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34. *Thickness Distribution of Sandstone Beds and Cyclic Sedimentations in the Turbidite Sequences at Two Localities in Japan.*

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Introduction

Since Daly proposed the idea of the turbidity currents and Kuenen and Migliorini (1950) clarified the relation between the ancient and recent turbidites, Flysch-like deposits have been generally thought to be formed mostly by the turbidity currents. The "rhythmic" sedimentation of alternated beds of sandstone and shale which is found in very thick Flysch-like sequences is not produced by cyclic oscillations.

In Japan there are many turbidite sequences from the Paleozoic to the Tertiary, especially in the Sambosan and the Shimanto terrain. The Permian-Triassic Sambosan group and the Jurassic- Cretaceous Shimanto include generally alternated beds of sandstone and shale. The number of beds sometimes exceeds several thousands. In the Tamagawa and Oigawa districts the sandstone beds of the alternation are graded ones and have many characteristics common in the turbidites. These are thought to be typical geosyncline deposits in Japan. In these districts I found cyclic sedimentations, a remarkable feature in the turbidite sequence. Thickness distributions of sandstone and shale beds and the cyclic sedimentations in the turbidite sequences are dealt with in this paper.

Here I wish to acknowledge my indebtedness to my colleagues of the Earthquake Research Institute, Geological Institute and Institute of Earth Sciences, University of Tokyo, for their kind advice and discussion. I am also indebted to Mr. T. Ichikawa who helped me with the illustrations and some statistic calculations.

The turbidite sequences of the Sambosan group along the Tamagawa (=Tama river) in the Kanto mountainous land and of the Shimanto group in the Oigawa (=Oi river) district

The Sambosan group The Sambosan group is distributed in the southernmost part of the Chichibu terrain throughout Southwest Japan (Fig. 1). Middle Triassic fossils were found at Sambosan and Permian

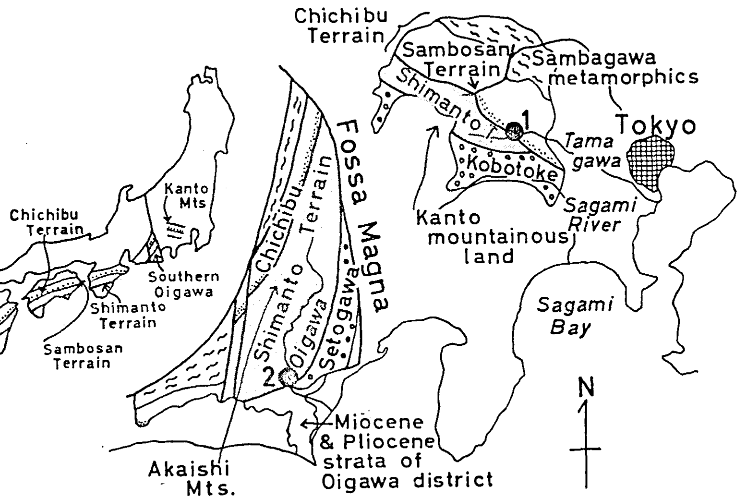

Fig. 1. Distribution of the Permian-Triassic Sambosan and of the Jurassic-Cretaceous Shimanto group.
1....Unazawa area in the Tamagawa district.
2....Southernmost part of the Shimanto terrain in the Oigawa district.

fossils were reported from the other localities in Shikoku. Kobayashi (1931) proposed the name of the Sambosan group for the Permo-Triassic strata. Recently Kanmera and Furukawa (1964) clarified the gradual transition from the Paleozoic strata to the Triassic in Kyushu.

The Sambosan group is principally composed of white crystalline limestone, thick chert, thick sandstone and shale with subordinate volcanics. The sandstone is graywacke, although it contains rather poor clay matrix and much quartz and chert grains (Kimura, 1954, 1957).

The less- and non-metamorphosed Paleozoic strata to the south of the Sambagawa-Mikabu crystalline schists are distributed in three zones trending in the equatorial direction: the northern, central and southern zones. The southern zone is the Sambosan terrain. These zones are separated from each other by thrust faults (Kobayashi, 1941, 1953).

The Paleozoic strata in the northern zone are characterized by thick volcanics, limestone and shale. The sandstone often contains volcanic rock fragments and much clay matrix (Kimura, 1957). The sedimentary facies is called the Choja facies in Shikoku (Kurata, 1941), and the Ogawago in eastern Kii (Kimura, 1957). The Paleozoic strata in the central zone are characterized by alternate beds of sandstone and shale. The sandstone has an intermediate character between those of the northern zone and the southern. The facies is called the Kamo facies in Shikoku and the Ichinose in eastern Kii. The facies of the Sambosan group is called the Bandagamori facies in Shikoku and the Nomisaka in eastern Kii.

The strata of these facies often contain turbidites. However, the deformation of strata becomes more intense toward north. The sandstone beds in the northern and central zones are usually so intensely sheared that they show lensular outlines by *Linsige Zerscherung* (Metz, 1957) and form a pseudo-stretched pebble structure (Hills, 1963). Therefore the study on the turbidites is rather difficult. On the other hand the sandstone beds of the Sambosan group show less deformation.

The turbidite sequence along the Tamagawa The Sambosan group in the Kanto mountainous land (Fig. 1) to the northwest of Tokyo was once thought to be of the Jurassic age together with the strata yielding the Jurassic Torinosu limestone (Huzimoto, 1939). However, Kobayashi (1939) found the Permian Fusulinid from the terrain, and later Takaoka (1954) also reported the Permian fossils from the other localities.

The Sambosan group in the Kanto mountainous land is principally composed of thick limestone, chert and sandstone together with shale. The strata resemble those in Kii, Shikoku and Kyushu.

Turbidite sequences are well distributed along the Tamagawa in the Kanto mountainous land. Fig. 2 is a route map of the Unazawa area, where the turbidite sequence is most well observed. Here the sandstone-rich strata are well developed in the southwestern part and the shale-

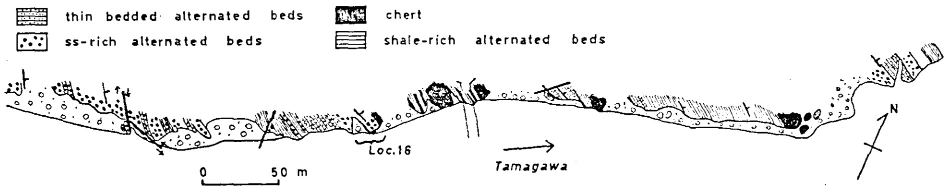

Fig. 2. A route map at Unazawa, in the Tamagawa district.

rich strata in the northeastern. All these strata are trending in the NW direction and dipping to the northeast. The strata seem to show a cyclic sedimentation. Such a cycle of sedimentation is also seen in other northeastern parts of the Tamagawa district. However, at those northeastern localities the deformation of strata is rather intense, and the study of the turbidite sequence is rather difficult.

The turbidite beds along the route in Fig. 2 at Unazawa show clear graded bedding (Fig. 28, h). Sole making is rather few, although it is clearly seen on the underside of thick (1 m or more) sandstone beds. The sandstone is quartz-rich graywacke, and resembles that in eastern Kii, Shikoku and Kyushu. However, the sandstone of thinner beds contains abundant clay matrix, and is less quartzose than that of thicker beds.

The sandstone beds gradually change into the shale beds. However, the transition zone is very narrow. Therefore, we can measure the thickness of the sandstone beds and shale beds separately. I measured the thickness of about 1,400 beds. The data were plotted on a sandstone-shale diagram as will be shown later.

The Shimanto group The Shimanto group is distributed throughout Southwest Japan to the south of the Sambosan terrain (Fig. 1). In the northern part of the Shimanto terrain the Torinosu-type limestone occurs. Therefore the strata may include those of the Jurassic Torinosu age. The fossils of the Lower and the Upper Cretaceous (Matsumoto *et al.*, 1952; Katto, 1961) were reported from several localities in Shikoku. The group has usually suffered more intense deformation in the northern part than that in the southern. Some strata in the northern part changed into phyllite (Hashimoto, 1962; Seki *et al.*, 1964; Matsuda *et al.*, 1965).

The Shimanto group contains much turbidite sequences. However, in the northern part of the group it is difficult to study the turbidites, because of deformation.

Turbidite sequence of the Shimanto group along the southern part of the Oigawa (=Oi river) The Shimanto group is well developed along the Oigawa (Fig. 1) in Central Japan. The group trends in the N-S direction in the northern part and on the other hand in the southern part in the NE-SW direction. The change of the trend is nearly parallel to the bend of the Median Tectonic Line in Central Japan (Kimura 1959).

The Shimanto terrain in the Oigawa district is divided into 5 zones from northwest to southeast: the Akaishi, the Shirane, the Oigawa, the Mikura, and the Setogawa zone (Akaishi Group, 1961). Among them the Setogawa terrain is occupied by the Paleogene Setogawa group. The northwestern zone is characterized by volcanics and alteration into phyllitic rocks. The main part of the Shimanto group along the Oigawa is principally composed of shale beds and subordinate sandstone. In the southernmost part, however, sandstone beds prevail. Most of the sandstone beds show graded bedding, some of which have sole marking that is clear in thick (70 cm or more) sandstone beds. These are turbidites. To the south of the strata, the Paleogene Setogawa group is distributed.

In the northern part of the Setogawa terrain schalstein-rich strata, the Takizawa group (Chitani, 1931), occur and in the southern part the sandstone and shale beds prevail. The sandstone beds are often turbidites. Further to the south of the Setogawa group, Miocene and Pliocene groups are distributed. Turbidite sequences are also found in these groups. Among them, the turbidite sequence of the Pliocene Kakegawa group, the Horinouchi facies, was studied by Makiyama (1954), Ujiie (1962) and others.

In this way turbidite sequences of several ages are well distributed in the southern Oigawa district. The older sequence occurs in the northwestern part and the younger in the southern. I studied that of the Shimanto group, the oldest among them.

The southernmost part of the Shimanto group is tentatively divided in this paper into three formations; The A, B and C formations (Fig. 3). They are the Kamio formation of the Nabeshima group (Matsumoto, E., 1964). These strata trend in the NEE direction and dip to the north to 15–50 degrees. The graded bedding (Fig. 28, b) always shows that the strata are overturned. The A formation is the oldest and the C is the youngest. The A and C formations are principally composed of sandstone and shale beds. The sandstone beds range from a few mm to 1.4 m. The average thickness is 28.5 cm for the A formation and 11.0 cm for the C (Table 1). The thickness of the shale beds is up 55 cm. The average is 10.4 cm for the A formation and 5.3 cm for the C (Table 3). The graded sandstone beds gradually change upward to the shale beds. However, the transition zone is usually very narrow. We can easily measure the thickness of sandstone and shale beds separately. But in the case where the graded sandstone bed is thin (1 cm or less) and the sandstone is very finely grained, the transition zone is rather thick compared with the sandstone bed, measurement of this thickness being rather difficult. This is the case of the turbidite-poor shale formation underlying the A and overlying the C formation. Almost all of the sandstone beds of the A and C formations are turbidites. The shale beds sometimes contain not well preserved minor Foraminifera. The A formation gradually changes into the underlying shale formation. On

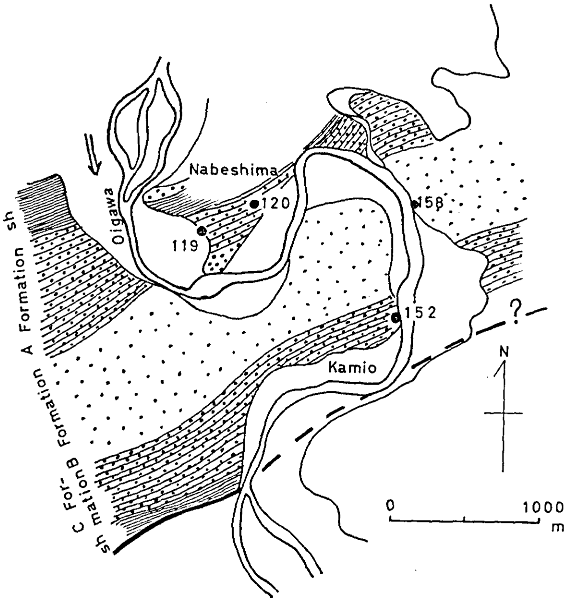

Fig. 3. Geological map of the southernmost part of the Shimanto group in the Oigawa district.

the other hand the C formation changes gradually into the overlying shale formation which may be of the Eocene (Makiyama, 1963).

The B formation is also composed of alternation beds of sandstone and shale. Some part of the B formation cannot be distinguished from the A or C formation in lithologic character. However, the main part of the B formation is principally composed of thick sandstone beds, some of which exceed 5 m in thickness, with very thin shale beds. Carbonaceous seams are found. Most of the sandstone is white and clean and frequently rich in lamina. The sandstone is different from that of turbidites in the A and C formations.

