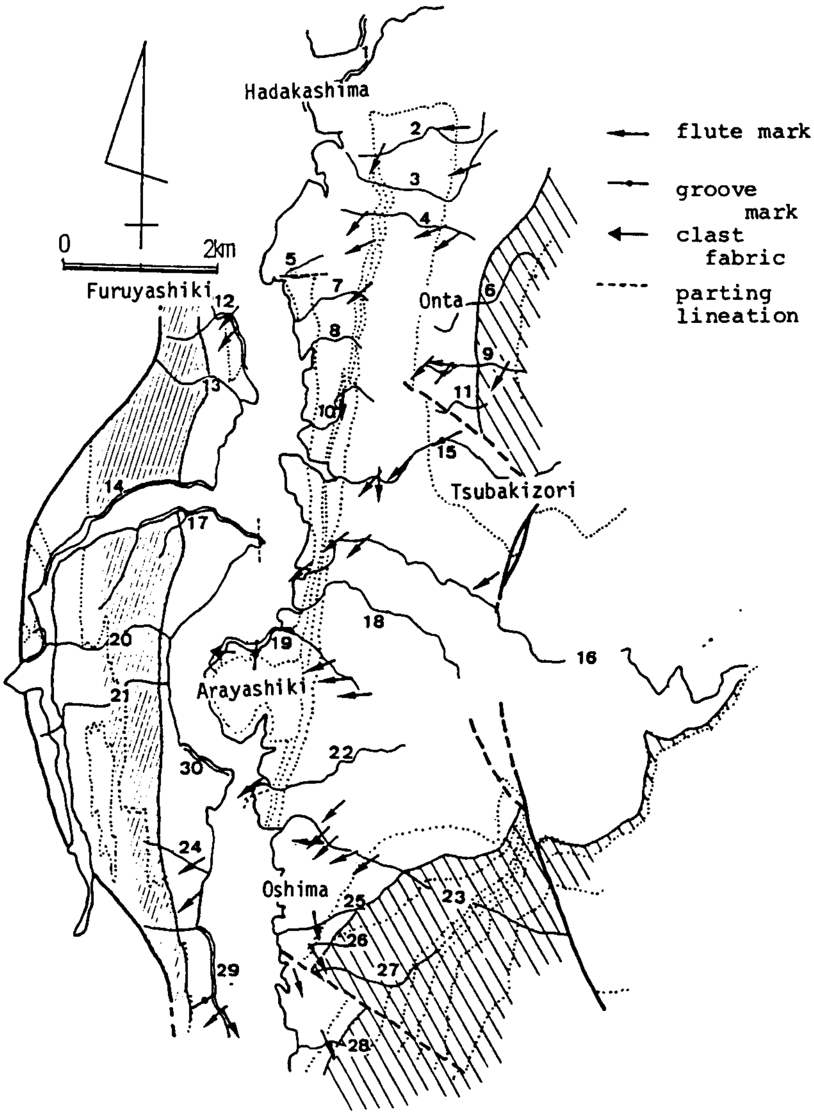


Fig. 23. Paleocurrent directions of SDA, GSA and SIA in Minobu area, showing fairly constant west-southwest transpoting, and concordant with that of the three facies associations.

measured mainly in SDA, GSA and SIA, by flute marks, groove marks, clast fabrics and parting lineations in Facies A3, A6, B1, C1 and C3. Slump folding showing the sliding to this direction has scarcely been observed. Results of paleocurrent direction in Minobu area, for example, are shown in Fig. 23. Noteworthy is that the significant difference of paleocurrent directions among three facies associations is not recognized.

CPA (Nishikatsura area)

Paleocurrent direction

Sole markings are infrequent in CPA of Nishikatsura area, but paleocurrent direction can be obtained by clast fabrics such as preferred clast orientation and imbrication (Plate 1-2). The paleocurrent direction is consistent with that measured from grain fabric and preferred orientation of carbonaceous fragments. All of those paleocurrent directions of sediments indicate west-southwestward transport,

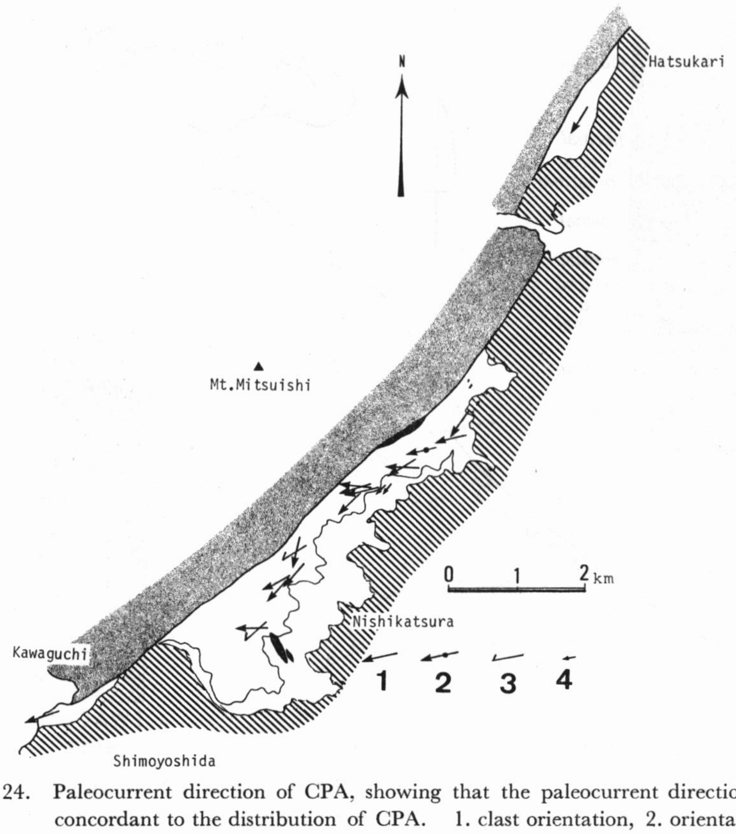


Fig. 24. Paleocurrent direction of CPA, showing that the paleocurrent direction is concordant to the distribution of CPA. 1. clast orientation, 2. orientation of carbonaceous fragments, 3. scour mark, 4. sandgrain fabric.

parallel to the long axis of the distribution of CPA (Fig. 24).

Clast fabric pattern

It is recognized that the pattern of the clast fabric is of difference between that in Iwadono (the northernmost part of Nishikatsura area) and that in Nishikatsura (the main part of Nishikatsura area) (Fig. 25). Clast fabric of Facies A3 in Nishikatsura is of typical A-type proposed by DAVIS & WALKER (1974), that is, long (a-) axis of imbricated clasts is parallel to flow and dipping upstream (Fig. 25). A-type clast fabric is interpreted to have been made by clast interaction such as collision within a high-density and high-concentration sediment gravity flow (WALKER, 1978). On the contrary, in Iwadono, fabric pattern is B-type of DAVIS & WALKER (1974), that is, long axis of clasts is usually transverse to flow direction with intermediate (b-) axis dipping upstream. This type is thought to be formed by drag of

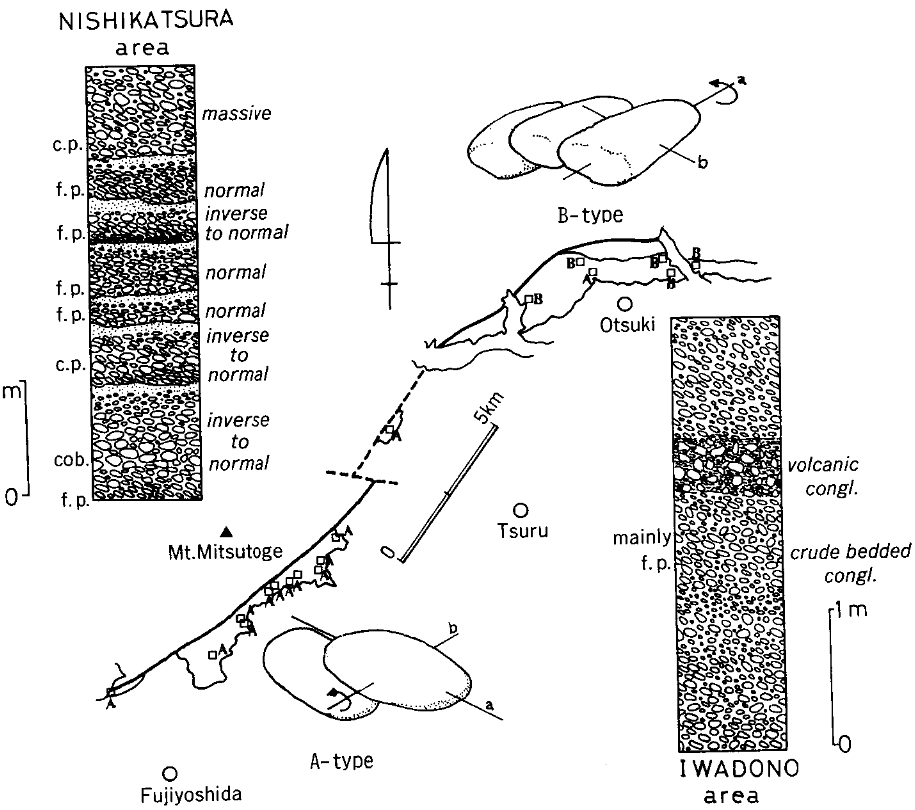


Fig. 25. Transition of clast fabric pattern from Iwadono of B type to Nishikatsura of A type, and bedding style, showing change of flow mechanism from fluid gravity flows to sediment gravity flow.

fluid gravity flow of MIDDLETON & HAMPTON (1973; 1976) (DAVIS & WALKER, 1974). Iwadono is situated at more upstream side judged from the relationships of paleocurrent direction and its distribution. The transition from A-type to B-type of clast fabric is found around Asari where the Katsuragawa Conglomerate corresponding to CPA becomes to unconformably overliy the Nishiyatsushiro Group.

Such change of clast fabric pattern from B-type to A-type is interpreted to be resulted from the change of transportational mechanism from fluid gravity flows to sediment gravity flows, due to rapid deepening of the sedimentary environment.

