REPORT No. 236
GEOLOGICAL SURVEY OF JAPAN

SEDIMENTATION OF THE CRETACEOUS FLYSCH SEQUENCE IN THE IKUSHUMBETSU AREA, HOKKAIDO, JAPAN

By

Keisaku TANAKA

GEOLOGICAL SURVEY OF JAPAN
Hisamoto-cho, Kawasaki-shi, Japan
1970

Report, Geological Survey of Japan, No. 236, 1970

Keisaku TANAKA: Sedimentation of the Cretaceous Flysch Sequence in the Ikushumbetsu Area, Hokkaido, Japan

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The following references should be added to the list :

KSIAZKIEWICZ, M. (1958) : Stratigraphy of the Magura Series in the Sredni Beskid (Carpathians). *Biul. Inst. Geol.*, **135**, p. 43—96.

KSIAZKIEWICZ, M. (1960) : On some problematic organic traces from the flysch of the Polish Carpathians. *Kwart. Geol.*, vol. 4, p. 745—748.

MINATO, M. and SUYAMA, K. (1949) : Kotfossilien von Arenicola-artigen Organismus aus Hokkaido, Japan. *Jap. Jour. Geol. Geogr.*, vol. 21, p. 277—279.

For the ill-printed formational boundaries and faults in Fig. 48 refer to Fig. 2.

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REPORT No. 236

GEOLOGICAL SURVEY OF JAPAN

Konosuke SATO, Director

Sedimentation of the Cretaceous Flysch Sequence in the Ikushumbetsu Area, Hokkaido, Japan

By

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CONTENTS

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Keisaku TANAKA*

Abstract

This paper describes the Cretaceous flysch sequence constituting the main part of the Middle Yezo Group, about 1,000 m thick, in the Ikushumbetsu area, central Hokkaido, with reference to its sedimentary features.

The sandstones in the flysch deposits are mostly of turbidity current origin. In order to make clear details of sedimentary features, statistical analysis was made of the lithology and thickness of the sedimentation units which are called here graded units, consisting of sandstone in the lower part and shale in the upper part. The relations of sedimentary features to thicknesses of graded units, the type of facies, the lateral facies variation and the cyclic sedimentation are discussed. Descriptions of the inorganic and biogenic sedimentary structures also constitute part of this paper. Palaeocurrent analysis is one of the main purposes of the sedimentological study. The sediment-transport pattern represented by the axial and lateral current directions is discussed in connection with the palaeogeographic control of sedimentation of the flysch sequence and the overlying formations in and around the present area.

I. Introduction

The epoch-making turbidity current hypothesis proposed by KUENEN and MIGLIORINI (1950) has found general acceptance among geologists and has had a strong influence especially on sedimentology through a large number of contributions on modern deep-sea sands and ancient flysch or flysch-like deposits in many parts of the world (see KUENEN and HUBERT, 1964, p. 222–246; DZULYNSKI and WALTON, 1965, p. 255–265). In Japan, however, few sedimentological investigations have been made as yet of flysch-type or turbidite formations in spite of the extensive distribution of such sediments. Actually, pioneer studies of such deposits did not go beyond a morphological description of peculiar types of sedimentary structures observed in certain limited areas. Very recently, intensive studies from various angles of flysch-type or turbidite series have been undertaken and are still under way in many parts of the country.

Under the circumstances, I feel it necessary to gain by myself sufficient knowledge of Japanese flysch or turbidite sequences. Therefore, I have endeavoured for some years to make clear sedimentary features of some such formations. For example, as to the Upper Cretaceous Izumi Group which consists mainly of turbidite sequence, in the Izumi mountain range about 45 km south of Osaka,