The three formations show the change from the sandstone-poor formation through sandstone-rich formation to the sandstone-poor one again. The change shows a cyclic sedimentation (Fig. 4). Such cyclic sedimentations with graded bedding sequence have been recently reported

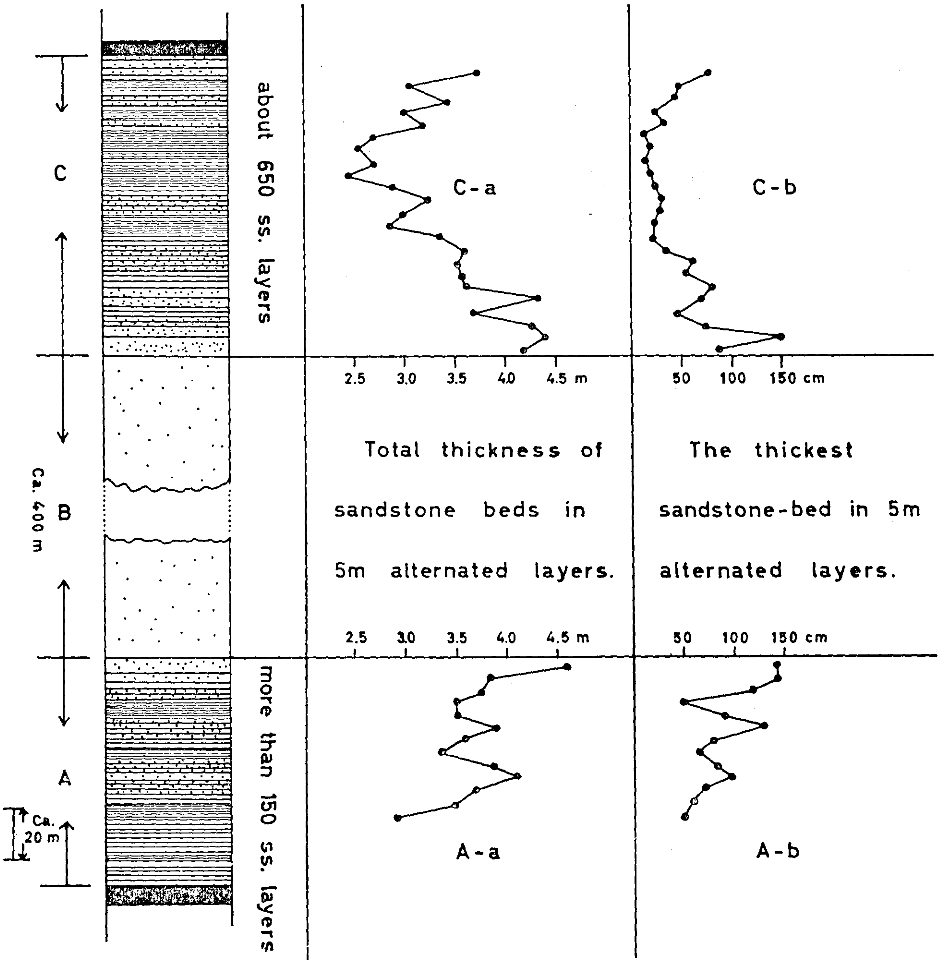

Fig. 4. Columnar section of the A and C formations and distribution of total thickness and thickest bed within each 5 m column.

from the Cretaceous Izumi group in Japan (Tanaka, 1965; Harada, M., 1965).

These formations are now overturned and there is a formation similar to the B formation about 3 km north of Loc. 158. To the north and the south of the formation, there are strata comparable with the A and C formations. I am now of the opinion that there is a grand recumbent fold in the southernmost part of the Oigawa district. The A, B and C formations are the southern overturned limb. There are many recumbent minor folds with half wave length of about 1 m in the A and C formations as shown in Fig. 28, a. The minor folds also may suggest the strata are overturned.

Some of sole marking on the overturned sandstone beds (Fig. 28, c) clearly shows the current from north to south in the present position. Therefore the current seems to have flowed originally from south to north. The northern limb of the recumbent fold contains less sandstone beds than the southern. These facts may show that the source of the turbidite is to the south of the southern Oigawa district. The observation does not accord with the prevailing opinion that the land mass as the source has lain to the northwest of the district from the Paleozoic to the Tertiary (Makiyama, 1950). Recently, Harata (1965) found that some of-turbidites of the Paleogene group in the Shimanto terrain in Kii have been transported there from the south.

Sandstone-shale diagram of the turbidite sequences of the Sambosan and Shimanto groups

The gradual change from the sandstone-rich part to the sandstone poor part or vise versa was observed in the turbidite sequences in the Sambosan group and the Shimanto. The change is clearly shown in the sandstone-shale diagrams. To make the diagrams about 4,000 sandstone and shale beds were measured in the Tamagawa and the Oigawa districts.

Sandstone-shale diagram A sandstone-shale diagram shows a thickness distribution of sandstone and shale beds as shown in Fig. 5. The accumulated thickness of sandstone is taken in the ordinate and the accumulated thickness of shale in the abscissa. A bed of sandstone or shale is shown as a short line parallel to the ordinate or the abscissa. The general trend of inclination of the diagram shows the sandstone-shale ratio.

Accumulated thickness of sandstone beds within a unit thickness column of the turbidite sequence and accumulation of sandstone during the deposition of a unit thickness of shale are easily measured from the diagram by the procedure shown in Fig. 5. The number of turbidites during the deposition of a unit thick shale can also be obtained from the diagram.

One sandstone-shale diagram was obtained from a continuous series of strata not cut by a large fault at one outcrop. When no faults appear to exist even if there are small non-outcropped spaces (1 m or less) at a large outcrop, the series is shown in a diagram. The non-outcropped spaces are shown by ? in the diagrams. In the Tamagawa and the Oigawa districts I could not obtain a diagram from top to bottom of the whole formations, because of non-outcropped spaces. The longest continuous sequence was measured at Loc. 152 in the Oigawa, which is about

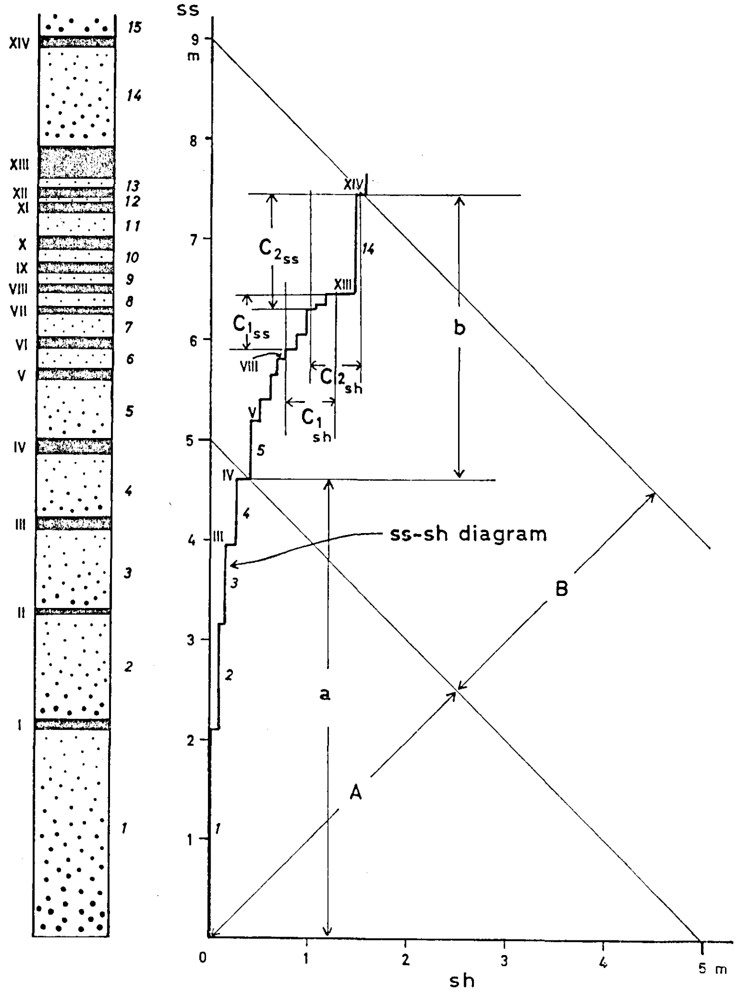

Fig. 5. Sandstone-shale diagram.
1, 2. 3....sandstone beds
I, II, III..shale beds
A, B......thickness of strata
a, b ......total thickness of sandstone beds within a column of A or B
C_{1ss}, C_{2ss} ..accumulation of sandstone during the deposition of shale of a unit thickness (C_{1sh})

110 m thick and contains about 1,300 beds (Fig. 15).

The sandstone-shale diagram and cyclic sedimentation near Unazawa in Tamagawa Sandstone-shale diagrams were made throughout the Unazawa area. The diagram of the westernmost part is shown in Fig. 6. Accumulated thickness of sandstone within a 5 m column of alternated strata was measured from these diagrams. The result is shown in Fig. 7, which clearly shows a major cyclic sedimentation in the Unazawa area. The strata which form the major cycle are about 400 m thick. In the cycle the supply of sand is quite large at first (80-95% of whole strata) and becomes gradually smaller. At the stage of minimum supply, the sandstone occupies 6-30% of the whole thickness. Then the supply becomes larger again.

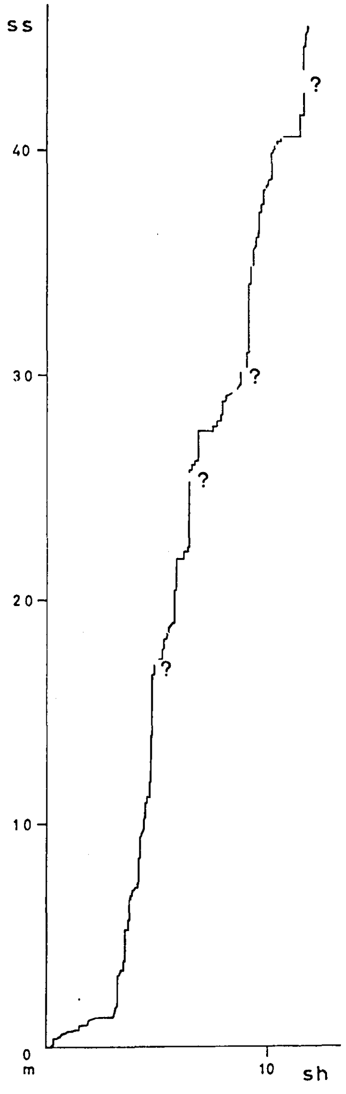

Fig. 6. Standstone-shale diagram of the Sambosan group at the westernmost part of Unazawa (Fig. 2).

The cycle of sedimentation is also clearly shown in Fig. 8, which was obtained from the measurement of the accumulation of sandstone during the deposition of 50 cm shale.

Besides the major cycle there are minor cycles in the turbidite sequence. The diagram of the westernmost part (Fig. 6) shows the feature. Five or more cyclic sedimentations can be seen in the strata of about 60 m thick. The minor cyclic sedimentation starts with thick (1 or 2 m) sandstone beds. These sandstone beds become thinner toward higher up. Thin shale beds are inserted among these sandstone beds. The sandstone bed of the uppermost part of the cycle is 5 cm or less. The next minor cyclic sedimentation begins again abruptly by a thick sandstone bed. The pattern of the minor cycle is schematically shown in Fig. 12.

In this way the turbidite sequence

in the Unazawa area forms a major cyclic sedimentation, which includes many minor cycles. The minor cycles are of course composed of "rhythmic" alternation beds of sandstone and shale which are turbidite sequence.

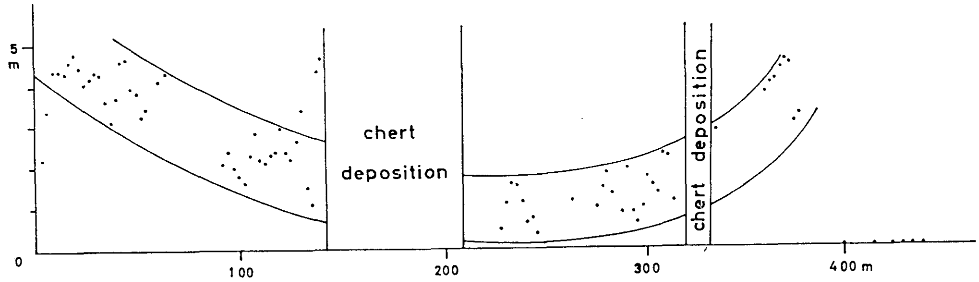

Fig. 7. Total thickness of sandstone beds within 5 m column of strata and chert at the Unazawa area. The abscissa: the thickness of the strata.

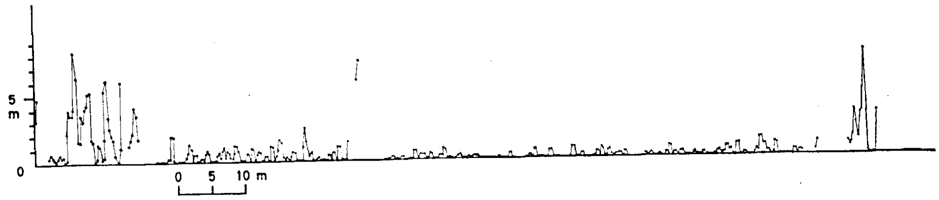

Fig. 8. Accumulation of sandstone during the deposition of 50 cm shale at Unazawa. The abscissa: accumulated thickness of shale.

The relation between the cyclic sedimentation and chert deposition
Fig. 7 also shows a remarkable relation between the major cyclic sedimentation and chert beds. The chert beds are inserted in two horizons in the cycle. The deposition of chert did not occur when the supply of sand was at a minimum.