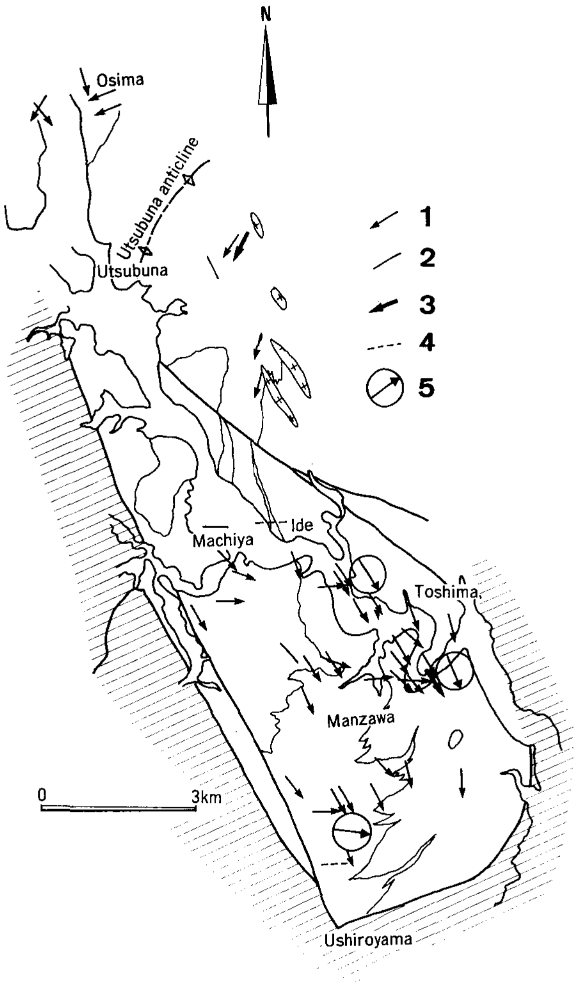


Fig. 26. Dispersal pattern of SCA, SSA, SMA and PMA in Manzawa area, showing a centripetal directional pattern of paleo-current.

This possibly suggests the transition from a subaerial fan-delta to a submarine channel on a slope setting.

South-southeastward Transport Direction

SCA, SSA, SIA and SMA (Minobuand Manzawa areas)

South-southeastward transport is obtained in SCA, SSA, SIA and SMA by flute marks, and less commonly by groove marks, clast fabrics and ripple marks (Fig. 26). Significant difference of paleocurrent directions between SCA and SSA is not recognized. However, SMA is not so clear because of lack of indicative structure of the paleocurrent direction.

When observing it in detail, the paleocurrent directions of SCA, SSA do not show a critically consistent south-southeastward transport. Because those in the western part of the distribution of SCA, SIA and SSA, to the west or south of Manzawa, sometimes show eastward transport. On the contrary, paleocurrents in the northeastern part of SCA and SSA associate with southwestward transport (Fig. 26). As summing up, south-southeastward transport show a centripetal and converging pattern.

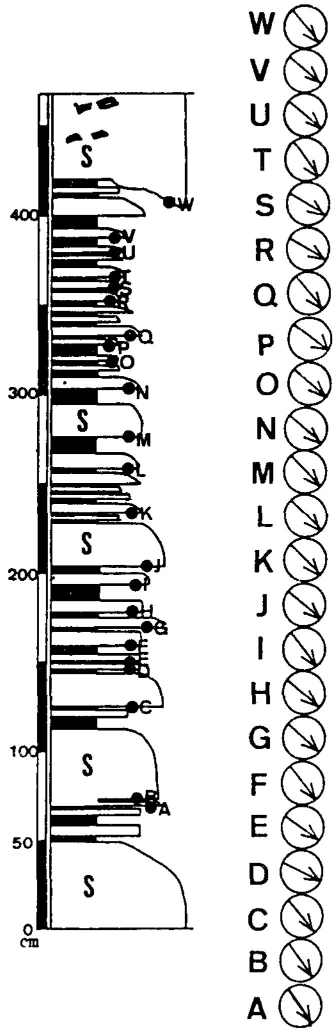


Fig. 27.
Bed-by-bed paleocurrent directions of SCA. Note that paleocurrent directions of Sandstone. Megafacies (S) is quite concordant with those of Alternation of Siltstone and Sandstone Megafacies. At west of Hashinokami.

Eastward Transport Direction

PMA (Akebono to Manzawa areas)

Sedimentary structure indicative of paleocurrent direction has not been observed in Facies D1. Dispersal pattern of PMA, however, is able to presume from analyses of the strike of channel walls (Plate 4-5), and of slump folding associated with Facies D1 (Plate 4-3). Dispersal pattern of PMA displays eastward transport (Fig. 22). Noteworthy is that prodominant eastward transport of PMA are quite different from that of the other clastic sediments.

7. PETROGRAPHY OF THE MINOBU FORMATION

Conglomerate clast composition

Conglomerate clast composition is a good indicator in consideration for the source and dispersal pattern of sediments. Conglomerate and Pebbly Sandstone Megafacies of the Minobu Formation and its equivalents are distributed in such three areas as Minobu, Nishikatsura and Manzawa areas. Clast compositions in the first twoare as were briefly reported by MATSUDA (1958) and YAMANASHI PREFECTURE (1969), but detailed study has not been carried out.

In the present study, more than 40 pebbles of over 1 cm in diametre, were sampled from 60 cm square space in both conglomerate and pebbly sandstone beds, and were examined by the naked eye. To confirm the results, eighteen pebbles were reexamined under microscope.

1) SDA and GSA (Minobu area)

In SDA and GSA, amount of Conglomerates and Pebbly Sandstone Megafacies attain approximately 3% and 62% of the measured sections composed of 128 meters in SDA and 214 meters in GSA.

Clast composition was examined in 18 points of both SDA and GSA. Conglomerate clast compositions of both facies associations are quite similar to each other. Matrix is medium to coarse-grained lithic wacke similar to sandstones of study area

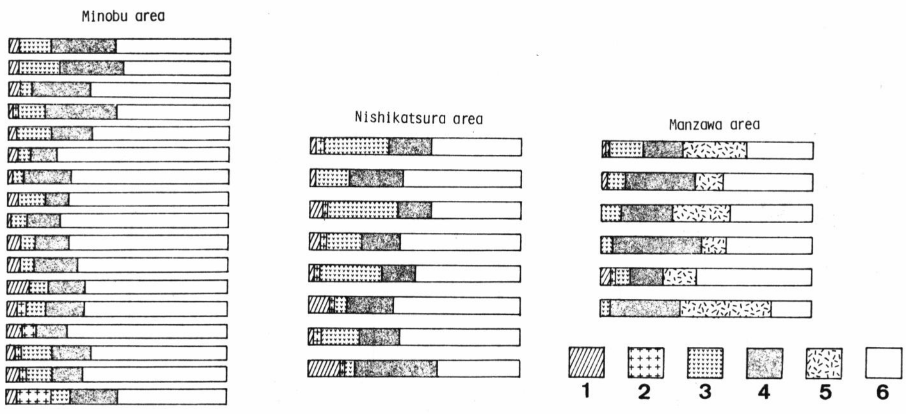


Fig. 28. Clast composition of conglomerates, showing similar compositions to one another. 1. chert and quartz rocks, 2. diolite and granite, 3. volcanic rocks, 4. black shale, 5. angular clast of "andesitic rocks", 6. sandstone.

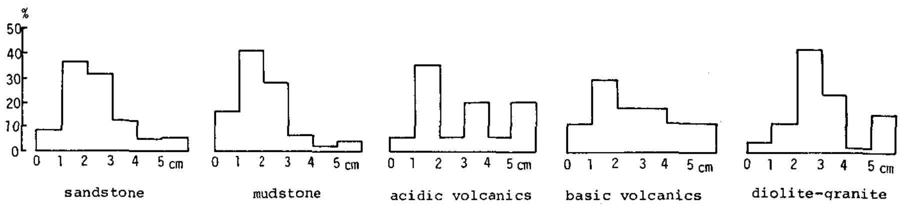


Fig. 29. Size distribution of the measured pebbles.

in composition and texture (see, sandstone petrography in next section). 983 clasts examined consist of 60% sandstone (including meta-sandstone), 25% black shale (including meta-shale), 8% volcanics (dacite-basalt), with 3% plutonics (diolite-granodiolite) and 4% other kinds of rocks (reddish chert, vein quartz and limestone, etc,) (Fig. 28). Size distribution of clasts are shown in Fig. 29. Clasts are generally subangular to subrounded with exception of diorite clasts that are subrounded to well-rounded (Fig. 30), and are 12% blade, 20% prolate, 29% spheroid and 39% oblate in shape (Fig. 31).

2) PCA (Nishikatsura area)

PCA comprises Conglomerate and Pebbly Sandstone Megafacies in an amount of up to 80%, and Sandstone Megafacies. Conglomerate clast composition of PCA

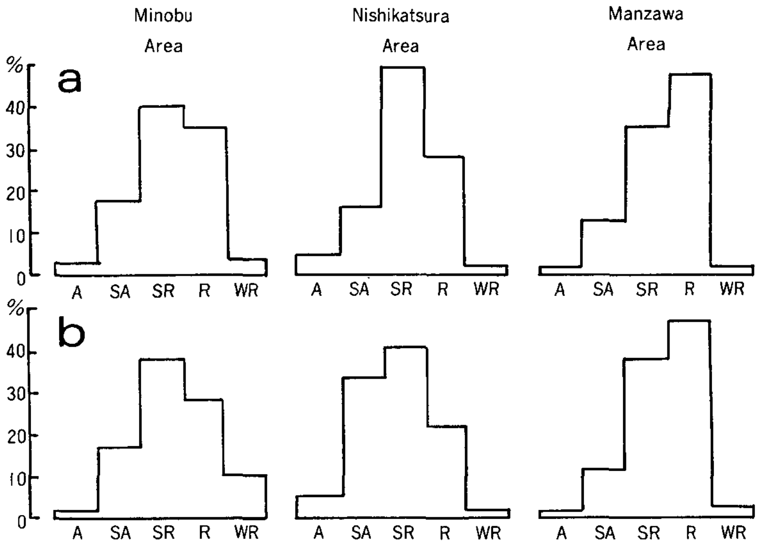


Fig. 30. Roundness of sandstone and shale clasts. a: sandstone, b: black shale, A: angular, SA: subangular, SR: subrounded, R: rounded, WR: well-rounded.