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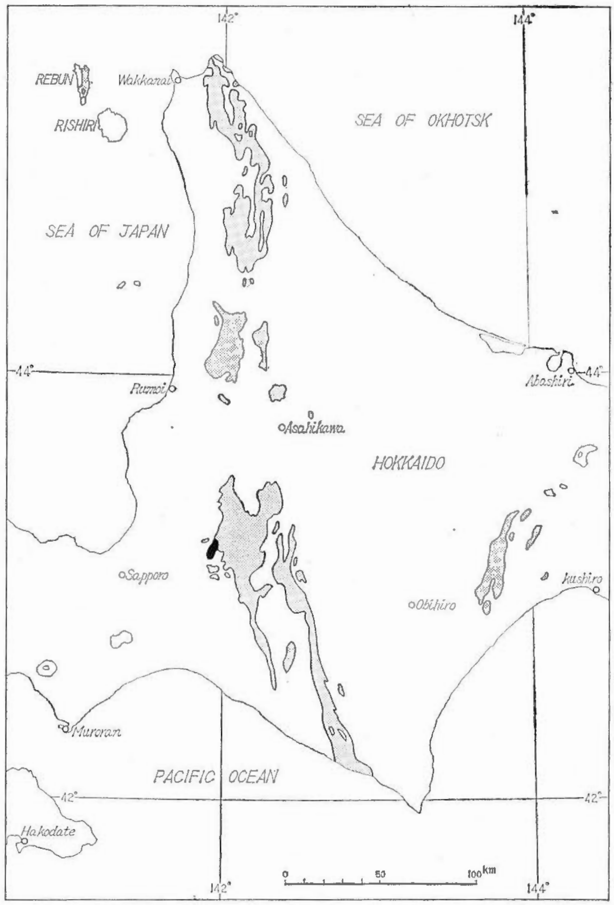


Fig. 1. Index map of the main part of Hokkaido showing distribution of the Cretaceous deposits.
The Ikushumbetsu area is indicated by a black spot.

study was directed to the sedimentary facies, cyclic sedimentation and current pattern (TANAKA, 1965). Then the Cretaceous flysch sequence in the Ikushumbetsu area, central Hokkaido (Fig. 1) has been investigated from the standpoint of sedimentology, and the results are described in this paper.

The Ikushumbetsu area is known as one of the classical and typical fields of the Cretaceous System in Hokkaido. The Cretaceous sequence in this area has been studied by various authors from the standpoint of stratigraphy, palaeontology and so forth. Of a number of geological contributions, outstanding and important studies succeeding to YABE's pioneer works (1903, 1909, 1926a, 1926b, 1927) are as follows: (1) stratigraphical or biostratigraphical works by FUKADA *et al.* (1953) and MATSUMOTO (1943, 1954, 1959, 1965); (2) sedimentological, especially petrographical, works by FUJII (1958) and OKADA (1965). Nevertheless, little attention has so far been directed to the sedimentary features of the flysch-type deposits constituting the main part of the Middle Yezo Group.

In 1958 and 1959 in the course of the sheet-map survey conducted by the Hokkaido Development Agency I engaged myself in the field work on the Cretaceous formations in the Ikushumbetsu area. The general geological results have already been published in "Iwamizawa," Explanatory Text of the Geological Map of Japan, scale 1:50,000, with some preliminary explanations of the sedimentary features and current patterns of the flysch succession (TANAKA *in* MATSUNO *et al.*, 1964). The litho- and biostratigraphical schemes established are generally in agreement with MATSUMOTO's schemes (see MATSUMOTO, 1959, plate 7, 1965, figs. 4,5; OKADA, 1965, fig. 6). Thereafter, more detailed investigations including statistical analysis of sedimentation units have been extended to the Cretaceous flysch deposits in the Ikushumbetsu area in order to obtain much information about the sedimentary features. In connection with the Cretaceous regional sediment-transport pattern of the Ishikari coal-field, palaeocurrent measurements were made of the contemporaneous flysch sequence in adjacent areas and of the overlying formations in and around the Ikushumbetsu area. On the basis of this sedimentological investigation the lithological characters, depositional features of sedimentation units, inorganic and biogenic sedimentary structures, lateral facies variation, cyclic sedimentation and sediment-transport patterns of the Ikushumbetsu flysch are to be described in the present paper.

Acknowledgements

I wish to express my sincere gratitude to Professor Tatsuro MATSUMOTO of the Department of Geology, Kyushu University, who has constantly encouraged me and kindly provided me with invaluable information concerning geology and palaeontology, and to Professor Kotora HATAI of the Institute of Geology and Palaeontology, Tohoku University, who kindly permitted me to use his valuable library for this study. Further, I am also indebted to the following persons for their help and advice in various ways: Dr. Koji KINOSHITA, Dr. Susumu NISHIJIMA and other geologists of the Japan Petroleum Development Corporation for their valuable suggestions; Dr. Yokichi TAKAYANAGI of the Institute of Geology and Palaeontology, Tohoku University for his great help in the identification of foraminiferal fossils; Dr. Yoji TERAOKA and Mr. Yasuo SUMI for helpful suggestions; Mr. Yoshio MASAI for the photographs appearing in this paper; Mrs. Chie AOKI for assistance in statistical calculations.