The Sambosan group is generally rich in chert throughout Southwest Japan. The group, 3,000 m thick or more, contains in general 30% or more chert. On the other hand the group is also rich in medium and coarse sandstone. If the deposition of chert is considered to have occurred under the condition of almost no supply of clastics, the coexistence of thick chert and thick sandstone is quite peculiar (Kimura, 1957). However, the figure clearly shows that the deposition of chert did not occur under the condition of minimum supply of sand. During the formation of a turbidite sequence the depositional rate is not equal throughout the sequence. Instantaneous deposition of sand beds is caused by turbidity currents; on the other hand very slow deposition occurs when turbidity currents do not take place. Flysch-like sequences were deposited generally at a rate of 0.1–0.9 m per 1,000 years (Kay, 1955). The figure shows the long duration of a non or very slow depositional stage through the turbidite sequence. If chert beds could deposit very quickly compared with the very slow deposition of shale they may occur in any horizon of the turbidite sequence. This may be the case in the Unazawa area.

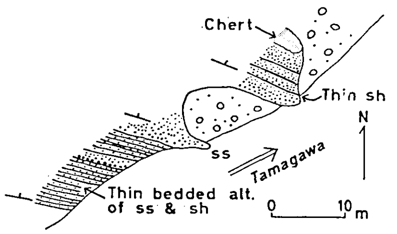

Fig. 9. A relation between a chert bed and turbidites at Loc. 16 (Fig. 2), Unazawa.

One of the thick graded sandstone beds in the Unazawa area gradually changes into chert toward the upper layers (Fig. 9). The same gradual

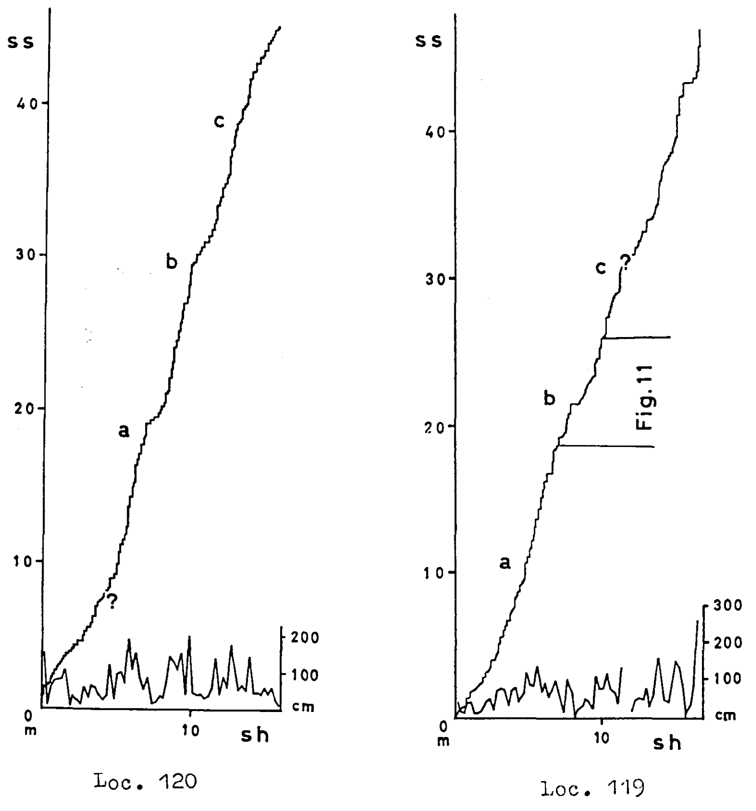

Fig. 10. Sandstone-shale diagrams at Loc. 119 and Loc. 120, the A formation. a, b and c at two localities are correlated with each other.

transition is often seen in Shikoku and Kii. The facts may show that turbidity currents sometimes flow into the area under the condition of chert deposition.

Sandstone-shale diagram of the A formation in southern Oigawa In the southernmost part of the Shimanto group in the Oigawa district, the A formation (Fig. 4) gradually changes toward lower layers to the shale formation with some very thin turbidites, and toward upper layers to the B formation, the sandstone-rich formation. The gradual changes can be seen at Loc. 120 and Loc. 158.

The main part of the A formation is outcropped at Loc. 119 and Loc. 120. The sandstone-shale diagrams are shown in Fig. 10. Two diagrams at two localities resemble one another and at a glance are fairly well correlated with each other. The correlation has also been checked by the study of the distribution of the sandstone bed thickness according to the sedimentation order (Fig. 19). The sandstone-shale diagram appears to be useful to the correlation of the turbidite sequences.

The strata at Loc. 119 and Loc. 120

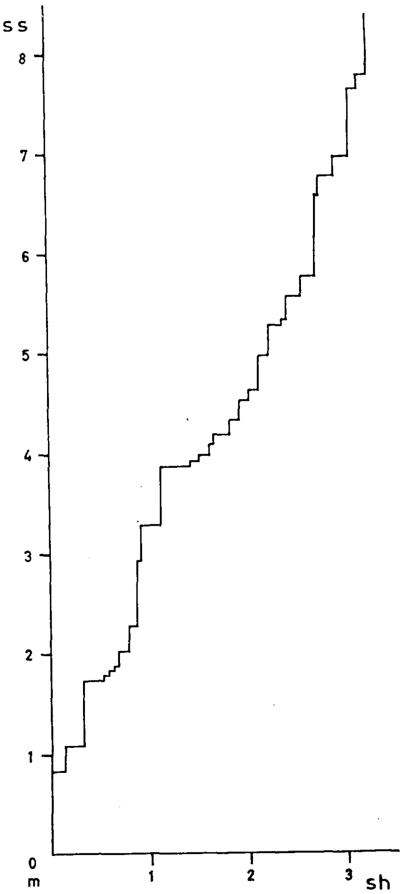

Fig. 11. A part of a sandstone-shale diagram at Loc. 119 (Fig. 10). This part clearly shows the "increasing" pattern.

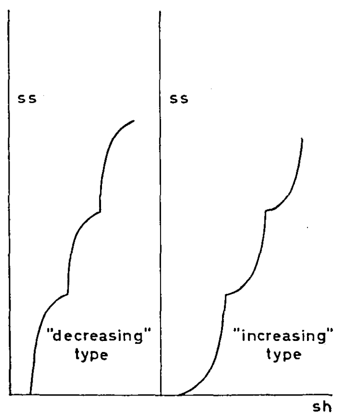

Fig. 12. Schematic patterns of minor cycles. The "decreasing" type and the "increasing" type.

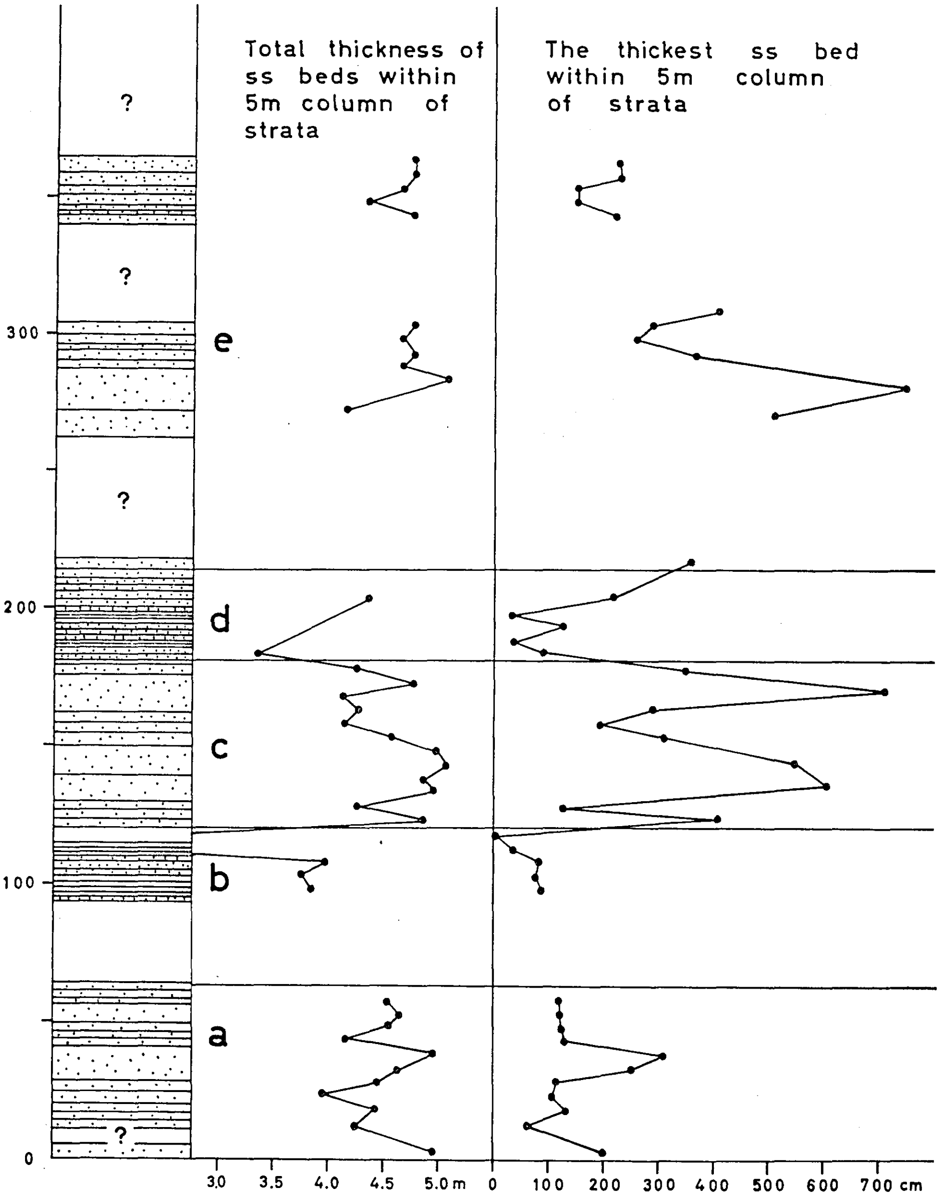

Fig. 13. Columnar section, and total thickness and maximum thickness of sandstone beds within 5 m column of the B formation.

are about 80 m thick and occupy the most part of the A formation. The strata include at least 4 or probably much more minor cyclic sedimentations (Fig. 11; Fig. 28, f). The minor cycles start with about 50 cm thick or less shale. The sandstone beds in the lower part are very thin

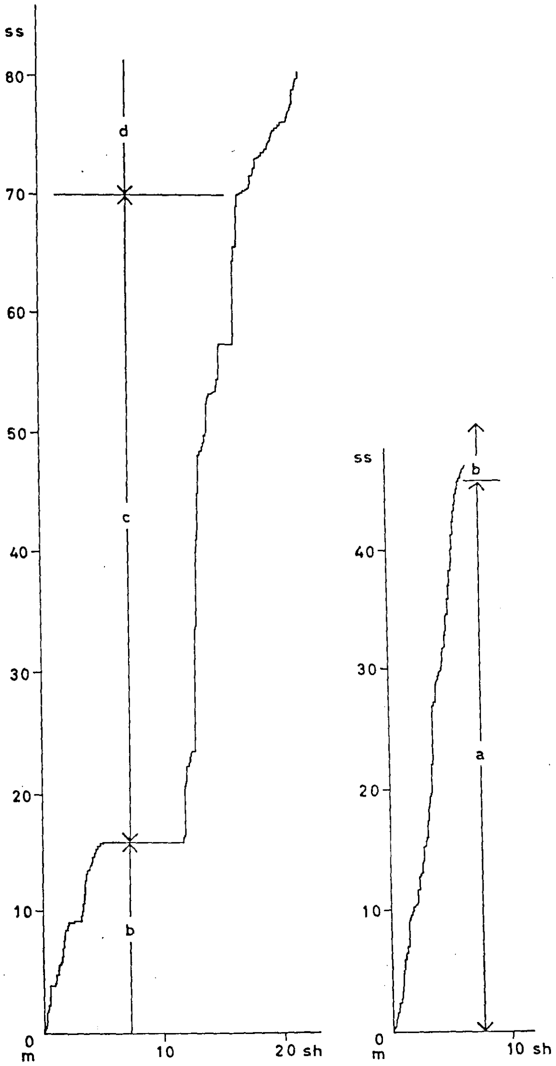

Fig. 14. Some parts of sandstone-shale diagrams at Loc. 158, the B formation.

a and c are turbidite-poor parts.

b and d are turbidite-rich parts.

(1-5 cm). The beds become thicker toward the upper part, the uppermost part of the beds being 1.5-2 m thick. The total thickness of the minor cycles is about 5-10 m thick. The cycles resemble those at the Unazawa area. However, at the latter area the cycles begin by a thick sandstone bed. I tentatively call the minor cycle beginning by a thick sandstone bed the "decreasing" type, and that beginning by a shale and thin sandstone bed the "increasing" type. The two types of minor cycles are shown schematically in Fig. 12.

Accumulation of sandstone during the deposition of a unit shale of 1 m thick is shown in the lower part of Fig. 10. This also shows the minor cyclic sedimentations. These figures, especially that of Loc. 119, show a general trend of gradual increase of sand supply. The trend is also shown by a diagram A-a in Fig. 4, which is made by the measurement of the total thickness of sandstone within each 5 m column of strata.