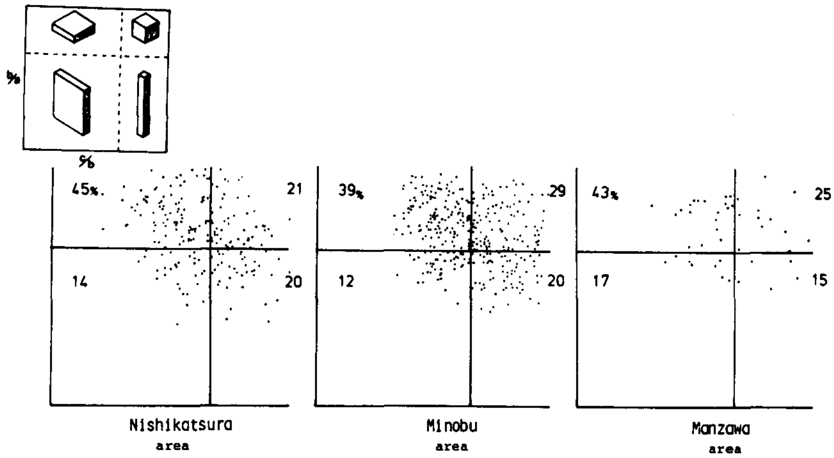


Fig. 31. Clast shape of the measured conglomerates.

was examined at eight localities. Matrix of the conglomerate is medium- to coarse-grained lithic wacke similar in texture and composition to sandstone. Clasts, on average, consist of 50% sandstone, 25% black shale, 20% volcanics (dacite & basalt), with 3% plutonics (diolite & granite) and 5% others (reddish chert, etc.) (Fig. 28). Pebble-size clasts are generally subangular to subrounded (Fig. 30) and 14% blade, 21% spheroid, 20% prolate and 45% oblate in shape (Fig. 31).

3) SCA (Manzawa area)

Conglomerate and Pebbly Sandstone Megafacies occupies less than 4% of SCA (the measured section of 600 m) in Manzawa area. On an average, clasts consist of 24% angular andesite and basalt, 39% sandstone, 27% black shale, 7% volcanics and 3% other rocks (diorite and quartz rocks) (Fig. 28). Pebble-size clasts are generally subrounded (Fig. 30) with exception of andesite clasts which are mostly subangular (Plate 3-6). Clasts consist of 18% blade, 25% spheroid, 14% prolate and 43% oblate in shape (Fig. 31).

It is noteworthy that conglomerate clast composition of SCA differs from those of SDA and GSA in having many subangular andesitic clasts like that in Facies D1 (Plate 3-6). This andesitic clasts are commonly larger in size than those of other rocks. However, clast composition excluding the andesitic clast is similar to those of GSA and PCA.

4) PMA (Akebono to Manzawa areas)

Pebbly siltstone differs greatly from the conglomerate in clast composition. In pebbly siltstone, andesitic clasts attains to more than 80% of total clast composition. Andesitic rocks which include andesite and basalt clasts are mostly angular to subangular (Plate 4-1, 4-2). As the others clasts, black shale and sandstone are included. Moreover, rip-up clasts and transported clasts of thin-bedded turbidite are contained in PMA.

Difference in local clast composition is recognized. In Manzawa area, pyroxene andesite and greenish altered andesite predominate as main volcanic clasts, but in Akebono area, most clasts are basalt.

Sandstone Petrography

Sandstone is predominant element of the most sequence of the Minobu Formation and its equivalents, but a minor component of CPA and SIA. In the present study, samples for petrographic examination were taken mostly from massive part of medium to coarse-grained sandstones of Sandstone Megafacie and Alternations of Sandstone and Siltstone Megafacies. Modal composition was obtained by counting more than 500 points in one thin-section for each specimen. Numbers of analyzed samples are as follows.

SDA, GSA and SIA (Minobu area)....................................18
PCA (Nishikatsura area) 8
SCA and SSA (Manzawa area) 9

Main framework grains are monocrystalline quartz, plagioclase, rock fragments of volcanic and argillite. The result of study on composition is shown in Fig. 32.

1) SDA, GSA and SIA (Minobu and Akebono areas)

Sandstones of SDA, GSA and SIA are quite similar in petrographic character-

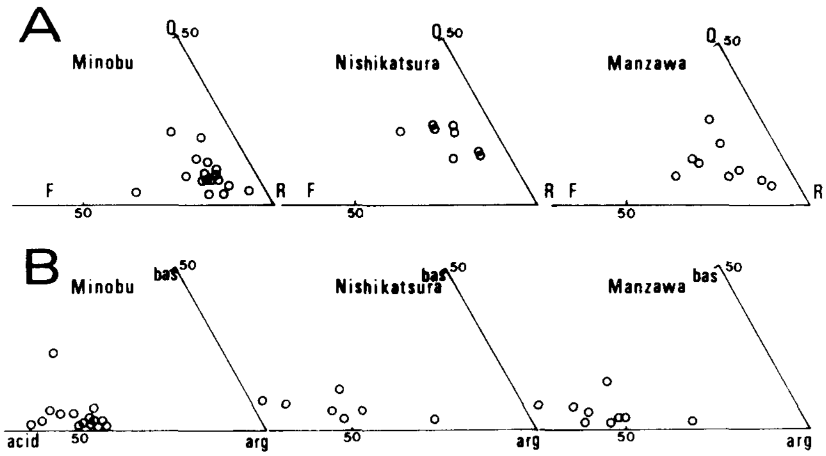


Fig. 32. Sandstone composition of the study area, showing similar composition to one another. A: Q-F-R diagram. B: compositional diagram of lithic fragments. bas: basic volcanics, acid: acidic volcanics, arg: argillite.

istics with one another. They belong mostly to lithic wacke with modal compositions of quartz: 12.3%, feldspar: 11.5%, lithic fragments: 76.2%. Mineralogically, they are volcanic lithic and argillite lithic-rich wacke. Average matrix content is 14.8%. They are generally moderaely to poorly sorted with subangular to subround grains. Lithic fragments contain argillite, basalt and dacite, and some plutonic fragments. It is important that argillite and dacite rock fragments constitute the majority in the sandstone composition (Fig. 32–B). Matrix is composed of true matrix of fine grains smaller than 0.03 mm in diameter, and subordinate pseudomatrix of DICKINSON (1970), so for it is mixed with calcite cement. Accessory minerals are pyroxene and opaque minerals (iron oxides) comprising up to 1% of the terrigneous material fraction. Small amount of biotite, epidote and chlorite are also contained. Accessory minerals can be regarded to be derived mostly from basaltic rocks.

2) **PCA (Nishikatsura area)**

Sandstones of PCA are mostly classified as lithic wacke with modal composition of quartz: 21.5%, feldspar: 14.2% and lithic fragments: 64.3%. Mineralogically, they are volcanic lithic and argillite lithic-rich wacke which are 13.8% of matrix in an average. Sandstone is moderately to poorly sorted, with subangular to subrounded grains.

Sandstone composition of PCA is nearly the same as that of sandstones of SDA, GSA and SIA in Minobu area. Matrix of many sandstones are mixed with calcite and silica cements, and pseudomatrix. Accesory minerals comprise pyroxene, opaque minerals, biotite, epidote and chlorite. Pyroxenes are mostly altered into pseudomorph of calcite.

3) **SCA and SSA (Manzawa area)**

Sandstones of SCA and SSA in Manzawa area have the same petrographic characters. They are mostly classified into lithic wacke with modal compositions of quartz: 15.7%, feldspar: 16.0%, lithic fragments: 68.3%. Mineralogically, they are lithic wacke with 17.5% matrix on an average. Most sandstones are moderately to poorly sorted, with subangular to subrounded grains. Quartz and feldspar are minor compositions in comparison with lithic fragments, which are mainly composed of two different origins; basaltic and dacitic rocks, and argillite. Matrix consist of true matrix of fine grains smaller than 0.03 mm, and pseudomatrix. Interstitial calcite cement is also seen instead of matrix. Accessory minerals include pyroxene and opaque minerals, reaching 0.6% of total amount, along with biotite, epidote and chlorite.

In sandstone petrographic composition, the Minobu Formation and its equivalent strata has very good similarity.

8. INTERPRETATION OF FACIES ASSOCIATION

In order to interprete the facies associations, the following points must be taken into account; 1) morphologic analysis of facies association, 2) dispersal pattern and 3) comparative studies of sedimentary facies and facies association in the study area with modern and reported typical ancient examples. As a result, it is inferred that coarse clastic association group represents channel fillings, and fine clastic association group are interchannel sediments. PMA, showing the opposite dispersal pattern to clastic sediments, is regarded as a product of debris flow running down on a steep slope.

a) SDA and GSA as channel sediments

As stated already, SDA and GSA are developed in Minobu and Akebono areas. At first, morphology of SDA and GSA are analysed. In N-S profile, normal to the paleocurrent direction, the sedimentary body constituted by two associations is always lenticular in shape (Figs. 6 and 7). The bottom surface of SIA and GSA is demarcated by distinctive boundary. It is concave-up and erosional to underlying SIA. Additionally, strike of the boundary surface is originally parallel to paleocurrent direction of the sedimentary body. Each individual bed within the sedimentary body pinches out toward the boundary surface, and it abuts directly on the erosional surface.