II. Stratigraphy

II. 1 General Remarks

The Cretaceous deposits extensively developed in the Ishikari coal-field (FUKADA *et al.*, 1953; MATSUMOTO, 1959, 1965; MATSUMOTO and HARADA, 1964; TANAKA, 1959, 1963, *in* SHIMIZU *et al.*, 1953, *in* MATSUNO *et al.*, 1964, *in* SASA *et al.*, 1964), including the Ikushumbetsu area, are a western representative of the Cretaceous sequence in the meridional folded zone of Hokkaido, i.e., the Yezo geosyncline (Figs. 2, 3). The Cretaceous sediments are covered by the coal-bearing Palaeogene Ishikari Group with a slight clino-unconformity and are complicatedly deformed by a number of folds and faults. The fundamental structure of the Cretaceous rocks was finally completed at the close of the Tertiary Period. It comprises an anticlinal structure which is called the Sorachi

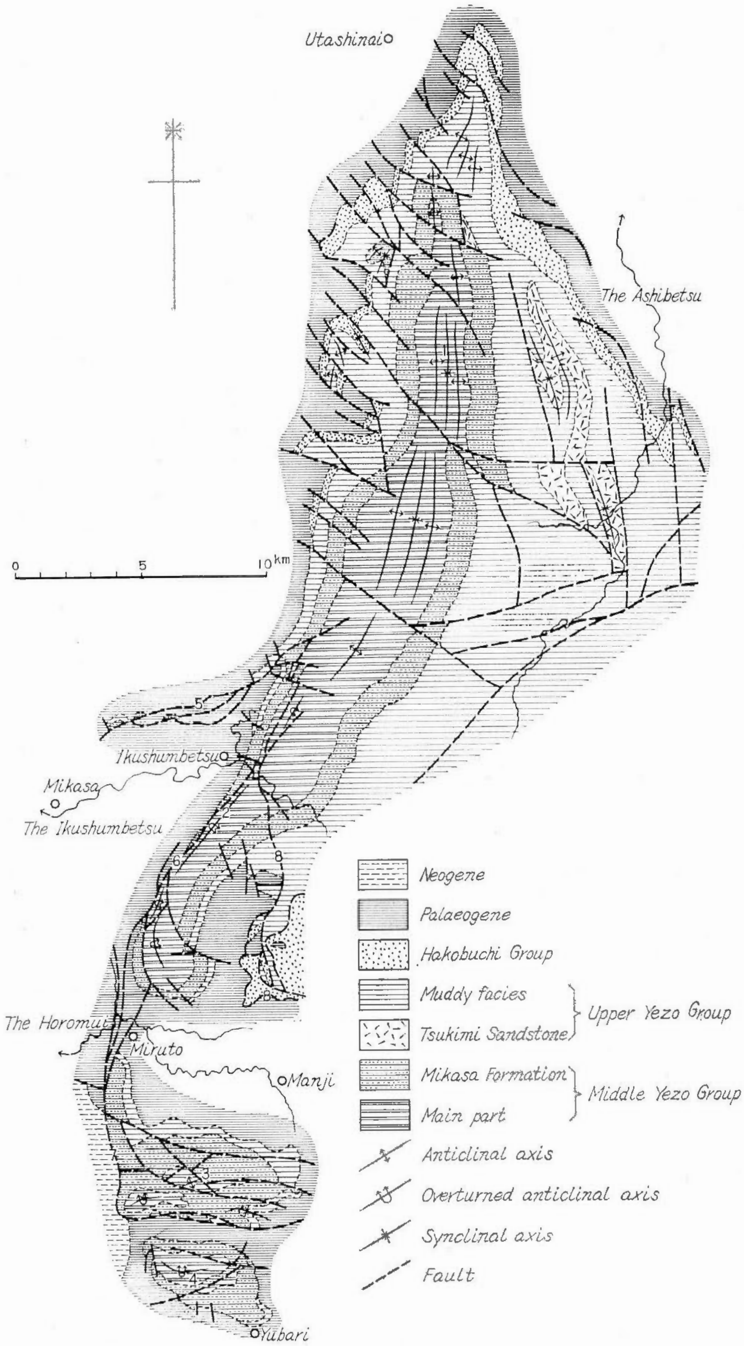


Fig. 2. Compiled geological map of the outcrop areas of the Cretaceous deposits in the Ishikari coal-field, central Hokkaido.