Sandstone-shale diagram of the B formation in southern Oigawa The B formation, which overlies the A formation, is not always the turbidite sequence. The strata a, c and e in the formation (Fig. 13) are rich in thick sandstone beds and sometimes include carbonaceous seams, rather similar to the Molasse-like sequence. The sandstone is white compared with that in the turbidite sequence. The thick sandstone beds gradually change to shale beds on both sides of them, namely they are not graded ones. Thin sandstone beds, however, sometimes show graded bedding The strata of a, c and e are turbidite-poor parts. On the other hand the strata b and d are turbidite-rich parts and somewhat similar to the turbidite sequence in lithology as well as the thickness distribution of sandstone and shale beds. The sandstone beds generally show graded bedding.

The sandstone-shale diagram of the turbidite-poor sequence shows very high inclination because of very thick sandstone beds (Fig. 14). However, some intercalations of thin sandstone and shale beds sometimes show minor cyclic sedimentations similar to the "increasing" type. Such minor cycles in the turbidite-poor sequence remind me of the cyclothem in the Molasse-like sequence.

The turbidite-rich sequence in the B formation clearly shows minor "increasing" type cyclic sedimentations (Fig. 14).

Sandstone-shale diagram of the C formation in southern Oigawa The C formation gradually changes to the underlying B formation and to the overlying shale formation (Loc. 152). Almost all strata of the C formation are seen at an outcrop at Loc. 152. There the measured strata consist of about 1,300 sandstone and shale beds. All these sandstone beds are graded and overturned.

The sandstone-shale diagram clearly shows a major cyclic sedimentation (Fig. 15). The inclination of the diagram is very high in the lower part, rather gentle in the middle and then high again in the upper. This means that the sandstone-shale ratio is high at first and then becomes rather low and at last again the ratio is high. The major cycle is also clear in the lower part of Fig. 15, which shows the change of the accumulation of sandstone during the deposition of shale of 1 m thick. In addition, the diagram C-a in Fig. 4 also shows the major cycle. The figure was made by the measurement of total thickness of sandstone beds within each 5 m column of strata.

The major cycle of the C formation includes many minor cyclic sedimentations. The minor cycles are shown by small wavy curves in the sandstone-shale diagram. The minor cycles in the lower part of the C formation are mostly the "decreasing" type (Fig. 15).

Cyclic sedimentation of the Shimanto group in southern Oigawa
I have mentioned the sandstone-shale diagrams of the A, B and C formations in the southernmost part of the Shimanto group in the Oigawa district. The A formation shows the general trend of the increase of sandstone beds. The B formation is a sandstone-rich formation, although it includes alternation beds of turbidites. In the C formation, the sandstone beds prevail in the lower part and gradually decrease, the upper part increasing again. The tendencies are well shown by the total thickness of sandstone beds within each 5 m column or during the deposition of a unit thickness of shale (Figs. 4, 10, 13, 15).

The tendencies show that the A, B and C formations form a major cyclic sedimentation. The thickness of the thickest beds within each 5 m column also quite clearly shows the major cycle (Fig. 26). The whole strata are about 600 m thick, comparable with that of the Sambosan group in the Unazawa area. The cyclic sedimetation also includes many minor cyclic sedimentations. The minor cycles are the "increasing" type in the A and the lower part of the B formation where there is a tendency for an increase of sand supply toward the upper part in the major cycle., and the "decreasing" type in the lower part of the C formation where the decrease of sand supply toward the upper part occurs in the major cycle. Thus the "increasing" type of minor cycles appears to occur when regression takes place, and on the other hand the "decreasing" type occurs when transgression takes place.

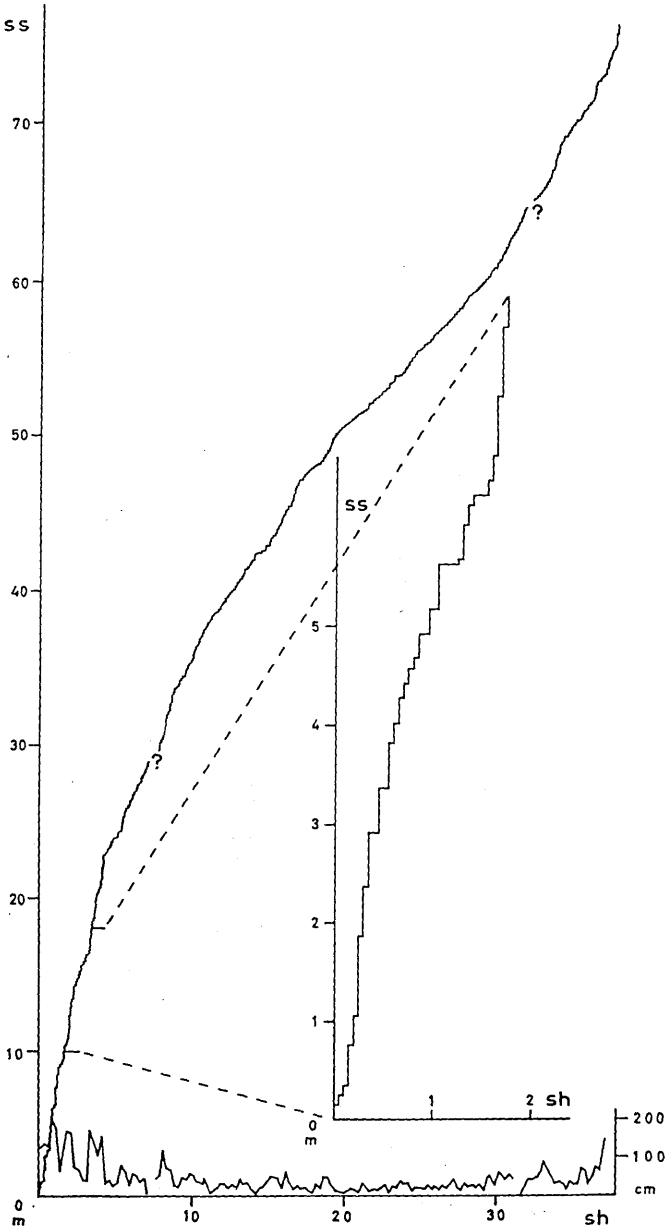

Fig. 15. Sandstone-shale diagram of the C formation at Loc. 152.

Thickness distribution of sandstone and shale beds of the southern Shimanto group in the Oigawa district

Sandstone Thickness of sandstone beds in this district varies widely. It ranges from 1 cm to 143 cm in the A and C formations and from 1 cm to 740 cm in the B formation. Average thickness and standard deviation of sandstone beds (Bokman, 1957) are shown in Tables 1 and 2, together with the maximum and minimum thickness of sandstone beds within each 5 m column. The tables clearly show that the average thickness of sandstone beds is quite large in the B formation, 48 cm, while the average of the A and the C formation is much smaller. Moreover, the turbidite-rich part of the B formation has average sandstone thickness comparable with the A and C formations. Therefore the B formation except for the turbidite-rich part has quite large average thickness (58 cm). These facts are also clearly shown in the sandstone-shale diagram (Fig. 14).

The thickness distribution of sandstone beds in the A and C formation does not show a curve similar to a normal distribution curve (Figs. 16, 17), but a log-normal. Such a feature has also been reported

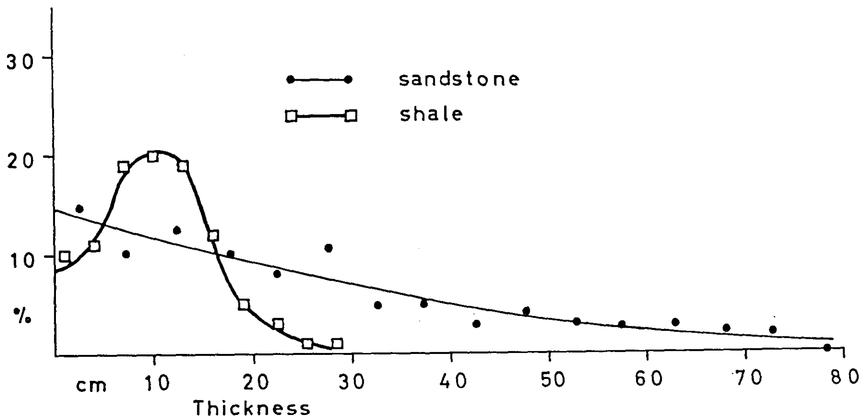

Fig. 16. Thickness distribution of sandstone and shale beds at Loc. 119 and Loc. 120 of the A formation.

by Pettijohn (1949), Bokman (1953), McBride (1962), Dott (1963) and Tanaka (1965). The standard deviation is very large compared with the average thickness (Table 1). Some of them exceed the average thickness. The standard deviation varies with the maximum and not minimum thickness. The thickness distribution of sandstone beds shows a curve

Table 1. Average thickness and maximum thickness of sandstone beds of the A formatiom (Loc. 119) and the C formation (Loc. 152).

A formation (Loc. 119)

Horizon in the A formation	Average thickness	Number of beds	Standard deviation	Maximum bed	Minimum bed
25- 30 m	20.7 cm	14	15.7	53 cm	5 cm
30- 35	29.2	12	16.1	60	2
35- 40	24.8	12	19.1	65	4
40- 45	47.2	10	22.9	75	3
45- 50	40.2	10	25.0	85	5
50- 55	19.8	16	22.2	65	1
55- 60	24.6	15	21.9	83	2
60- 65	34.6	11	35.9	128	2
65- 70	22.0	13	24.5	86	6
70- 75	19.5	15	14.2	45	1
75- 80	27.4	15	28.3	115	2
80- 85	57.1	7	60.9	143	2
Total	28.5	150	26.7	143	1

formation (Loc. 152)

Horizon in the C formation	Average thickness	Number of beds	Standard deviation	Maximum bed	Minimum bed
5- 10 m	27.2 cm	15	25.8	85 cm	3 cm
10- 15	27.3	16	36.0	141	2
15- 20	21.9	20	12.2	46	3
20- 25	12.9	30	9.7	34	1
25- 30	19.1	22	10.7	44	2
30- 35	11.5	33	10.9	50	1
35- 40	13.8	24	7.3	28	2
40- 45	14.6	20	11.4	25	2
45- 50	11.0	30	4.2	20	1
50- 55	13.1	27	6.1	26	4
55- 60	13.0	23	6.6	24	3
60- 65	9.5	29	8.0	29	2
65- 70	9.7	35	7.1	31	1
70- 75	7.5	38	5.0	22	1
75- 80	6.2	38	3.4	16	1
80- 85	6.9	39	3.5	15	2
85- 90	6.3	42	4.3	16	1
90- 95	6.5	42	4.2	17	1
95-100	8.6	38	7.2	32	1
100-105	9.3	27	5.8	24	2
105-110	8.7	40	8.6	37	1
110-115	9.2	34	8.3	50	1
Total	11.0	662	10.9	141	1

Table 2. Thickness distribution of sandstone and shale of the B formation (Loc. 158).

	Horizon in the B formation	Average thickness of ss	Nnmber of ss beds	Average thickness of sh beds	Number of sh beds	Maximum ss bed	Maximum sh bed
a	5- 15 m	21.8 cm	22	4.8 cm	22	56 cm	15 cm
	15- 20	40.5	11	5.3	11	133	13
	20- 25	27.1	14	7.9	14	105	23
	25- 30	31.1	14	4.3	14	112	8
	30- 40	123.4	8	6.6	7	305	10
	40- 45	24.1	17	4.8	18	126	20
	45- 50	42.9	8	5.9	7	120	15
	50- 55	66.6	8	4.9	9	121	12
	55- 60	40.7	12	4.3	12	115	9
b	60- 65	13.9	14	4.4	14	64	10
	?						
	90-100	27.9	22	5.1	22	82	12
	100-105	15.7	23	7.7	22	73	65
	105-110	26.3	15	4.1	15	79	14
	110-115	9.4	22	8.9	22	30	68
c	?						
	120-130	77.9	15	7.1	14	420	30
	130-150	168.9	9	3.0	9	600	5
	150-155	49.3	13	3.9	13	300	8
	155-160	41.3	10	5.9	10	185	14
	160-175	121.1	13	17.3	13	700	123
d	175-185	18.8	25	8.8	26	93	25
	185-190	9.9	28	5.5	28	27	17
	190-195	27.4	14	6.7	13	120	20
	195-200	11.6	15	5.0	15	25	11
	200-205	15.6	24	3.0	24	210	9
	205-210	27.9	15	3.1	15	95	5
e	?						
	270-275	52.1	14	4.2	12	500	9
	280-290	92.3	11	3.7	11	740	11
	290-300	67.4	14	14.1	14	355	51
	300-310	86.2	12	2.7	11	400	6
	?						
	340-345	36.5	13	2.7	12	210	10
	345-355	69.2	13	5.2	13	140	15
	355-365	80.7	12	5.2	12	220	11
	Total	48.0	480	5.9	474	740	123
	non-turbidite part	58.0	277	5.9	272	740	123
	turbidite part	18.1	202	5.9	202	210	68

(Strata a, c and e are turbidite-poor sequence, and strata b and d are turbidite-rich sequence.)

near the normal distribution curve when logarithm of sandstone thickness is taken in the abscissa (Fig. 18).