In contrast to those in N-S profile, the sedimentary body in E-W profile parallel to paleocurrent direction, does not show the lenticular geometry. It seems to be continuous and uniform in thickness as well as the feature of sedimentary structures. The sedimentary body of SDA and GSA changes gradually into overlying SIA. Upper boundary of the sedimentary body is parallel to bedding plane not only in outcrop but also in mappable orders. Furthermore, the distribution of the sedimentary body extends parallel to the direction of paleocurrent measurements. Thus, such morphologic features of two different profiles indicates that the sedimentary bodies of SDA and GSA form concaved "shoestring bodies" elongated parallel to paleocurrent direction in three dimentions having the erosional base.

In respect to sedimentary facies of the two associations, they are thought to be transported by of high density and high concentrat sediment gravity flows, and sedimentary facies consisting of the two associations, show fining-upward sequences starting from an erosional surface. These sedimentary facies and fining-upward regularity observed by the two associations are similar to those of channel fillings of fluvial sediments (e.g. Scott type and/or Donjek type in MIALL, 1977; 1978) in spite of the fact that these sediments of SDA and GSA are deposited in a deep-sea environment. In addition, these characteristics are also described and interpreted as those of the paleo-submarine channel-fills by MUTTI & RICCI-LICCHI (1972, 1975), MUTTI (1977), WINN & DOTT (1979), ERIKSSON (1982), HEIN & WALKER (1982), PICKERING (1982) and so on.

Table 5. Summary of channel fill sediments in Minobu area.

sedimentary bodys name (location*)	facies association	paleocurrent direction	strike of channel wall	dip of channel wall	width of channel	maximum thickness of fills	sedimentary sequence
FURUYASHIKI (Loc. a)	SDA	from N25°E N40°E	N 35°E	about 5° to 15°	650m+	73m+	fining and thinning upward sequence
OBIKANE (Loc. d)	GSA	from N50°E N60°E	N 60°E	?	about 3.2 km	300m+	?
MARUTAKI (Loc. b)	GSA	from N30°E N80°E	N 40°E to N 70°E	about 30° to 40°	4 km+	1800m+	fining upward sequence

In conclusion, basing on such characteristic features of its morphology and facies and its transitional pattern, SDA and GSA are regard as the fill sediments of submarine channel. Width and direction of submarine channels reconstructed from their morphologic analyses are given in Table 5.

When reconstructing GSA in detail, GSA are interpreted as fillings of a single submarine channel system. This is because the reconstructed channel filled by GSA has a width of more than a few kilometres, which is larger than that filled by SDA, and they are not associated with any other sedimentary body in the same horizon. In the stratigraphy, the sedimentary bodies of GSA are confined to the lower part of the Minobu Formation. On the contrary, sedimentary bodies of SDA are confined to the upper part of the Minobu Formation. In case of SDA, two or more sedimentary bodies are distributed on the same stratigraphic horizon (Figs. 7 and 8). The reconstructed channels filled by SDA are up to a few hundred metres wide. Thus, they are suggested to form multi-branching, net-work channel systems. In summary, the two different submarine channel systems, single submarine channel system and net-work multichannel systems should have developed in the Minobu Formation in Minobu area. Accordingly, channel systems in the Minobu Formation had shifted from the former to the latter.

b) SIA as interchannel sediments

SIA differs from SDA and GSA in its distributional pattern and facies transition. SIA is considered as interchannel sediments (sense of NORMARK, 1980) by the following evidence. 1) SIA is distributed surrounding SDA and GSA of channel fills, that is, vertical and lateral juxtaposition with both associations. 2) As a whole, characteristic sedimentary structures and bedding styles are similar to those of interchannel sediments that have been described by many authors (e.g. MUTTI, 1977; WINN & DOTT, 1979; CARTER, 1979; MOORE *et al.*, 1980; ERIKSSON, 1982; PICKERING, 1982).

It is noteworthy that the interchannel sediments in the area differ from "typical" ones which show a divergent paleocurrent system (e.g. Mutti, 1977). Predominant paleocurrent direction of SIA as interchannel sediments in the study area is parallel to that of GSA and SDA as main channel fill sediments as mentioned already. The direction of supposed crevasse channels of the area, does not cross at a high angle, approximately 40 degree at its maximum, to the main paleocurrent direction of the submarine channel.

Such difference, however, may not reject the interpretation that SIA is interchannel sediments. Because the paleocurrent system is controlled not only by the sedimentary process but also by topographic condition. I believe that a relatively steep slope of this area must have compelled current direction of the spilled over flows from main channel parallel to paleoslope direction. A similar phenomenon of interchannel sediments is reported by CARTER (1979) in the Jurassic Otekura Formation of New Zealand, which is interpreted as the interchannel sediments on trench slope.

c) CPA as channel fill sediments

The sedimentary body constituted by CPA is distributed along longitudinal profile parallel to paleocurrent direction only. So that, three dimensional reconstruction of the sedimentary body was hardly taken. To interpretate the sedimentary environment of CPA, the following facts are made much accounts. 1) The sedimentary body is continuously distributed along paleocurrent direction, and the original strike of erosional base of the sedimentary body is parallel to elongation of the sedimentary body. 2) The sedimentary facies show that CPA was deposited from high-density and high-concentration flow similar to the case of GSA. Such sediments are generally explained to be transported and deposited under "confined condition", because high-density and high-concentration flows must be maintained to the last depositional stage. In comparison with GSA, sedimentary facies of CPA indicate a deposition directly from the higher energy level of sediment gravity flows, because of development of Facies A1 and A2 in CPA.

Thus, the prolonged shoestring shape and erosional base of the sedimentary body of CPA are interpreted as a channel origin, and the association is also regarded as channel fill sediments.

d) SCA as channel fill sediments

Complete three dimensional morphology of sedimentary body of SCA can not be reconstructed due to lack of transverse profile in many cases. The sedimentary body of SCA, however, has the same characteristics as those of SDA and GSA in Minobu area not only in sedimentary facies, pattern of facies transition and bed features, but also the contact relationship to underlying strata. Thus, SCA is also interpreted as fill sediments of the paleo-submarine channels.

Multi-storeyed sedimentary body is beleived to be a geometric record of the multi-storeyed channel fill sediments. Thick multi-storeied sedimentary body in this area is considered to be constructed by the frequent shifting of channel course as a sedimentary process, and by continuous subsidence to keep the channel in the same pasition. Similar morphologic characteristics of channel fillings in the geologic record is known in the fluvial sediments under conditions prevailing in an active synsedimentary subsidence, such as the Trassic Lower Kane Springs Member, Chile Formation (BLAKEY & GUBITOSA, 1984).

The depth of paleosubmarine channels filled by SCA is not known. The widths are roughly estimated from lateral extension of the sedimentary body as several hundred meters to a couple of kilometers.

b) SSA as interchannel sediments

SSA is distributed surrounding SCA, and is comtemporaneous but heterotopic with SCA channel fills. This association shows a decrease in coarse-grained sediments away from the margin of SCA, channel-fill sediments as mentioned above. Characteristic features of the sedimentary facies are also similar to those reported as interchannel sediments (e.g. MUTTI, 1977; WINN & DOTT, 1979). Sediment dispersal of SSA, however, is of the same pattern as that of SIA, and does not directly correspond to that of the "typical" interchannel sediments.

3) Pebbly siltstone association (PMA)

As mentioned previously, many pebbly siltstone (facies D1) are intercalated in turbidites and associated coarse clastic deposits along Fujikawa domain. PMA forms a lenticular sedimentary body, up to few meters across, with an erosional base and crude normal grading (Fig. 29).

It is generally believed that pebbly mudstone, with the exception of drop stone origin, is formed by debris flow. Since JOHNSON (1970) and HAMPTON (1972), Bingham plastic model has been regarded as rheological behavior of debris flows. Because debris flow has the matrix strength, that is, yield strength due to cohesion of fine-grained particle in the matrix. It is also generally considered that behavior of debris flows is laminar rather than turbulent (JOHNSON, 1970; HAMPTON, 1972; 1975; 1978; CARTER, 1975; MIDDLETON & HAMPTON, 1973; 1976; HISCOTT & MIDDLETON, 1979; and others). Laminar debris flow produces characteristic internal and external sedimentary structures such as inverse grading and/or massive structures (FISHER, 1971; NAYLOR, 1980; SHULTZ, 1984) and a smooth bed base without erosional structures (JOHNSON, 1970; SWARBRICK & NAYLOR, 1980; MIDDLETON & HAMPTON, 1973; 1976, and others).

Sedimentary structures of Facies D1 of PMA in the study area, however, are quite different from sedimentary structure probably making laminar debris flow described above. I interprete that PMA could be formed by the freezing from the flow in an intensely turbulence or at least due to the failure of turbulence rather than in a laminar fashion, which could make the characteristic sedimentary structure such as the erosional base and the grading.

Based on his laboratory work, HAMPTON (1975) pointed out that the transitional condition of Bingham materials from laminar to turbulent, depends on the relationships of two dimensionless numbers; critical Reynolds Number (Re) and Bingham Number (B) (Fig. 33).

$$Re/B > 1000$$
$$\rho Vc^2/k > 1000$$

Additionally, according to ENOS's (1979) empirical equation, the transitional condition is given as;

$$\log k = -2.88 + 2.03 \log Vc$$

Where k, Vc and ρ are matrix strength, velocity and density of flow respectively.