1. Sorachi anticline.
2: Ikushumbetsu anticline.
3: Manji dome.
4; Hatonosu dome,
5: Pombetsu fault.
6: Ikushumbetsu fault.
7: Yubari fault.
8; Ban-no-sawa fault,

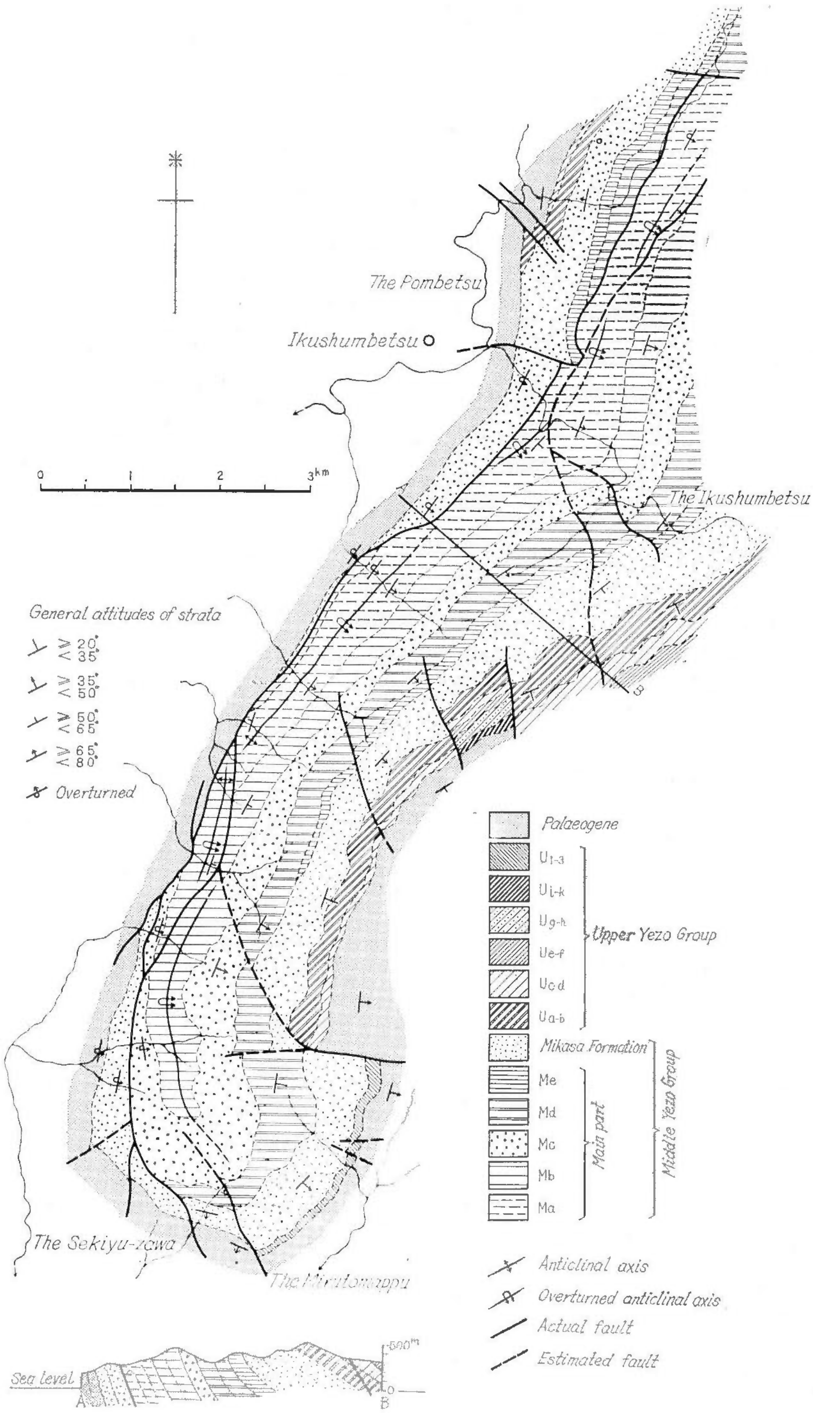


Fig. 3. Geological map of the Ikushumbetsu area, central Hokkaido.

anticline in the north and the Ikushumbetsu anticline in the south, the Manji dome and the Hatonosu dome (or Yubari dome) from north to south. In these four major structural units transverse faults of NW-SE trend are prominent and the strata on the western wing of the anticlines and domes tend to be more steeply inclined than those on the eastern wing. Except for the first-named unit the strata are even overturned.