The B formation shows different patterns of distribution from the A and C formations. The distribution curve of the turbidite-poor part of the B formation with logarithm of thickness in the abscissa shows very wide range of distribution and has two modes (Fig. 18). One of the modes is of the thinner beds and coincides with one of the turbidite-

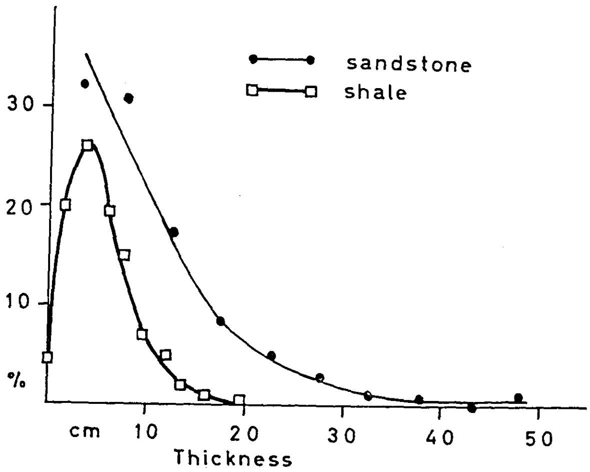

Fig. 17. Thickness distribution of sandstone and shale beds of the C formation at Loc. 152.

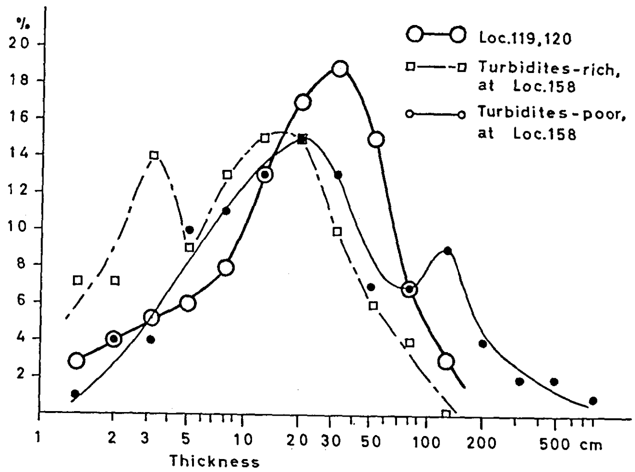

Fig. 18. Thickness distribution of sandstone of the A formation (Loc. 119, 120) and B formation (Loc. 158).

rich parts of the B formation. This mode is formed by some of the thin sandstone beds in the turbidite sequence, which show graded bedding. Thus the turbidite-poor sequence also includes some turbidite beds, although total thickness of the turbidite beds is rather thin. The other mode, characteristic of the turbidite-poor sequence, is represented by a rather small number of sandstone beds. However, they occupy the main part of the turbidite-poor sequence in the B formation owing to the great thickness of the beds.

The sandstone beds of the turbidite-rich sequence of the B formation have also two modes in the thickness distribution curve. This may be also due to the different kinds of transportation.

In this way, the B formation has a different distribution of sandstone thickness from the A and C formations, although there are some similarities owing to the intercalation of many thin turbidite beds in the B formation.

The thickness of maximum bed within each 5 m column is related to the average thickness of sandstone beds and standard deviation as well as the total thickness of the sandstone beds within each 5 m column. The average thickness and the total thickness vary with the major cyclic sedimentation. Therefore, the maximum thickness of sandstone bed is related to the major cycle as in Fig. 26. The maximum thickness is a most useful one to detect a major cycle in such sequences.

The variation of sandstone bed thickness according to the sedimen-

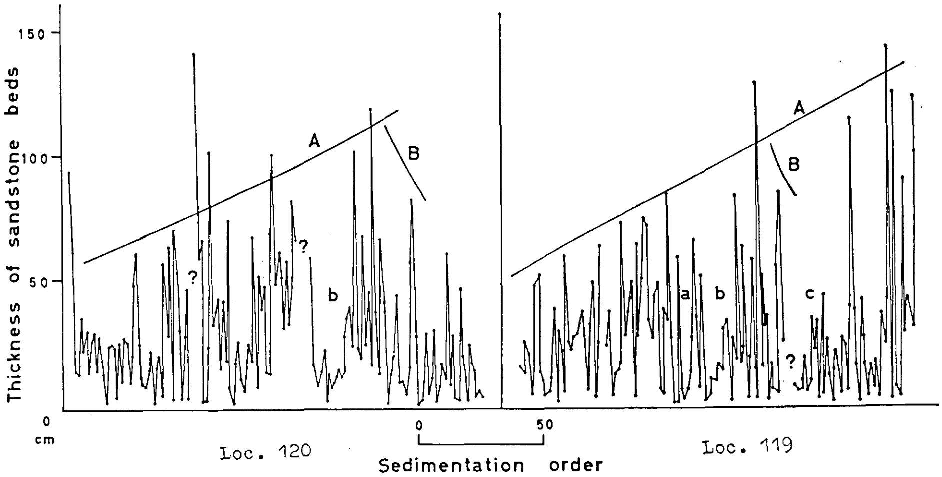

Fig. 19. Variation of thickness of the sandstone beds according to the sedimentation order. The A formation.

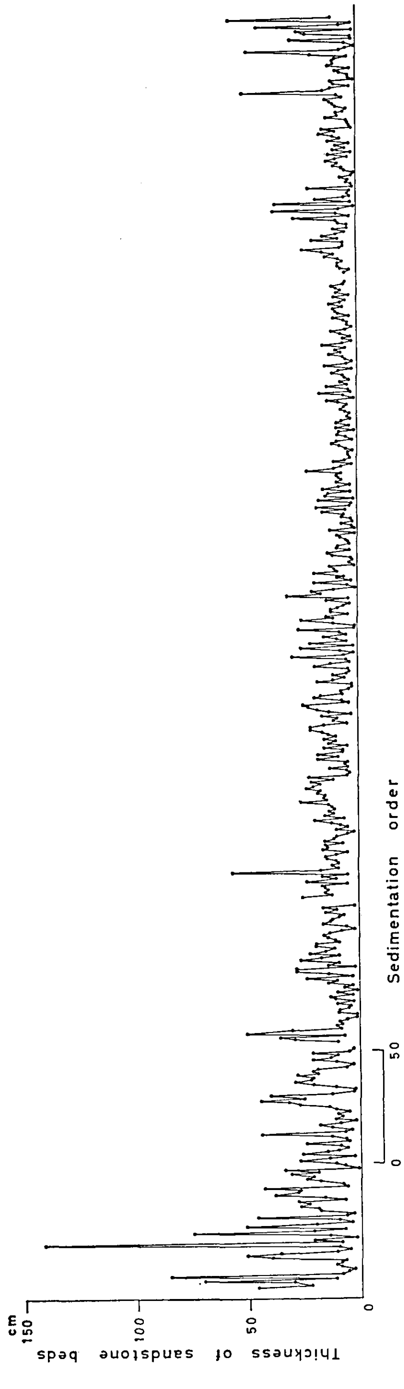

Fig. 20. Variation of thickness of the sandstone beds according to the sedimentation order. The C formation.

tation order shows also the following remarkable features. The Fig. 19 shows the variation, in which thickness is taken in the ordinate and the sedimentation order in the abscissa. The figure clearly shows the major cycle mentioned already as well as the minor cycle. For example, as for Loc. 119, there are thicker beds in about every 10 beds. There is a tendency for the sandstone beds at first to be very thin, then beds generally become thicker and the 10th bed approximately is the thickest. Then a sudden decrease of thickness occurs. The minor cycle is the "increasing" type and is shown in Fig. 19 as a, b, etc. The thickness of the thickest sandstone beds in the minor cycle varies also again with the sedimentation sequence. In the A formation the thickness incerases toward the upper part as shown in Fig. 19 as A line, although a slight decreasing tendency is also seen as the B line. This shows the general tendency for an increase of sand supply toward the upper part. Fig. 19 also shows some similarities of the distribution curve between the two localities.

The thickness variation in accordance with the sedimentation order in the C formation (Fig. 20) shows the general tendency of a major cycle; at first the sand supply decreases and increases later toward the upper part. In the lower part of the C formation the "decreasing" type minor cycles are predominant.

I have mentioned the general increase or decrease tendency of the maximum sandstone bed within each 5 m column toward the upper part. The general tendency is clearly related to the thickness of the maximum bed in such a minor cycle.

Shale The distribution of the shale bed thickness is considerably narrow compared with that of the sandstone beds (Table 3). This is different from the case reported by Bokman (1953) and Tanaka (1965). In the A, B and C formations it varies from 0 cm to 50 cm in general. In this paper 0 cm means that the bed is thinner than 0.5 cm. There are shale beds of 123 cm and 600 cm thick in the B formation. The distribution range of shale bed thickness is much wider in the B formation than in that of A and C.

Average thickness of shale within each 5 m column is almost constant in the A and C formations, that is it does not actually vary with the horizon, although there is a slight variation with the horizon in the C formation as shown in Fig. 21. The feature is quite different from that of the sandstone bed. However, the standard deviation is also rather large for a shale bed. The intercalation of thicker bed is closely

Table 3. Average thickness and maximum thickness of shale beds of the A formation (Loc. 119) and the C formation (Loc. 152).

	Horizon in the A formation	Average thickness	Number of beds	Standard deviation	Maximum bed	Minimum bed
A formation (Loc. 119)	25- 30 m	15.3 cm	13	7.2	25 cm	0 cm
	30- 35	12.2	12	8.2	30	0
	35- 40	9.7	12	5.6	21	2
	40- 45	9.6	9	5.4	14	1
	45- 50	11.0	10	8.1	24	0
	50- 55	9.5	17	4.6	23	1
	55- 60	10.5	14	3.9	15	1
	60- 65	10.0	11	3.7	16	4
	65- 70	7.6	12	4.1	13	0
	70- 75	8.3	16	5.1	17	1
	75- 80	8.6	15	4.5	17	2
	80- 85	17.4	7	6.0	55	1
	Total	10.4	148	7.1	55	0 cm

	Horizon in the C formation	Average thickness	Number of beds	Standard deviation	Maximum bed	Minimum bed
C formation (Loc. 152)	5- 10 m	5.4 cm	15	3.0	11 cm	1 cm
	10- 15	3.4	16	2.4	10	0
	15- 20	3.9	20	2.2	8	0
	20- 25	4.0	30	4.2	20	0
	25- 30	2.9	22	1.6	6	0
	30- 35	4.0	33	2.5	11	1
	35- 40	5.1	24	2.8	12	1
	40- 45	4.2	20	2.2	8	1
	45- 50	4.8	30	3.0	11	1
	50- 55	6.4	27	4.2	12	1
	55- 60	9.0	23	6.1	20	2
	60- 65	6.6	29	5.6	28	1
	65- 70	5.2	34	3.7	13	0
	70- 75	5.4	39	3.7	15	1
	75- 80	7.1	38	3.6	18	0
	80- 85	5.9	39	3.7	18	0
	85- 90	5.9	42	3.8	20	0
	90- 95	5.4	41	3.5	14	0
	95-100	4.8	38	3.9	15	0
	100-105	5.7	27	3.3	11	0
	105-110	3.9	41	5.4	12	0
	110-115	5.8	33		19	0
	Total	5.3	661	3.8	28	0 cm

(0 cm in minimum beds shows the bed less than 0.5 cm)

related to the variation of the standard deviation as well as the average thickness within each 5 m column. The average thickness of shale bed within each 5 m column does not vary with the major cyclic sedimentation, because the intercalation of the thicker beds of shale is not related

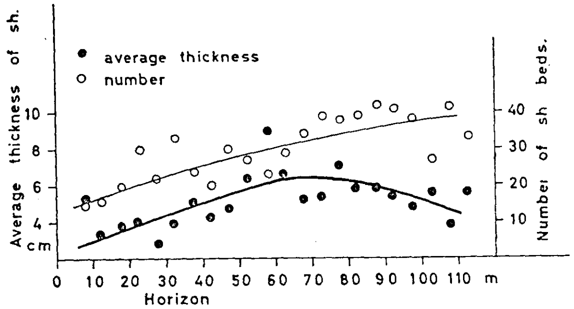

Fig. 21. Variation of average thickness of shale with horizon in the C formation. Black spot: average thickness.

to the major cycle.

In the B formation, however, the average thickness of shale bed varies with the horizon (Table 2). This is quite different from that in the A and C formations. In the B formation, the average sandstone thickness of the turbidite-poor part is very different from that of the turbidite-rich part. On the other hand, as for the shale bed thickness, that of the turbidite-poor part is nearly the same as that of the turbidite-rich part.

The thickness distribution curve of the shale bed in the A or C formation is similar to a normal one, although the skewness is rather large and the mode lies at the thinner part (Figs. 16, 17). The normal distribution is quite different from the log-normal distribution curve of the sandstone bed. It is also different from those of shale reported by Bokman (1953), McBride (1962), and Tanaka (1965), which show log-normal distributions. The difference between the thickness distributions between sandstone and shale means that the mechanism of sedimentation is different between them.

The thickness distribution curve of shale of the turbidite-poor sequence in the B formation has wider distribution and is quite different from those of the A and C formations. This is due to the fact that the B formation is composed of turbidites as well as non-turbidites.

Interpretation of thickness distributions of sandstone and shale

There are marked differences between the thickness distributions of the sandstone and shale beds in the A and C formations. We can summarize the main differences as follows.

1) The distribution curves are different from each other; that of sandstone being log-normal and shale normal.