If k is defined, the transitional condition depends directly on the flow velocity of Bingham materials. Considering that the largest clast diameter within the association, with approximately 2.6 g/cm in density, is 120 cm (Plate 4-2), and that

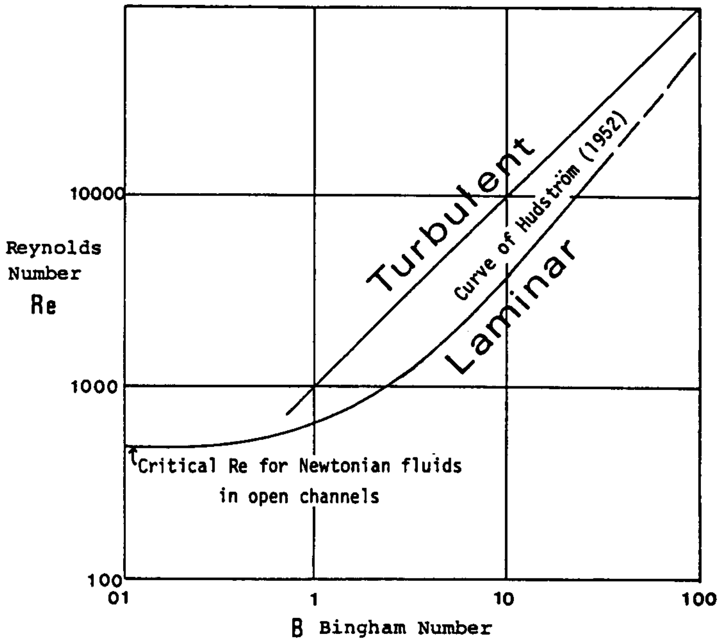


Fig. 33. Transitional condition of Bingham material from laminar fashion to turbulent one (after Hisccot & Middleton, 1979).

matrix density of flow is supposed to be 1.5 g/cm, and approximately 50% volume concentration of non-cohesive particles are included, matrix strength k of 7 Pa is obtained from HAMPTON (1975; 1979)'s equations. Thus, the critical maximum velocity of approximately 21 m/sec is calculated from these equations as transitional condition. Therefore, turbulent condition can be expected even in Bingham materials containing large clasts, if flow velocity is sufficiently high. Moreover, according to HAMPTON (1975), flow of Bingham materials is sheared once through the flow, it is changed into turbulent flow, and value of matrix strength of the flow is abruptly decreased. As a result, the flow comes under more favorable condition for turbulent flow. In this case, driving force of high speed flows is considered to have a fairly positive relationship to slope gradient.

On the other hand, TAKAHASHI (1981) proposed that flow behavior of debris flow having a relative high-concentration of non-cohesive particles, is well-explained by his dilatancy model rather than Bingham plastic model. If this model is accepted, however, relative steeper slope is also required to be initiated and developed as the large-scale debris flow under the problem. In conclusion, to produce PMA with such sedimentary structures, a steep slope setting is required.

9. RECONSTRUCTION OF SEDIMENTARY ENVIRONMENT

Kwanto Mountainland as provenance

With regard to regional geologic distribution, two different interpretations on the material provenance of the Minobu Formation and its equivalent strata have been proposed. One provenance stated by MATSUDA (1958, 1961) is located in and around the Kwanto mountainland, and the other was inferred by TSUNODA (1979) to be in and around the Akaishi mountainland.

Basing on the results of sediment petrography as stated above, especially those represented by clast composition with the exception of the angular andesitic clasts of PMA, can be divided into two different rock types, sedimentary and volcanic rock origin. The former consists mostly of sandstone and black shale with a small amount of reddish chert. It is similar to the composition of sedimentary rocks of the Shimanto Supergroup in Kwanto and Akaishi mountainlands in lithologic characteristics. However, the latter clast type, comprising dacitic and basaltic volcanic sediments, can be correlated with the sequence of the Nishiyatsushiro Group itself of the northern part of the Southern Fossa Magna Region, because of lack of clasts of alkaline volcanic rocks and of lithologic similarity.

In addition, an important fact on the problem is the dispersal pattern of clastic sediments of the Minobu Formation and its equivalent strata. The main paleocurrent direction of clastic sediments show westward to west-southwestward transport.

Therefore, the compositional feature and dispersal pattern of clastic sediments indicate that provenance of the clastic sediments is located on north-eastward of the study area. The author believes that the main provenance of the Minobu Formation and its equivalents is situated around Kwanto mountainland rather than around Akaishi mountainland. Additionally, large amount of clastic sediments also provided from Kwanto mountainland, which formed the equivalent turbidite sequence in Boso Peninsula to the east off the Southern Fossa Magna Region (TOKUHASHI, 1977).

Nishikatsura Channel

Although Nishikatsura area is separated 35 kilometres from Minobu area by the presence of the Quarternory Fuji Lava at Fuji Lava of Aokigahara, CPA interpreted as channel fill sediments is considered to continue to GSA and SDA of channel fill sediments in Minobu area. This is deduced from the following evidence. 1) As stressed formerly, compositional features of clastic sediments are similar to each other, and predominant paleocurrent directions in these areas are concordant with the distribution of these facies associations in two areas (Fig. 46). 2) As shown in Fig. 34, the talweg of the low Bouguer anomaly area is traceable along Minobu-

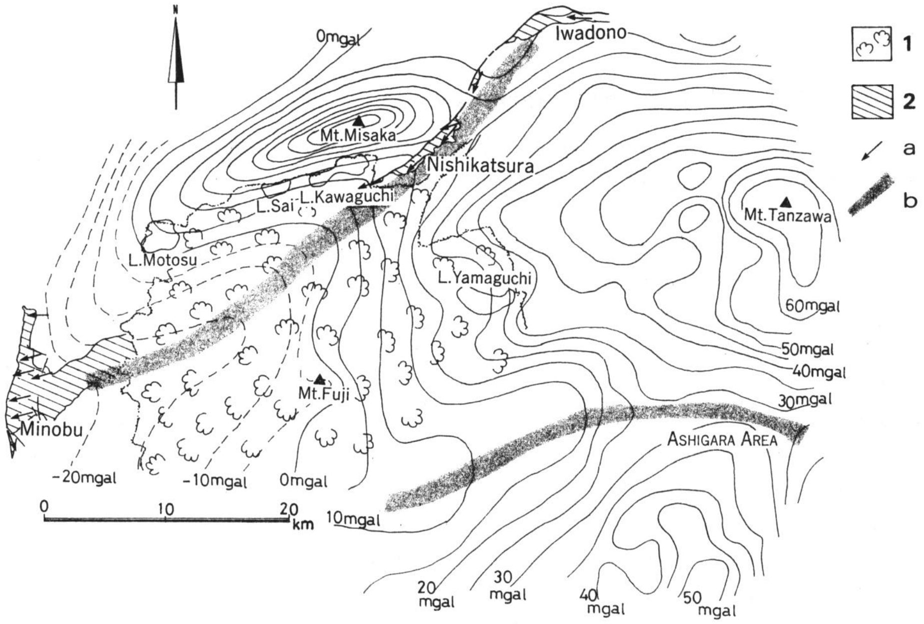


Fig. 34. Distribution and paleocurrent direction of Nishikatsura and Minobu areas, and Bouguer anomaly (from Hagiwara personal communication). Note that southern one of talwegs of low Bouguer anomaly is considered to be modern plate boundary by Nakamura et al. (1984). 1. Fuji lava, 2. distribution of channel fill sediments, a. paleocurrent direction, b. talweg of low Bouguer anomaly.

Aokigahara-Nishikatsura line (HAGIWARA, Y., personal communication, 1984), which suggests the presence of thick sediments of lower density than those of the underlying Nishiyatsushiro Group. Thus, it is reasonable to consider that thick piles of equivalent coarse clastic sediments are buried beneath Fuji Lava at Aokigahara.

Sequences of channel fill sediments in Nishikatsura and Minobu areas, thus, are thought to constitute a continuous channel system, that is, two areas are interpreted as upper and lower reaches of the same submarine channel respectively. Judging from the enormous volume of channel fillings, this channel running through Nishikatsura to Minobu areas played an important role as a feeding system. It appears that the submarine feeder channel provided clastic sediments from shallow marine environments such as fan-delta setting around Kwanto mountain paleoland to the deep Fujikawa basin, and that had been located on a relatively steep slope as discussed above. It is named herein Nishikatsura Channel (Fig. 35).

It suggests that Nishikatsura Channel was the tectonic channel which had been originally controlled by tectonic movement such as folding and faulting. This is deduced from the following evidence. 1) Nishikatsura Channel has a nearly straight-course and shows a very low-sinuosity (Fig. 34). Additionally, there is no sedimentological evidence to suggest the presence of tributary submarine channel.

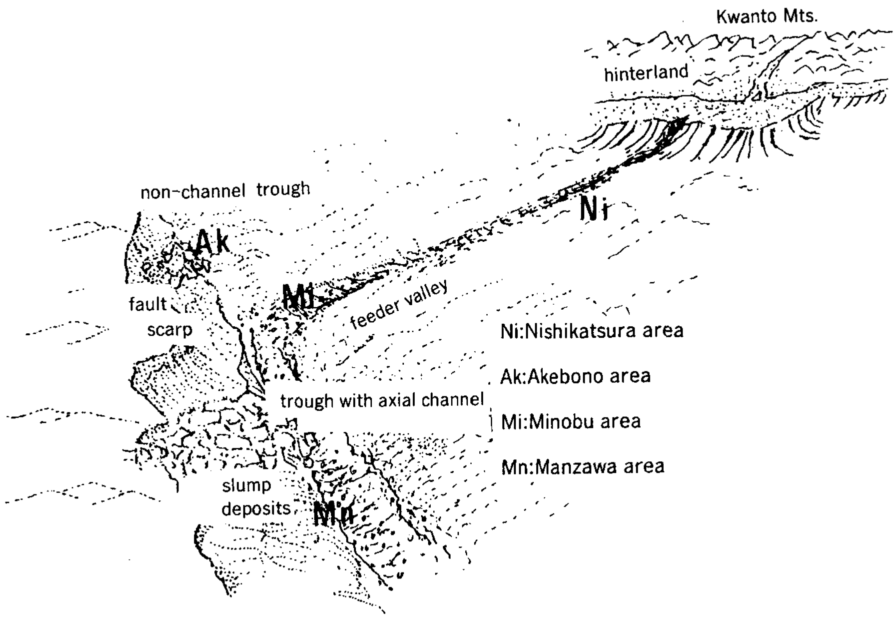


Fig. 35. Reconstructional models of sedimentary setting of the western half of the Southern Fossa Magna Region.

2) The course of Nishikatsura Channel, extending ENE-WSW, is concordant with the tectonic trend in the region (Figs. 3, 6 & 34).