The Cretaceous formations in the Ishikari coal-field are a thick, conformable, marine sequence ranging from Albian to Maastrichtian in age, and are divided into the Middle Yezo, Upper Yezo and Hakobuchi Groups in ascending order. The Hakobuchi Group is not exposed in the Ikushumbetsu anticlinal area nor in the two domes in the Yubari area. Before the deposition of the Ishikari Group the Cretaceous deposits were eroded away, and roughly speaking, the erosion was greater in the west than in the east and more in the south than in the north. The stratigraphic succession of the Cretaceous in the Ikushumbetsu area is shown in Table 1.

The Cretaceous sequence in the coal-field changes from a relatively near-shore, shallow facies to a relatively offshore, deep facies with increasing thickness of the strata from west to east. Therefore, the source area is suggested to have always been situated to the west of the Cretaceous domain. Furthermore, the southern part of the eastern wing of the Sorachi anticlinal area was usually brought into most intensely subsided environments, whereas the Yubari area along with the southernmost part of the Ikushumbetsu anticlinal area was continuously under the conditions quite contrary to the former.

II. 2 Middle Yezo Group

The Middle Yezo Group in the Ishikari coal-field, though its lower limit is not observable in the field, measures up to about 1,600 m thick, and is divided into the main part (Middle Albian? to Upper Albian in age) and the uppermost part called Mikasa Formation (generally Cenomanian to Upper Turonian in age). The main part of the group with a thickness of nearly 1,300 m consists chiefly of mudstone which is frequently interlaminated and interbedded with sandstone, thus being dominated by flysch-type sediments. It shows a similar lithostratigraphic succession all over the coal-field, but considerably decreases in thickness in the southernmost part of the Ikushumbetsu anticlinal area and in the Yubari area including two domes. Ammonoids, inocerami and other molluscan fossils occur sparsely throughout the sequence.

The main part of the Middle Yezo Group in the Ikushumbetsu area is about 1,000 m thick and consists predominantly of flysch-type deposits on which the present sedimentological study is focussed. It is stratigraphically divisible into five members (Ma through Me), each of which can be subdivided into several facies (e.g. α, β, γ and δ) according to their lateral variation of rock-facies (Figs. 4, 5; Table 1).

In Member Ma the argillaceous sediments themselves are generally coarser grained in facies β than in facies α. Member Mb corresponds to the lower part of the Yunosawa Sandstone (FUKADA *et al.*, 1953). In the lower part of the member, Mb_1, the sandstone of facies β is thicker and coarser grained than that of facies α and γ. The sandstone of the upper part of the member, Mb_2 becomes thinner and finer grained in the order of facies α, β and γ. Member Mc is referred to as the upper part of the Yunosawa Sandstone. Bedded sandstone is