2) The sandstone bed thickness decreases or increases successively in the minor "decreasing" or "increasing" cycle, but the shale beds do not show such a feature, that is the shale bed thickness remains almost constant during the minor cycle.

3) The thickness of the thickest bed in the minor cycle increases or decreases successively in the major cycle, but the shale bed thickness remains nearly constant.

4) The thickness distribution of the sandstone and shale beds in the turbidite-poor sequence of the B formation is quite different from those of the turbidite-rich part of the same formation as well as the A and C formation.

These features are probably caused by the differences of the sedimentation mechanism of sandstone and shale together with the sedimentary condition in the turbidite sequence. The sandstone bed thickness is probably related to the transportation agency and transport distance or other factors of the turbidity currents, because the standstone beds are turbidites in the A and C formations.

On the other hand, the thickness of the shale beds appears to be proportional to time. If clay and silt particle deposited almost constantly over a long period of time, thickness of the shale bed is proportional to time. The fact that the average thickness of shale bed does not vary greatly, although that of the sandstone bed does so considerably, may support the interpretation.

If the thickness of the shale is proportional to time and the turbidites occur almost at a constant rate during a long period of time, the number of turbidites which have been formed during the deposition of a unit thickness of shale must be constant throughout the deposition of the whole turbidite sequence. Such numbers of turbidites during the deposition of 1 m of shale have been obtained from the sandstone-shale diagrams of the A and C formations and the turbidite beds of Unazawa (Table 4). The average number is nearly 9 in the A formation, 13 in the C and 11 at Unazawa. The standard deviations are small. These features are easily explained, if the thickness of shale is proportional to time and turbidity currents flowed into the basin at fairly regular time intervals. Such numbers of the B formation vary rather widely with the horizon (Table 5). This is due to the fact that the formation includes non-turbidite sandstone.

In the shale formation underlying the A formation, the upper part of the turbidite beds is muddy (Fig. 28, e), this mud being produced by the turbidity currents. In this case the thickness of the shale bed may

Table 4. Number of sandstone beds during the deposition of a unit shale of 1 m thick.

Loc. 119		Loc. 152				Unazawa (Tamagawa)	
Approximate horizon in the A formation	Number of ss beds	Approximate horizon in the C formation	Number of ss beds	Approximate horizon in the C formation	Number of ss beds	Approximate horizon from the base	Number of ss beds
25-27 m	6	5-12 m	16	74- 76 m	11	0- 1 m	11
27-30	6	12-19	17	76- 78	11	1- 3	7
30-33	6	19-24	15	78- 80	12	3- 4	5
33-37	9	24-28	18	80- 82	11	4-13	13
37-41	10	28-34	15	82- 85	16	13-22	13
41-47	8	34-37	13	85- 87	13	22-30	9
47-51	7	37-41	15	87- 89	11	30-36	9
51-54	9	43-48	18	89- 91	11	36-38	12
54-57	8	48-50	13	91- 93	12	38-48	15
57-60	8	50-54	15	93- 95	12	48-52	14
60-65	10	54-57	8	95- 98	11		
69-72	8	57-59	8	98-101	15		
72-76	10	59-62	13	103-106	12		
76-80	11	62-63	8	106-109	15		
80-85	7	63-67	15	109-111	12		
		67-70	14	111-114	12		
		70-72	10	114-117	14		
		72-74	14				
n=15 $\bar{x}$=8.8 s=1.4		n=35 $\bar{x}$=13.0 s=2.6				n=10 $\bar{x}$=10.8 4=3.1	

(n=number of samples, $\bar{x}$=mean, and s=standard deviation.)

be related to that of the underlying sandy part of the turbidites, although I cannot show precisely this because the measurement of thickness is difficult owing to the thick transitional zone from sand to shale. The thickness of the shale beds in the shale formation seems to have a much wider distribution range than the A and C formations and do not have a normal distribution curve. This may suggest the condition that some turbidity currents flowed into the sedimentary basin after a very long time compared with the other ones. Thickness distributions of sandstone in turbidite sequences may be mostly log-normal. However, those of shale beds may be log-normal, normal and other types according to the rate of deposition of the mud of turbidity currents as well as the non-turbidity currents origin, the time frequency of the arrival of turbidity currents and other factors. A fairly regular rate of turbidity currents and the constant deposition of shale probably make a normal distribution curve of shale thickness in turbidity current sequences. Shale beds with log-normal distribution reported by Bokman (1953) and others are possibly due to the irregular time intervals between turbidity currents.

The shale in the A and C formation has not been mostly produced by turbidity currents. There is no relation between the thickness of the shale beds and their underlying sandstone beds (Fig. 22). In this connection, thickness of sandy turbidites are thought sometimes to be related to the underlying shale bed thickness, because in some cases stronger turbidity currents may occur after the longer depositional periods

Table 5. Number of sandstone beds during the deposition of a unit shale of 1 m thick in the B formation (Loc. 158).

Approximate horizon in the B formation		Number of ss beds
a	5- 15 m	21
	15- 22	19
	22- 27	13
	27- 35	16
	35- 50	24
	50- 60	20
b	93-100	20
	100-105	21
	105-107	7
	107-112	20
	112-115	10
c	115-120	2
	120-128	11
	128-155	21
	155-160	14
	160-170	11
	170-175	2
d	175-180	8
	180-184	13
	184-187	21
	187-190	13
	195-202	22
	202-210	32
e	280-298	22
	340-353	23

of shale, and in some other cases strong turbidity currents may scour out the underlying shale beds. These are also not the case in the A and C formation (Fig. 23). The thickness of sandstone beds are not related to the thickness of the underlying shale beds.

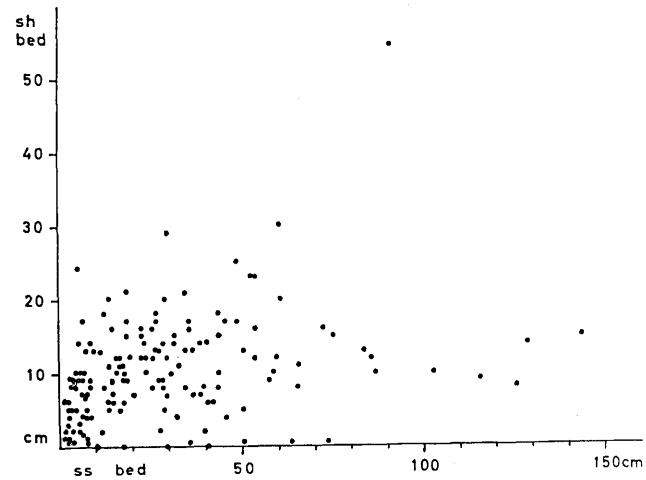

Fig. 22. Thickness of shale beds and their underlying sandstone beds.

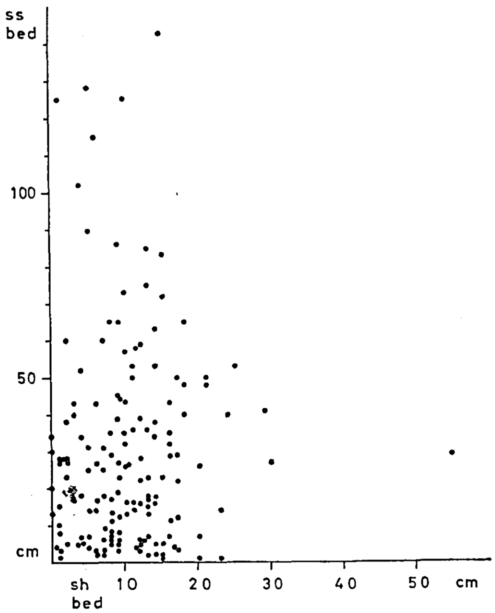

Fig. 23. Thickness of shale beds and their overlying sandstone beds.

The relation between the sedimentary character and the thickness of sandstone beds

The thickness of the sandstone beds varies very widely, as already mentioned. The thickness is also related to the sedimentary characteristics of the turbidite beds. However, I have not yet finished the study of the sedimentary features. I shall mention below the important relationship among them.

Clasticity The clasiticity (Carozzi, 1957) is the largest grain size at the base of the beds. The clasticity is a measure of the intensity of the turbidity currents which have formed the turbidites. I measured the clasticity in field by peek lens with micrometer. The result was that the clasticity increases with the thickness of sandstone beds as reported by Kingma (1958) and Dott (1936) (Fig. 24). Therefore it is concluded that stronger turbidity currents have formed thicker turbidites in general. However, the relation of the clasticity with the thickness of sandstone beds is somewhat different between those of the A and the C formation. The clasticity is generally larger in the C formation than the A for the same thickness of the sandstone beds. It may mean that the nature of the turbidity currents, for instance mud content, inclination of slope or other factors, are somewhat different between these formations.

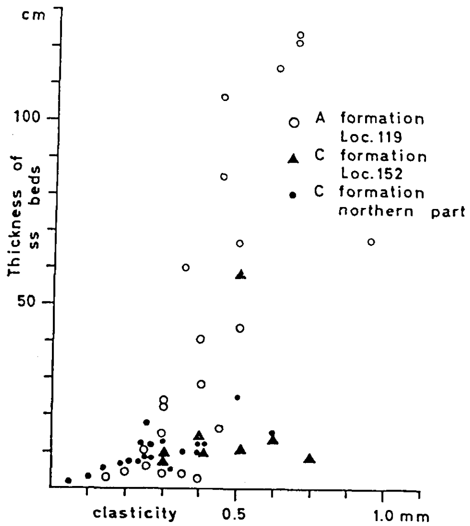

Fig. 24. Clasticity and thickness of sandstone beds.

Sole marking The development of the sole marking is also sometimes remarkable in the turbidites (Kuenen and Carozzi, 1953). The sole marking (Fig. 28, c) is also related to the thickness of sandstone beds in southern Oigawa. It is rather frequently observed on the underside of the sandstone beds of 70 cm or more thick. The beds of 30–70 cm thick have or have not the sole marking. However, the beds of 30 cm or less rarely have it. These features also may show that the turbidity currents, which have stronger power to disturb the underlying shale bed, have formed the thicker sandstone beds. However, it cannot be said that the strong turbidity currents have disturbed the underlying shale beds to greatly reduce the shale thickness, because the thickness of the shale beds underlying the turbidite sandstone beds does not vary with the thickness of the sandstone in the A and C formations (Fig. 23).

Lamina and convolute structure The sandstone beds thicker than 10 cm are usually of graywacke. Sometimes lamina-like structures are seen. However, I am now of opinion after the microscopic study that most of the lamina-like structures in the thick sandstones bed are probably of diagenetic origin, some of them being micro-stylolitic structures. There are also lamina-like structures formed by shear planes (Fig. 25, b).

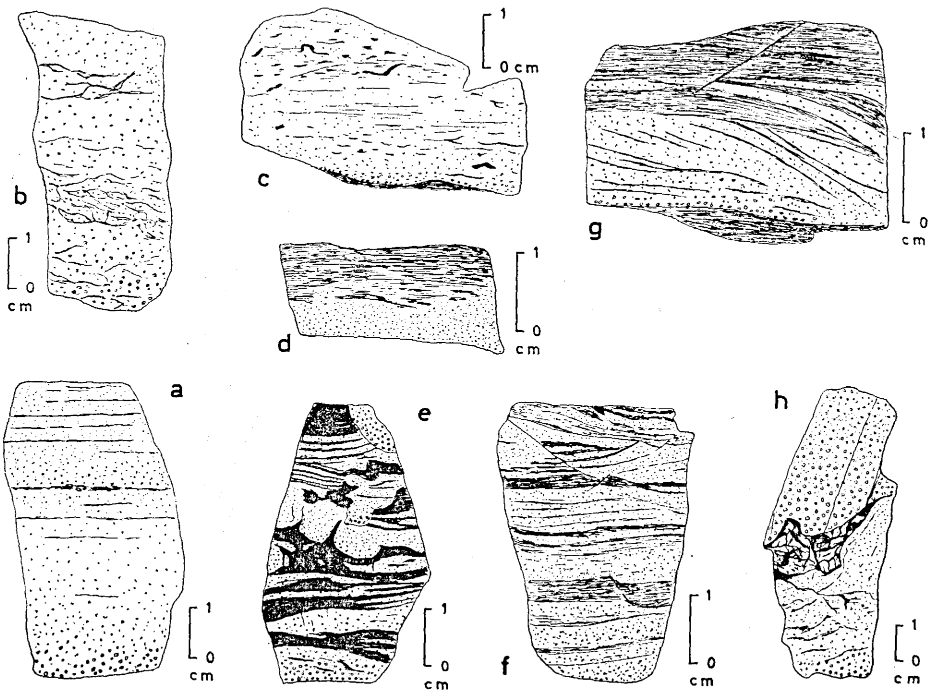

Fig. 25. Sedimentary structure of thinner sandstone beds.

a. Loc. 152; b. Loc. 167; c. Loc. 110;
d. Loc. 104; e. Loc. 120; f. Loc. 250;
g. Loc. 252; h. Loc. 200

The turbidite beds of 4-10 cm thick sometimes have in the upper part of the beds frequent intercalations of shale lamina, which sometimes show cross stratification (Kuenen, 1953).