Fujikawa Trough

Because the paleocurrent direction is strongly controlled by topographic condition of sedimentary basin, the pattern of the paleocurrent direction is useful for reconstruction of paleotopography of the sedimentary basin. As mentioned above, there are three main directions; SSE, WSW and E, in the study area. The first of them corresponds to the elongation axis of Fujikawa domain. It is the main paleocurrent direction of Fujikawa domain from Akebono area to Manzawa area through Minobu area. Among them, it is dominated in Manzawa area and the southern part of Minobu area. The second direction is of concordance with the direction of Nishikatsura Channel as the main feeder channel, and is developed in Minobu and Akebono areas. Eastward transport is observed as the minor paleocurrent element in these three area. In summary, the paleocurrent pattern of Fujikawa domain, on the whole, shows a convergent and centripetal pattern to southwest-southward. In addition, the paleoslope direction estimated by slump folding is of concordance with the paleocurrent pattern. Therefore, the paleotopography of Fujikawa domain can be interpreted to be a trough basin extending NNW-SSE in direction with a southsouth-westward tilted axial floor.

When giving a circumstancial account of the internal topography of this trough basin, the existence of western boundary paleoscarp in parallel to elongation of this trough basin is postulated. Because the results of facies analysis on PMA shows 1) to need a steep slope gradient as discussed above, 2) to need abundant supply of angular and large-size andesitic blocks and of slump-folded breccias, and 3) to need scattered sources of sediments extending along N-S direction west of the trough basin, causing the difference in local clast composition.

On the other hand, SCA of Manzawa area is interpreted as fill sediments of the axial channel of the trough basin by the following reasons. 1) The channel fill sediments are located in the central part of Manzawa area, and are enclosed in interchannel sediments. Considering the paleotopography estimated from the paleocurrent pattern and slumping, the channel fill sediments always kept their position in the lowest part of the basin. 2) Paleocurrent directions of the channel fill sediments are parallel to the extension of this trough basin (Fig. 35). Recently it has been shown that axial channels are prominant features in modern troughs and trenchs where active sedimentation is proceeding (e.g. the Aleutian Trench: VON HUENE, 1972; the Southern Chile Trench: SCHWELLER & KULM, 1978; the Middle America Trench: MOORE et al., 1982; the Nankai Trough: MOGI, 1977; TAIRA & NIITSUMA, in press).

In addition, benthic foraminifer analysis by KANO *et al.* (1985), suggest that this basin is located on upper bathyal or more deeper zone. Judging from these geomorphologic features, it is possible to state that Fujikawa domain was fill sediments of a trough extending N-S with an western boundary fault and an axial channel. It is named herein Fujikawa Trough.

10. COMPARISON WITH MODERN SEDIMENTARY ENVIRONMENTS

Sedimentary setting of the Minobu Formation and its equivalent strata are probably not unique, when compared with modern and ancient sedimentary environments reported. In comparison with features of the Minobu Formation and its equivalent strata with modern analogues of the trough environment, the modern Suruga trough has the closest similarity. There are several facts in favor of this; 1) similarity of intra-basinal topography between Fujikawa trough and the modern Suruga trough, 2) similarity of the axial direction of both troughs, 3) similarity of sedimentary ratio of fill sediments within both troughs.

Concerning the first point, it is confirmable that those two troughs are morphologically similar to each other, although complete reconstruction of Fujikawa Trough is out of hands due to a lack of marginal deposits. Results of analysis of SCA indicate the existence of an axial channel with a width probably more than a few kilometres. In Suruga Trough, it is recently reported from acoustic records, that there is a large-scale deep-sea axial channel which is a few kilometers in width (KATO *et al.*, 1982; H.D.M.S.A. & G.S.J., 1981). It is also considered that this channel is filled with turbidites and associated coarse clastic deposits. According to the reconstructed model in Fig. 47, there were fault scarps extending in N-S direction which demarcate the western boundary of Fujikawa Trough, and at the eastern side of the trough basin, there existed a steep slope as mentioned already. Similarly, in the modern Suruga Trough, fault scarps extending NNE to SSW form the western boundary of the trough axis (SAKURAI & MOGI, 1980). On the eastern margin of Suruga Trough, a steep slope is also developed toward Izu Penninsula and Zenisu Spur.

In respect to the second point, the reconstructed sedimentary setting is composed of three main sedimentary environments; Kwanto mountainland as main source region, Nishikatsura Channel of ENE-SSW trend and the N-S trending Fujikawa Trough. Distributional trend of Nishikatsura Channel sequence and Fujikawa Trough fill sediments are concordant with its dispersal pattern mentioned above. Furthermore, the deepening direction of the sea-bottom is also concordent with the azimuth of the paleocurrent from ENE to WSW. The three main environments, thus, are considered to have kept their original position since late Miocene age. This leads to the conclusion that the reconstructed Fujikawa Trough and the modern Suruga Trough have the same axial trend oblique to the general trend of the continental margin of the southwest Japan. This is a strikingly characteristic feature common to these two troughs, because many modern and ancient trough axes are parallel to the general trend of the continental margin (McBRIDE, 1962).

Considering the third point, the sedimentary ratio of the Minobu Formation is nearly equal to that of modern Suruga Trough, which has very high values for turbidites and associated coarse clastic sediments. The sedimentary ratio of coarse clastic sediments of piston core samples obtained from the axial part of the southernmost portion of Suruga Trough in the cruise KT-78-19 of Tansei-maru, attains up to approximately 150 cm/1000 year (SHIKI T., personal communication, 1985). Thus, sedimentary ratio in both troughs are similar to each other.

11. RECONSTRUCTION OF TECTONIC SETTING OF THE SOUTHERN FOSSA MAGNA REGION

Geomorphology in deep-sea environments differs basically from that of subaerial one where it is always destroyed by various kinds of external erosional processes such as storm and glacier. The geomorphology in the deep-sea must be strongly controlled by tectonic movements (MOGI, 1977). The similarity of geomorphologic features between the modern Suruga and Fujikawa Troughs is the most important. Because it suggests that similar tectonic movements to those now active in the modern Suruga Trough took place in Fujikawa Trough in Mio-Pliocene age.

Modern Suruga Trough as a plate boundary

In relation to the genesis of the bending geomorphology in and around the present region, EHARA (1953) proposed first that it was formed by the collision of his "Izu-shichito batholith" into central Honshu. Since 1970's, it has been argued that Suruga and Sagami troughs represent the plate boundary between Philippine-sea and Eurasian plates (e.g. SUGIMURA, 1972), and that Izu Peninsula on Philippine-sea Plate has been continuously driven to collide into Southwest Japan Arc on Eurasian Plate (KAIZUKA, 1975; MATSUDA 1978; NAKAMURA & SHIMAZAKI 1981; NAKAMURA *et al.*, 1984; MOGI *et al.*, 1982).

On the geomorphologic setting of Philippine-sea and Eurasian plates around Izu Peninsula, geophysical and geological studies have been carried out. NAKAMURA *et al.* (1984) pointed out that the material boundary of Philippine-sea and Eurasian plates is situated on the north of Hakone volcano running along talweg of the low Bouguer anomaly (A-A' line in Fig. 36). ISHIBASHI (1976) proposed that the modern plate boundary has already jumped to the Izu-toho Line, off the eastern and southern coast of Izu Peninsula (B-B' line in Fig. 36), basing on analysis of local-uplifting phenomenon in the Kwanto earthquake of 1923. Furthermore, on the basis of change of the stress field pattern, MATSUDA (1978) reconstructed the tectonic

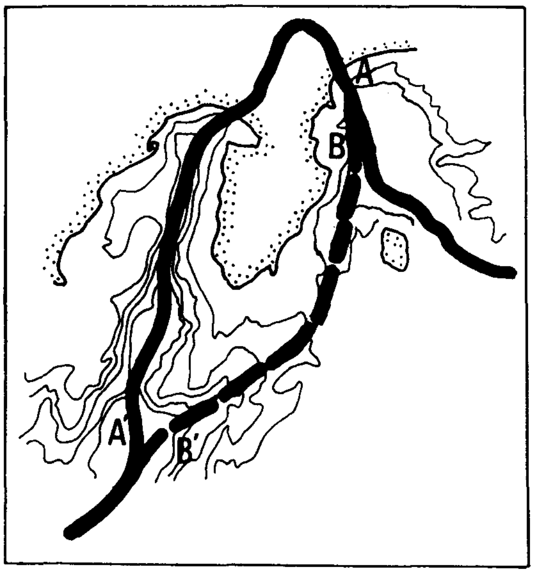


Fig. 36. Proposed plate boundaries in the southern Fossa Magna Region between Eurasian and Philippine-Sea plates. A-A′: boundary of Nakamura et al. (1984), B-B′: boundary of Ishibashi (1976).

history of this region as a subduction zone of the Miocene, which in turn changed to a collision zone in the Quaternary, and also proposed that a new subduction zone may have begun to shift to south.

Collision of Tanzawa block

Assuming that modern geomorphology of Suruga and Sagami troughs has been construcied by collision of Izu Peninsula into Southwest Japan Arc and that the plate boundary is shifting to south, it follows that Fujikawa Trough might be also constructed by ancient collision event.

A remaining question is what did collide at that time into Southwest Japan Arc, instead of Izu Peninsula. It is important facts for the question that the main frame work of geologic structure in the Southern Fossa Magna Region shows a half-dome structure around Tanzawa Mountains (Fig. 3), and that the thick-bedded coarse clastic sediments of the Minobu Formation and its equivalent strata are developed around Tanzawa Mountains only (Fig. 2). Additionally, there is a resemblance in rock appearance and in chemical composition between the sequences, mostly of volcanic origin, in Tanzawa Mountains and Izu Peninsula (Matsuda, 1978). The sequence of Tanzawa Mountain seems to have belonged originally to the northern part of Izu-Bonin Arc, and not to the Neogene system of the southwest Japan Arc. I believe that the sequence of Tanzawa Mountain, here called Tanzawa Block, played the same role as a collision mass just as Izu Peninsula does at present, and that collision of Tanzawa Block began prior to deposition of the latest Miocene to early Pliocene Minobu Formation.