The turbidite beds less than 4 cm thick generally contain shale lamina. Minute sliding deposits, minute faults probably caused by the sliding, and cross lamination (Fig. 25, Fig. 28, d) are frequently seen. Sometimes shale lamina becomes as thick as the sandstone lamina adjacent to it. Graded bedding is not generally seen in this sandstone lamina. All these structures are seen in the upper part of the beds 4 cm or less thick, the lower part of the beds showing graded bedding. Such features are reported from recent turbidites (Gorsline and Emery, 1959).

There are many varieties of sedimentary structures of the turbidites in the A and C formations. The assemblage of the structures shows a very wide range, and many intermediate patterns can be seen from the beds showing only the clear graded bedding to those showing complicated structures or laminated ones. In the Oigawa district, complicated structures prevail in the thin (10 cm or less) beds.

The structures depend also entirely on the sedimentary conditions. The complicated structures are more common in the turbidites of the shale formation than in the A and C formations for the same thickness of turbidites. In the shale formation underlying the A formation, turbidites of 5 cm or less thick are frequently intercalated at some horizons. The main part of the turbidites is muddy, this feature being quite different from those of the A and C formations. This muddy part is composed of lamina of silty sand, sandy silt and silt. The lamina sometimes show convolute structures (Fig. 25, e). The graded sandstone part generally occupies only the lowest part of 5-7 mm thick, one-tenth of the whole turbidite beds.

In this way, the sedimentary structures generally depend on the thickness of the sandstone part. The structures are complicated in the thin turbidite beds or in the turbidite beds with a thin graded sandstone part. The variation of the sedimentary structures is probably caused by the intensity, mud content and other qualities of the turbidity currents, and some depositional conditions. Minute sliding structures, lamina or cross lamination in the upper part of the turbidite beds may show the occurrence of minute sliding and minor currents similar to the turbidity currents or other kinds of currents after the passing away of the main turbidity currents. Such sliding or currents may repeat themselves again and again. These structures are all confined in the turbidite sequences and are developed always on the top of the graded parts. The structures cannot be seen in the shale beds of the A and C formation, which are not the products of the turbidity currents but of the secular deposition of silt and clay particles.

Frequency of turbidites through geologic time in southern Oigawa

The thickness of turbidite sandstone varies in the A and C formations quite widely. On the other hand the thickness of the shale beds intercalated between the sandstone does not vary so widely. Moreover, the number of the turbidite beds during the deposition of 1 m thick shale is almost constant in a certain area (Table 4). This means that the turbidity currents have occurred with nearly constant time intervals over a long time in a certain area.

The rate of sedimentation of turbidite sequences varies widely with localities. However, that of the sediments of geosyncline, some of which are probably the turbidite sequences, is usually of 0.1–0.9 m/1,000 years (Kay, 1955). The A formation in the Oigawa district is rich in thick turbidite sandstone beds. Therefore the rate of sedimentation may have been quite large. On the assumption that the rate is 1.0 m/1,000 years, one turbidity current has occurred in about every 400 years for the A formation, because there are about 150 turbidite beds within 60 m strata, that is during 60,000 years, at Loc. 119. On the other hand, the C formation has less thick sandstone beds, (average thickness is 11.0 cm), than the A formation (average 28.5 cm). Therefore the rate of sedimentation of the C formation may be less than half of the A formation. On the assumption that the rate of the C formation is 0.5 m/1,000 years, one turbidity current has occurred per 330 years, because there occur 660 turbidite beds within 110 m strata, that is during 220,000 years. These rates are of the same order as that of one turbidity current per 460 years in recent ocean deposites (in Kuenen, 1964). However, the rate of sedimentation of 1 m/1,000 years for the A formation may be too large, because the rate is an exceptionally large one for the geosynclinal deposits. The time intervals between turbidity currents in the A and C formations may be more than 400 years. However, it is probably of the order of several hundred years.

The average thickness of shale beds between turbidites in the A formation is 10.4 cm and that in the C formation 5.3 cm. The shale has probably deposited during several hundred years. Therefore the rate of sedimentation of the shale beds is about 20 cm/1,000 years for the A formation and about 10 cm/1,000 years for the C. The rate is similar to the rate of green mud reported by Gorsline and Emery (1959) and within the range of the sedimentation rate of recent terrigenous mud (Kuenen, 1950).

For the above-mentioned reasons, the turbidites of the A and C formations in the Oigawa district appear to be formed by the turbidity currents which have occurred with rather regular time intervals of several hundred years.

Turbidity currents are thought to be produced by slumping (Moore, 1961), caused by overloading, earthquake, volcanism, flood etc. In the Oigawa district the flood may be excluded because the time interval is rather constant and is of the order of several hundred years. Volcanism can also be excluded because here are no distinct volcanic sediments in the sequences.

Great earthquakes, magnitude 7 or more, occur in about every 100–150 years to the south of Shikoku and Kii (Yoshikawa *et al.*, 1964). It is highly probable that great earthquakes occur every 100 years near Tokyo (Kawasumi, 1951). The great earthquakes appear to have produce sometimes strong turbidity currents as in the case of the Great Banks earthquake (Heezen *et al.*, 1954), and a salient change of submarine topography caused by submarine slumping has been reported from the Sagami Bay after the great Kanto earthquake in 1923 (Shepard, 1933). All such earthquakes have not occurred in the same submarine drainages. Therefore, one turbidity current may be flowed into a certain submarine drainage per several hundred years by such a great earthquake. The rate is nearly the same as that in the Oigawa district. It is highly probable that the turbidites in the Oigawa have been produced by great earthquakes, although it is possible that overloading or steepening of the slope has caused the turbidites.

Cyclic sedimentations in the turbidite sequence

It is a remarkable fact that there are major and minor cyclic sedimentations, and that there are turbidite sequences in rather deep water as well as those in rather shallower water. The major cycles quite resemble the cycles of sedimentation by Stamp (1921). Such cyclic sedimentations have probably not occurred in the sea which is far from land and is very deep.

In the Oigawa district, the total thickness and average thickness and thickest bed within each 5 m column of strata generally increase at first and then gradually decrease. The shale formation beneath the

A formation contains only muddy turbidites, the A formation is the sandstone-rich turbidite sequence, the B formation is rich in the non-turbidite sandstone with carbonaceous seams, the C formation is again the sandstone turbidite sequence, and the shale formation overlying the C contains muddy turbidites. The B formation is somewhat Molasse-like and rather similar to the case reported by Kingma (1960). The thickness of the thickest bed within each 5 m column is most useful to

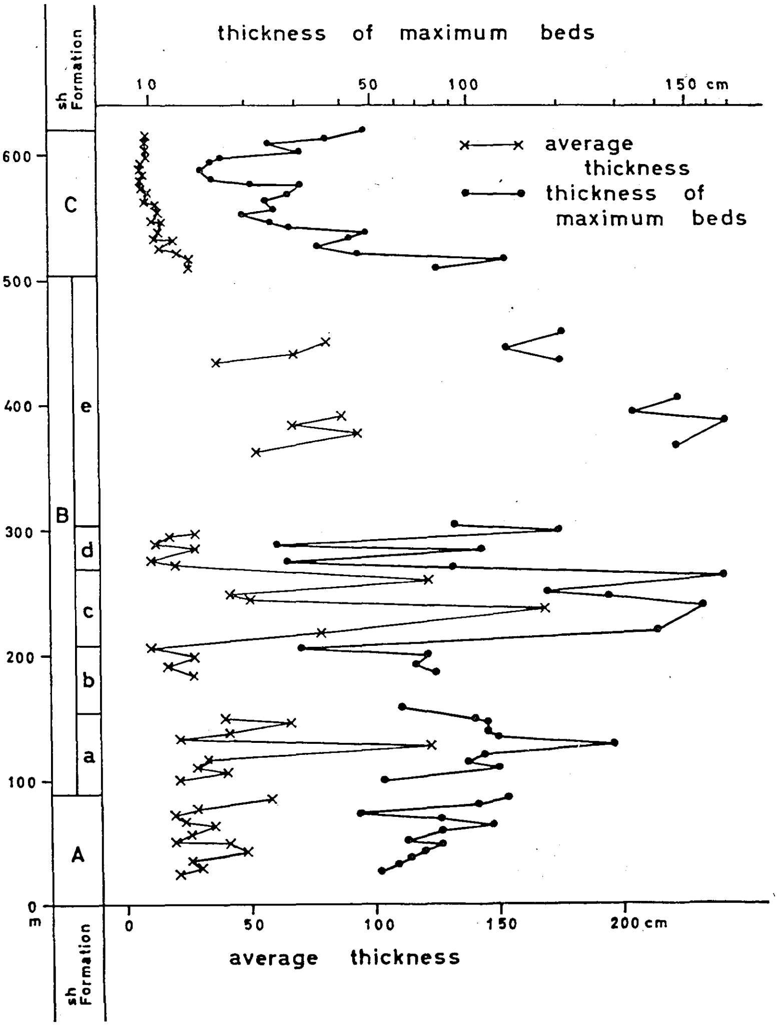

Fig. 26. Distribution of average thickness and maximum bed of sandstone within each 5 m column of the A, B and C formations, in the southern Oigawa.

detect such a major cycle (Fig. 26).

The major cycle in the Oigawa probably took several hundred thousand - one million years, because the duration of the A formation and the C are probably more than 60,000 and 220,000 years respectively, and the B formation is much thicker than the A and C.

To understand the circumstance under which such cyclic sedimentations have occurred is a very difficult problem, because the distribution of the turbidite is not known in detail. However, the circumstance must have been that non-turbidites with a very thick sandstone bed were gradually changed vertically into a turbidite sequence and further into a turbidite-poor shale formation. The lateral changes of the facies are found in the northern limb of the grand recumbent fold. There the shale formation changes toward southwest into the turbidite sequence correlated to the C formation and further into the sandstone-rich formation similar to the B formation. Only two layers of conglomerate with mud matrix, supposed to be submarine sliding deposits, have been found about 2 km north of Loc. 119 in the northern B formation. Therefore it is not the condition that the sliding deposits interchange with the turbidites as shown by Stanley and Bouma (1964) and Dzulynski *et al.* (1959). There has been a normal sedimentary basin with laterally adjoining turbidity current drainage.

A broad and not very deep sedimentary basin with a very gentle slope and with very steep cliff somewhere as shown in Fig. 27 may be suitable for the occurrence of the major cyclic sedimentation of the Oigawa. When the sea level is high, sand is transported by traction

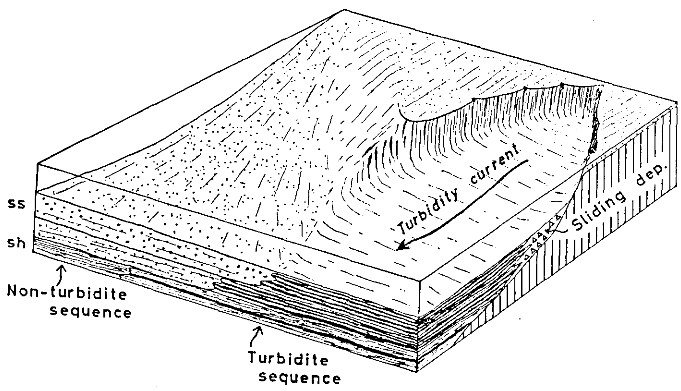

Fig. 27. Supposed sedimentary basin of the Shimanto group in southern Oigawa.

along the gentle slope. When transgression occurs, sand is not transported into the basin and shale deposition occurs and on the top of the slope thick sand and mud may deposit. This sand and mud may be slumped down and transported into the basin by turbidity currents when great earthquakes occur. In this case it is expected to be found that lateral facies change from a non-turbidite sequence to a turbidite one. As in the case of the Oigawa. Winterer and Durham (1962) reported that in the Ventura basin Pliocene turbidites occur in the sea at about 700 m (2,000 ft) deep or shallower and that non-turbidites occur on a shelf shallower than 200 m (600 ft). On the assumption that the condition of the Oigawa was almost identical, the shale formations underlying the A formation and overlying the C have been deposited in the sea a depth deeper than 700 m, and the B formation shallower than 200 m, the difference being 500 m. The durations of the A and C formation are more than 80,000 years (the thickness is 80 m and sedimentation rate is 1 m/1,000 years) and 240,000 years (the thickness is 120 m and the sedimentation rate is 0.5 m/1,000 years) respectively. Thus the upheaval rate is less than 6 mm per year and subsidence rate is 2 mm per year. The rate is not very much different from the rate of 2 mm per year for the Quaternary upheaval of Muroto, southeastern Shikoku (Yoshikawa *et al.* 1964).

The minor cyclic sedimentations are the deposition during 5,000-10,000 years. The explanation for the minor cycles is much more difficult than the major ones. The important factors which cause the gradual change of the turbidite thickness according to the sedimentation order are as follows. 1) The angle of slope which may change the intensity of the turbidity currents. 2) The change of the rate of sedimentation and of the depositional condition on the top of the slope or at the original point of the turbidity currents. When the sedimentation rate of the original point is larger, the turbidity current may transport a greater amount of clastics. 3) The intensity of the trigger for the turbidity currents. A stronger trigger may produce stronger turbidity currents. 4) The distance from the depositional point to the original point of the turbidity currents.