Geologic history of the Southern Fossa Magna Region

The similarity of tectonic setting of modern and ancient troughs described before, brought a new interpretation to the geologic history of the Southern Fossa Magna Region. It will be briefly mentioned below (Fig. 37).

It has been stated that Southwest Japan Arc suffered the following tectonic events during early to middle Miocene age; rotation of Southwest Japan Arc due to opening of Japan Sea (OTOFUJI & MATSUDA, 1983; 1984) and initiation of subduction of Philippine-sea Plate after opening of Shikoku Basin (eg. KARIG & MOORE, 1975).

After early to middle Miocene events, the first collision took place in the Southern Fossa Magna Region in middle Miocene age (TONOUCHI & KOBAYASHI, 1983). As a result of the collision, the structural belts of the eastern part of the southwest Japan have suffered bending action to form an arch (stage 2 in Fig. 37). Until now, however, details on the first collision have not been made clear.

With the beginning of the second collision by Tanzawa Block, the geomorphologic frame work of the western part of the Southern Fossa Magna Region was constructed. This includes

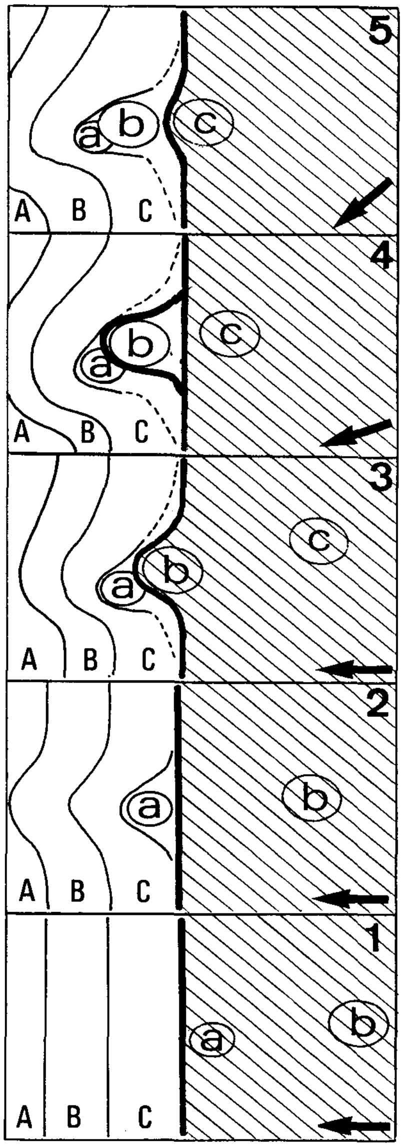


Fig. 37.
Schematic reconstruction of development of the Southern Fossa Magna Region. Heavy line is trench or trough as plate boundary. a: probably "Kushigata block", b: Tanzawa block, c: Izu block, A: Sanbagawa belts, B: Chichibu belts, C: Shimanto belts. Arrows mean the probably moving direction of Philippine-sea Plate.

features such as Fujikawa Trough, Nishikatsura feeder valley and uplift of Kwanto mountainland (stage 3 in Fig. 37).

In the following stage 3, Kwanto mountainland uplifted enough to provide abundant coarse clastic sediments during latest Miocene to early Pliocene in age. Nishikatsura Channel and the axial channel of Fujikawa Trough were constructed and filled by clastic sediments. Fill-sediments deposited thickly but had not sufferred remarkably synsedimentary deformation, same as that observed in the present of Suruga Trough as a collision zone. This contrasts to the features of accretionary prism in Nankai Trough as a subduction zone.

After jumping of the plate boundary to the north of Hakone, the third collision by Izu Block took place during 1 Ma to 0.5 Ma (SUGIMURA, 1972; KAIZUKA, 1975; MATSUDA, 1978). As a result of this collision, the sedimentary basin doposited coarse clastic sediments was migrated to the Ashigara area north of Izu Peninsula and the Minobu Formation suffered tectonic deformation such as faulting and folding causing abrupt uplift of the northern half of the southern Fossa Magna Region.

At this stage, the main provenance in and around the Southern Fossa Magna Region shifted abruptly from Kwanto mountainland to Akaishi mountainland. Thus, it is thought that the direction of plate motion of Philippine-sea Plate changed from northward to northwestward (MATSUDA, 1978; NAKAMURA, *et al*, 1984) (Stage 5 in Fig. 37).

In conclusion, it should be stressed to say that multiple collisions have played an important role for the geologic development of the Southern Fossa Magna Region.

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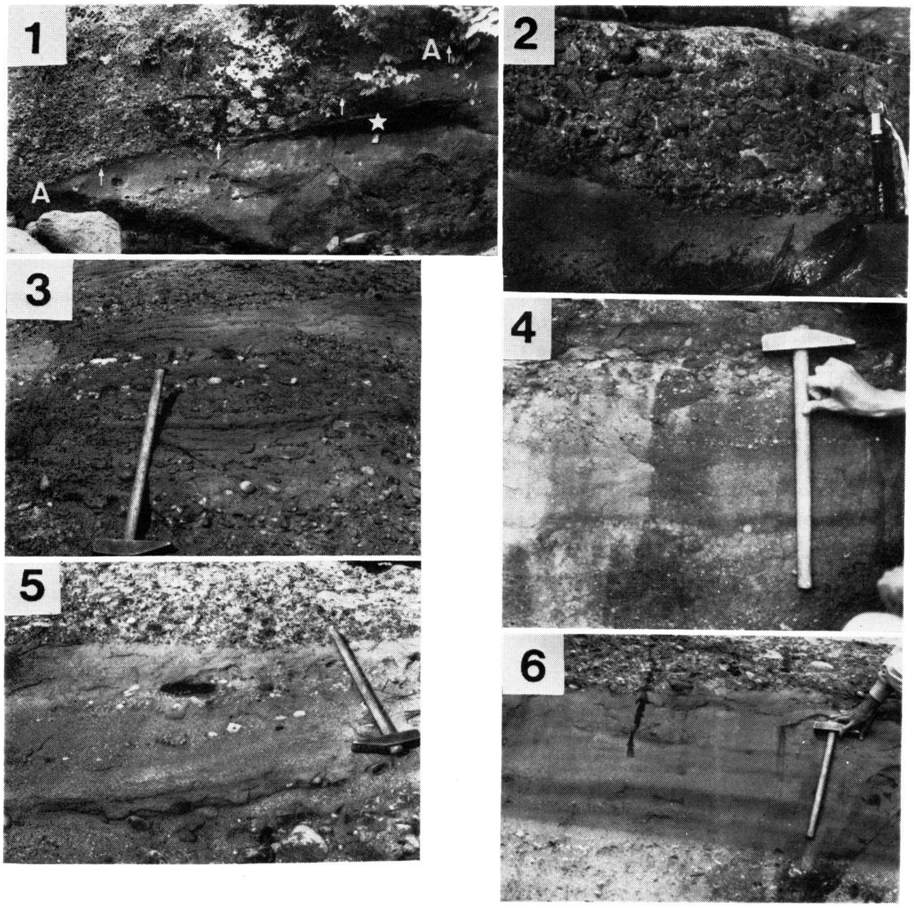
* in Japanese with English abstract ** in Japanese

Plates 1–4

Explanation of Plate 1

1 Relationships between CPA and the underlaying Furuya Sandstone at Hishakurusawa showing erosional base of channel structure (A-A'). Clinometer for scale (star).
2 Sedimentary facies of Facies A3 in CPA, showing inverse grading and clast imbrication.
3 Facies A4 in CPA. Hammer 14 long.
4 Facies B3 (lower) and Facies A4 (Upper) in CPA.
5 Facies A5 (lower) and Facies A3 (Upper) with scouring.
6 An example of facies transition, from Facies A4 to Facies A3 through Facies B2.