Furthermore, there is a tendency for the "decreasing" type minor cycle to occur during the transgression period of the major cycle, and the "increasing" type during the regression. This means that the mechanism of the minor cycle is also related to the major cycle. Among the above-mentioned factors, the angle of the slope and the rate of

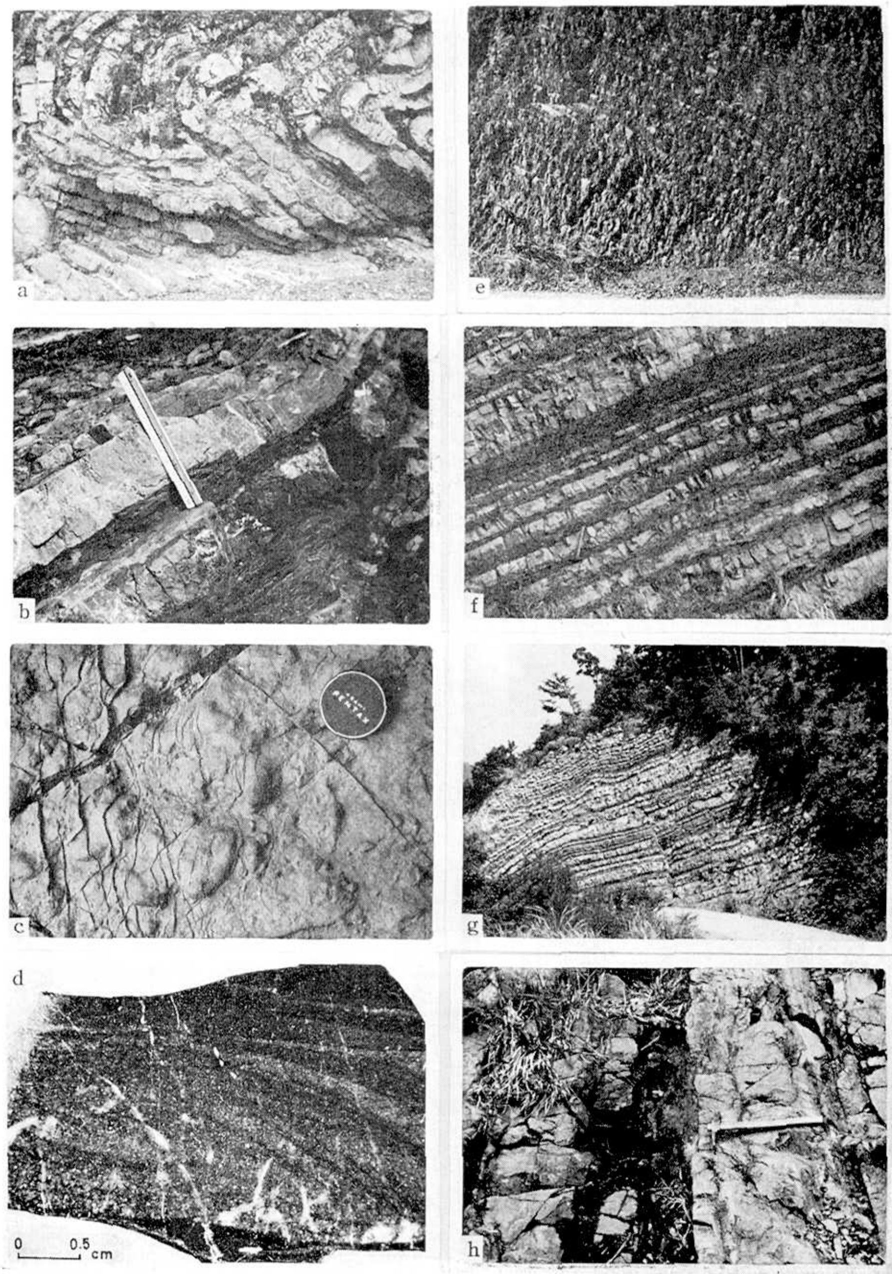

Fig. 28. a: A recumbent minor fold at Loc. 152. b: Sanbstone beds at Loc. 152, the C formation. Overturned. c: Sole marking underside of the sandstone bed, at Loc. 119. The A formation. Overturned. d: Cross-lamination in the sandstone bed, the lower part of which shows graded bedding. Loc. 252. (Fig. 25, g).

sedimentation on the top of the slope are related to the major cyclic sedimentation.

In the Miura (southern Kanto) and Muroto (southeastern Shikoku) peninsulas, the southern parts of these peninsulas uplifted instantaneously by great earthquakes compared with the northern parts. During the interval time of the earthquakes the southern parts were gradually sinking compared with the northern parts (Okada and Nagata, 1955; Harada, 1948). However, instantaneous uplifting is much larger than secular sinking. Quaternary sea terraces are now high above sea level in the southern part of the Muroto peninsula. The terrace of about 150,000 years old is now about 250 m high above sea level (Yoshikawa *et al.*, 1964). The terraces gradually decrease in altitude towards the north. There the whole area is tilting northward.

On the other hand, there is a 1,600-2,200 m plain below sea level off Shikoku to the south of the tilting area. The plain may be of the Pliocene age (Sato). It is highly probable that the angle of slope between the two areas is gradually changing. It is probable that the sedimentary condition on the top of the slope is also gradually changing.

On the assumption that the tectonic condition of the Oigawa area was nearly the same as that of the present Miura or Muroto, such features may explain the gradual change in the thickness of turbidites in the sedimentation order in the minor cycle, but not the abrupt change between the minor cycles. This phenomenon remains unsolved.

The mechanism of the major and minor sedimentation is thus quite a difficult problem. However the cyclic sedimentation may give us some information about the earth movements, especially the occurrence of earthquakes through long geologic time. We can sometimes see the displacement of Quaternary deposits or other features formed by earthquakes, but we cannot estimate the succession of many earthquakes at an outcrop. On the other hand we may obtain the succession of earthquakes or some other movements through long geologic time by turbidite sequences. The studies on the thick column of the Pliocene and Quaternary turbidites, and if possible of the recent turbidites, may be useful for estimating the succession of earthquakes or other earth movements through geologic time.

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e: Turbidites in the shale formation underlying the A formation. Loc. 120. Overturned. f: The "increasing" type minor cycle at Loc. 119. The strata are overturned. The A formation. g: The lower part of the turbidite sequence at Loc. 119. Overturned. h: Graded beds at Unazawa.

Summary

Turbidites are developed in the Permian-Triassic Sambosan and the Jurassic-Cretaceous Shimanto group in Japan. The Turbidite sequences are well distributed in the Tamagawa district, the Kanto mountainous land, and in the Oigawa district (Fig. 1). The sequence in the latter district occupies the southern wing of a grand recumbent fold. Here, turbidite-poor shale, turbidite (the A formation), non-turbidite with turbidite (the B), turbidite (the C) and turbidite-poor shale formations are distributed. Average thickness and standard deviation of the sandstone and shale beds within each 5 m column of strata were measured (Tables 1–3). Average thickness of sandstone beds varies with the horizon, especially with the major cyclic sedimentation. On the other hand the average thickness of shale beds is fairly constant in the turbidite sequences (the A and C formations).

Thickness of the sandstone beds in the turbidite sequences shows log-normal distributions (Figs. 16, 17). However, that of the shale in the turbidite sequences shows distributions similar to the normal ones. The distributions are probably due to the fact that the shale deposition is proportional to time and that the time interval of turbidity currents is fair constant. This is confirmed by a fact that the number of turbidites during the deposition of a unit shale is fairly constant (Table 4). The standard deviation of thickness distribution is related to the thickest bed within each 5 m column, especially for the sandstone beds.

Thickness distributions of sandstone and shale beds in the turbidite-poor and the turbidite-rich sequences (the B formation) are quite different from those of the turbidite sequence (the A and the C formation) in the Oigawa (Fig. 18, Table 2) and show much wider distribution.

The thickness of sandstone beds is not related to that of the overlying and the underlying shale beds in the A and C formation (Figs. 22, 23). However, turbidite beds in the turbidite-poor shale formation underlying the A formation are composed of a very thin sandstone part and rather thick silt part. In this case thickness of the overlying silt and shale appears to be related to that of the underlying sandstone part. The thickness of turbidite sandstone beds is also related to the clasticity (Fig. 24) and sedimentary structures. Sole marking is not common on the underside of the thinner beds (70 cm or less). Laminated structures, convolute structures and other are common in the thinner beds (10 cm or less), but not common in the thicker beds.

In the turbidite together with the non-turbidite sequences there are cyclic sedimentations. Sandstone-shale diagrams (Figs. 6, 10, 11, 14, 15), total thickness (Figs. 4, 7, 13), average thickness and the thickest bed (Fig. 26) within 5 m column, and accumulation of sandstone during the deposition of a unit thick shale (Figs. 8, 10, 15) show the cyclic sedimentations which are classified into major and minor ones. The major cyclic sedimentation is most well shown by the distribution of thickest bed within each 5 m column (Fig. 26). The bed usually corresponds to the thickest bed within each minor cycle (Fig. 19). The major cycle may be related to transgression and regression and is not related to the chert deposition at Unazawa (Fig. 7). Minor cyclic sedimentations are further classified into "increasing" and "decreasing" types (Fig. 12). The "increasing" type appears to be generally formed during the regression, the "decreasing" type during the transgression. The minor cyclic sedimentations are well shown by the sandstone-shale diagrams as well as by the thickness distribution of sandstone beds according to the sedimentation order (Figs. 12, 20).

There was a basin of the normal sedimentation with some steep cliffs at the regressional stage (Fig. 27), a part of this basin becoming the drainage of turbidity currents when the sea level was rather high. At the stage of transgression, shale deposited principally with muddy turbidites. The major cyclic sedimentation may have been formed under such a circumstance.

The frequency of great earthquakes and the tectonic position in the westernmost Pacific near Japan are comparable with those of turbidite sequences in the Oigawa district, the turbidites having been probably produced by such earthquakes.

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34. Turbidite よりなる地層の中の砂岩層の厚さの分布と，堆積りんね.——三宝山，四万十層群の二地域の例

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二畳紀一三畳紀の三宝山層群，ジュラ紀一白亜紀の四万十層群には Turbidites 層が発達している．この Turbidite 層は多摩川地域・南部大井川地域によく見られる (Fig. 1). 大井川地域のこの層群は大きな横臥せしゅう曲の南翼をなしており，Turbidite の少ない頁岩層，Turbidite 層 (A層), Turbidite を伴う non-Turbidite 層 (B 層), Turbidite 層 (C 層), Turbidite の少ない頁岩層からなつている．5 m の厚さの地層の中の砂岩層の平均層厚 (Table 1-3) は層準に応じて，特に堆積の大りんねに応じて変化する．一方頁岩層の平均層厚は A, C 層内では層準にかかわらずほぼ一定である．

Turbidite 層群内の砂岩層の厚さは log-normal の分布を示す．しかし頁岩層の分布は normal に近い．この頁岩の層厚の分布は，頁岩の堆積が時間に比例していることと，乱泥流が流れ込む時間の間隔がほぼ一定であつたことによつている．一定の厚さの頁岩が堆積する間の Turbidites の数がほぼ一定である (Table 4) ことはこれをよく示している．

Turbidites と non-Turbidites とからなる B 層の砂，頁岩層の厚さの分布は Turbidites よりなる A, C 層と非常に異なつており，分布幅が大きい (Fig. 18, Table 2).

泥岩質の Turbidites が発達する場合は例外であるが，大井川地域では砂岩層の厚さは，この上または下に重なる頁岩層の厚さと無関係である (Fig. 22, 23). Turbidites の砂岩層の厚さは clasticity (Fig. 24), sole marking のはいり方，堆積構造 (Fig. 25) にも関係がある．

non-Turbidites 層はいうまでもなく，Turbidites 層にも堆積りんねが見られる．これは砂岩頁岩ダイアグラム (Figs. 6, 10, 11, 14, 15), 5 m の地層の中の砂岩の全部の厚さ (Figs. 4, 7, 13), 平均の厚さ，一番厚い地層 (Fig. 26), 単位の厚さの頁岩が堆積する間に堆積した砂岩層の厚さ (Figs. 8, 10, 15) によくあらわれる．堆積りんねには大りんねと小りんねとがある．大りんねは，5 m の地層中の最大の砂岩層の厚さの分布 (Fig. 26) にもつともよくあらわれるが，これは小りんね中の最大の地層の分布 (Fig. 19) にあたるものである．大りんねは海進・海退と関係がある．そして，海沢(多摩川) ではこの大りんねはチャート層の形成と無関係である (Fig. 7).

小りんねはさらに“増加”型と“減少”型とに分けられる (Fig 12). “増加”型は海退期に“減少”型は海進期にできるようである．この小りんねは砂岩一頁岩ダイヤグラムや，堆積の順序に従つての砂岩層の厚さの変化の図 (Figs. 19, 20) によくあらわれる．

通常の環境を示す堆積盆地に，ところにより急な斜面のあるもの (Fig. 27) を考えると，このようなところでは，海水面が上昇すると，その一部は乱泥流が流れ込む地域となり，さらに海進がすすむ

と，主に泥が，そして時に泥質の Turbidites が堆積するところになるであろう．大井川地域の大りんねは，このようなところでできたものであろう．

大井川地域のかつての状態は，太平洋の日本近海の状態に近いもので，大地震の頻度や，地質構造上の位置もお互いに似たものであつたであろう．大井川地域の Turbidites は多分このような大地震で生じたものであろう．新しい地質時代の地層で Turbidites よりなる地層が非常に厚く発達するところを調べると，地震またはその他の地変が，どのような繰り返しでおこつているかを推定するのに役立つであろう．