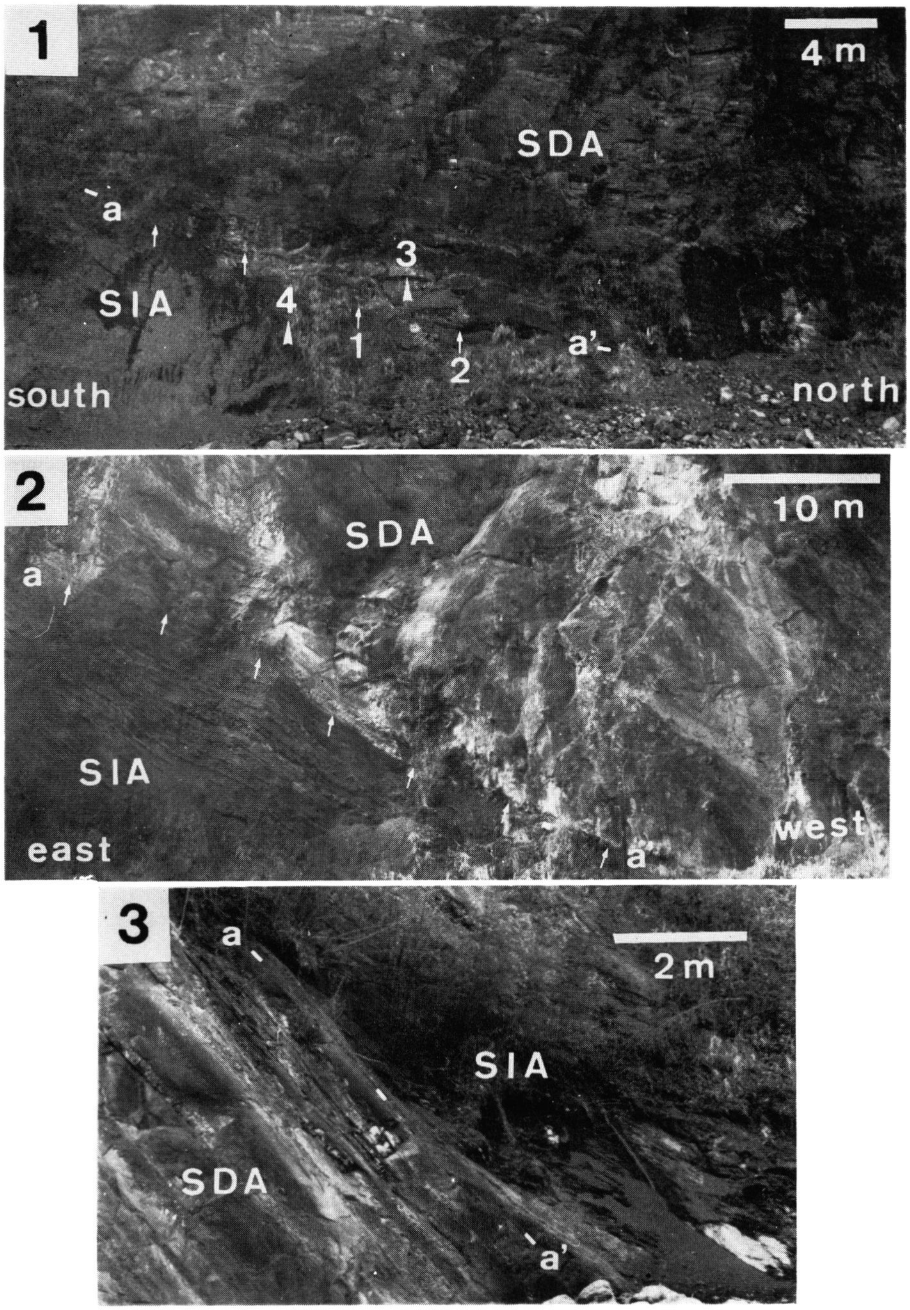

1
A
A
2
3
4
5
6

Explanation of Plate 2

1 An outcrop of profile normal to paleocurrent direction, Loc. a in Fig. 7 & 8, showing relationships between SDA (Furuyashiki Sedimentary Body) and the underlying SIA. Note the curved and slightly eroded boundary surface (a-a'). Dip and strike; 1, N5E 60W; 2, NS 45W,: (boundary surface); 3, N20E 40W; 4, N15E 40W,: (bedding plane).

2 An outcrop of profile paralell to paleocurrent direction, Loc. d in Fig. 7 & 8, showing the boundary between SDA (Arayashiki Sedimentary Body) and the underlying SIA, and the boundary surface of two associations (a-a') is concordant with the bedding planes of both associations.

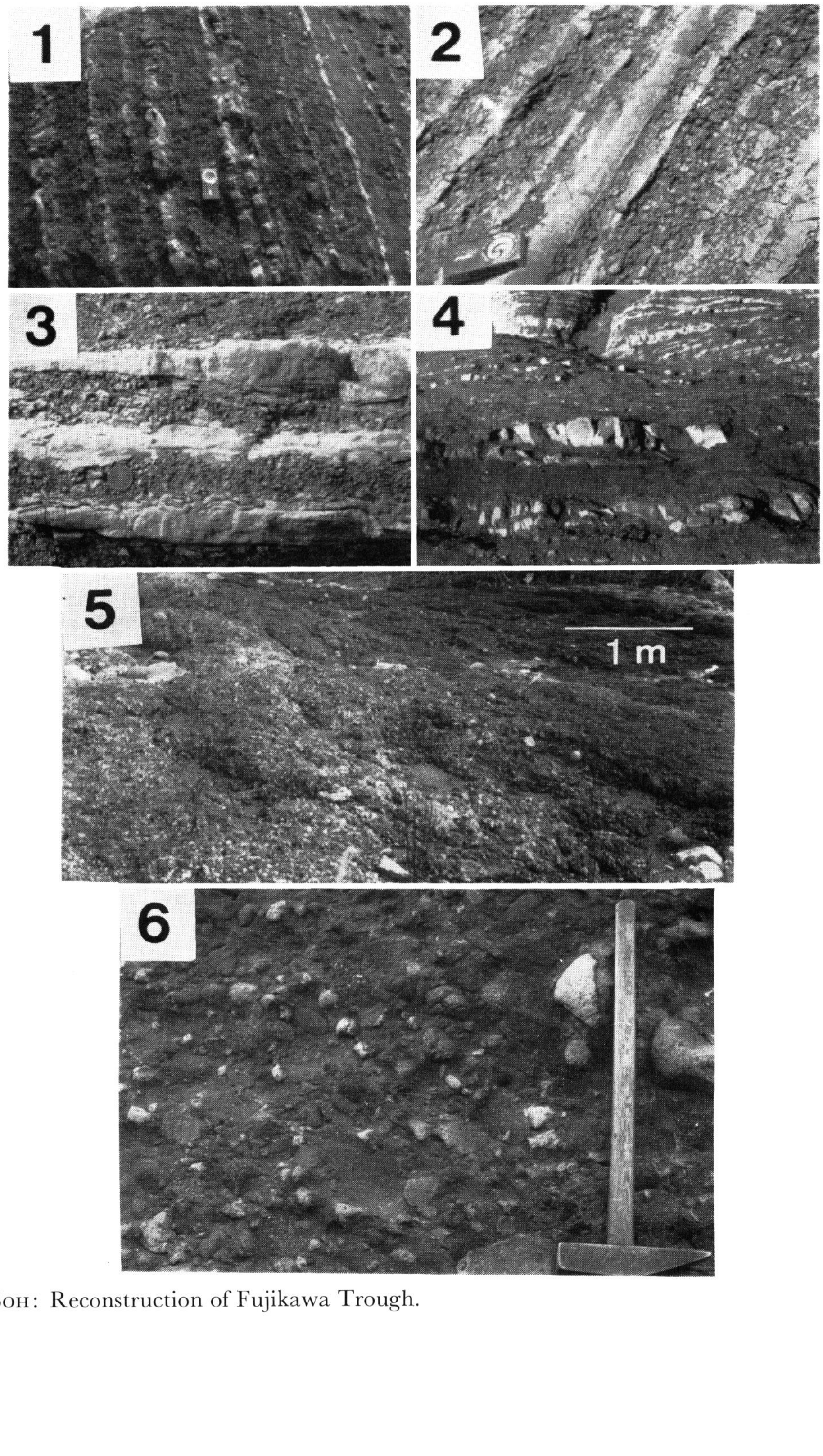
3 An outcrop at east Furuyashiki, showing the upper boundary (a-a') of SDA (Furuyashiki Sedimentary Body), and the overlying SIA. Note that SDA changes gradually into SIA.



SOH: Reconstruction of Fujikawa Trough.

Explanation of Plate 3

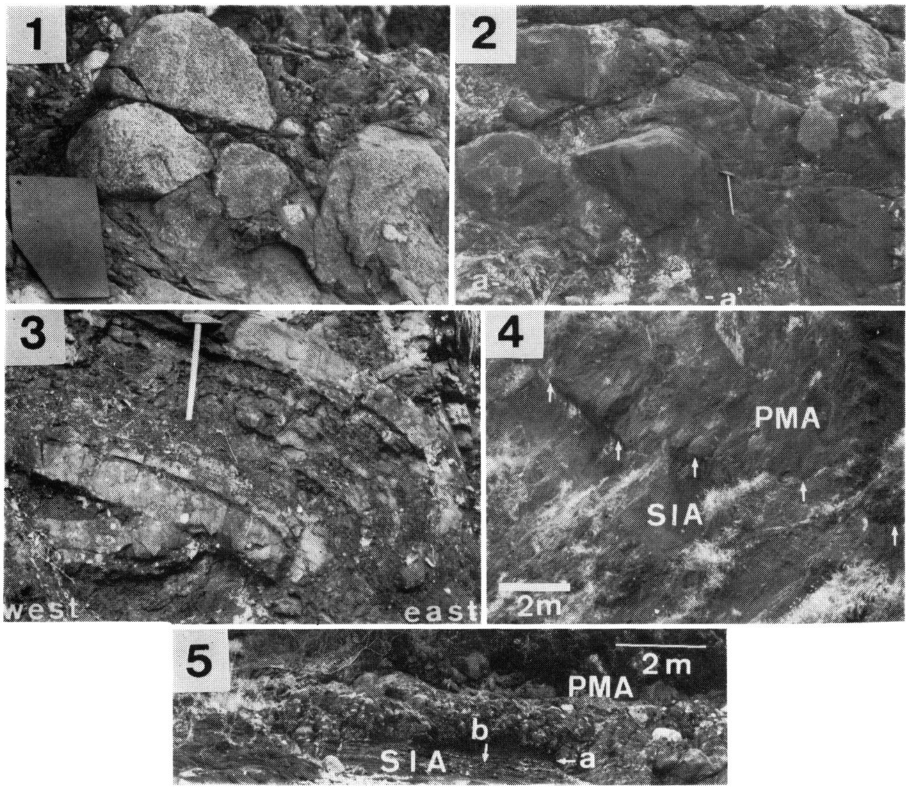
1 Sedimentary facies of interchannel sediments; a view of SIA. Beds younging to right. Clinometer 12 cm long. At Oshima in Fig. 7.
2 Closed-up of typical facies of SIA.
3 Three types of sandstone beds; upper and lower beds are subfacies C3-b and C3-a respectively, and middle one is Facies C2. Coin 2.5 cm in diameter.
4 Lenticular sandstone bed of subfacies C3-b, probably fill sediments of a minor crevasse channel. Measure 8 cm.
5 An outcrop of Facies A1 contained with angular andesitic clast in SCA.
6 Closed-up angular andesitic clasts. Hammer 40 cm long.



SOH: Reconstruction of Fujikawa Trough.

Explanation of Plate 4

1 Andesitic clasts in PMA, at Hadakashima. Scale board 14 cm long.
2 One of the maximum-size clast of andesitic rock in PMA. Boundary of PMA and SIA is shown as a-a'.
3 A slump-folding of PMA in SSA, showing a westward transporting at west Kobayama (See, Fig. 22).
4 An outcrop showing lenticular sedimentary body of PMA in profile normal to transport direction. Note the erosional basal boundary of PMA.
5 An example of outcrop showing erosional basal boundary of PMA. Boundary "a"; N85W 80W, and bedding plane of the underlying SIA "b"; N20E 60W (Sef, Fig. 22).



SOH: Reconstruction of Fujikawa Trough.