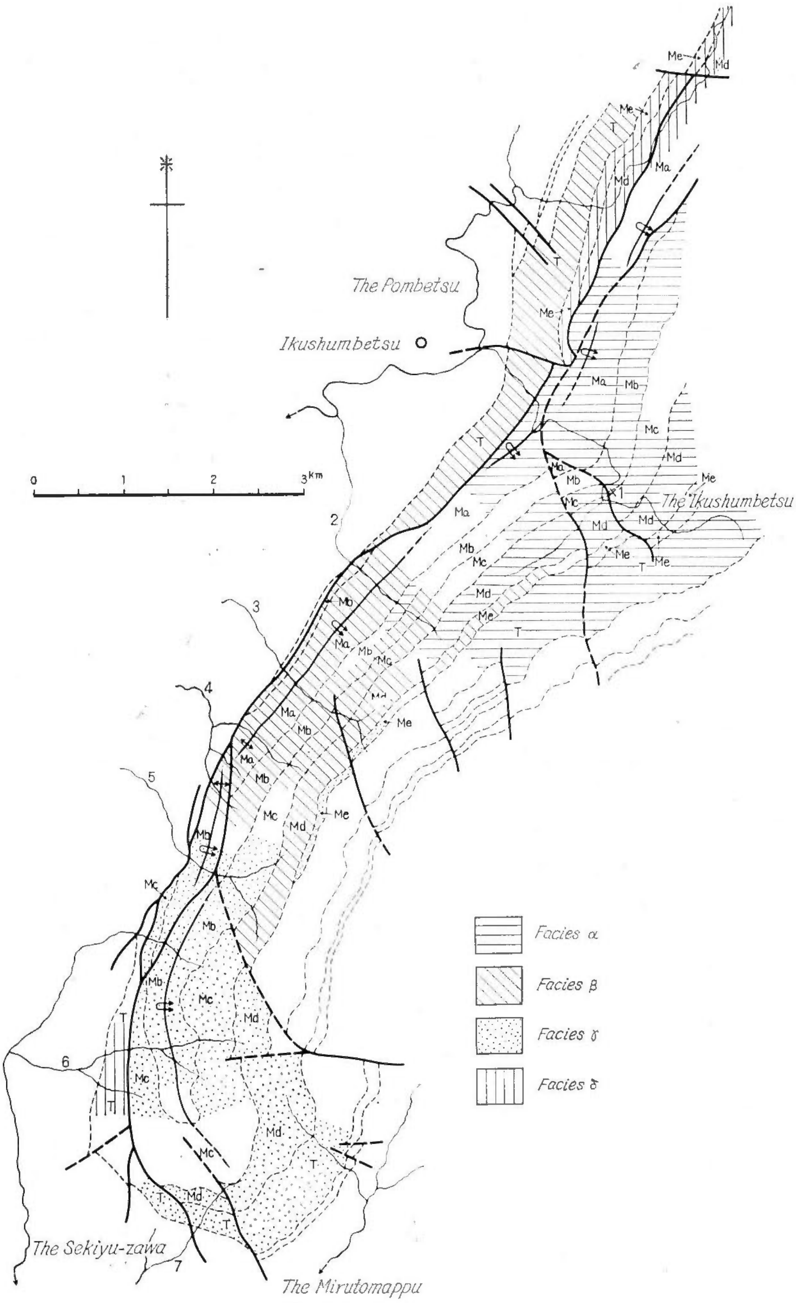


Fig. 5. Geological map showing the types of facies for the Middle Yezo Group in the Ikushumbetsu area.

Ma, Mb, Mc, Md and Me: main part of the Middle Yezo Group.

T: Mikasa Formation.
1: Katsurazawa Electric Station.
2: Takambetsu.
3: Pomporonai.
4: Nunobiki-no-sawa.
5: Honsawa.
6: Yamamoto-no-sawa.
7: Washi-no-sawa.

prevalent in all facies, but massive sandstone, too, is common in facies β and γ. Member Md which decreases in thickness southwards consists mainly of argillaceous sediments. In the member laminated mudstone and laminated sandy mudstone are predominant in facies α, while rather massive siltstone predominates in facies β and γ. The middle part of the member, Md_2, of facies δ is dominated by sandstone and mudstone in thin-bedded alternation. In Member Me the sandstone is generally massive in facies α, β and γ; it is frequently interbedded with mudstone in facies δ. The member on the eastern wing of the Ikushumbetsu anticline thins out southwards to be replaced by the lowermost part of the Mikasa Formation.

The Mikasa Formation, formerly called *Trigonia* Sandstone (YABE, 1909, 1926a, 1926b), is neritic, partly littoral sediments, consisting of sandstone with subordinate conglomerate and siltstone. Shallow-sea pelecypods such as trigonians are abundant throughout, and ammonoids and inocerami also are common. The formation is considerably variable in facies, thickness and time-range from place to place throughout the Ishikari coal-field.

The Mikasa Formation on the eastern wing of the Ikushumbetsu anticline is a little more than 400 m thick and comes to have a more offshore, deeper facies towards the south of the eastern wing of the Sorachi anticline where the formation shows a considerably short time-range as represented only by part of the Cenomanian. On the other hand, the formation on the eastern wing of the Ikushumbetsu anticline becomes a thinner and nearer-shore, shallower type towards the southernmost part of the Ikushumbetsu anticline where the formation is no more than 170 m thick, in spite of the longest time-range, and contains an oyster bed. The formation on the western wing of the Ikushumbetsu anticline is about 300 m in thickness and fairly resembles that on the western wing of the Sorachi anticline in sedimentary facies and thickness. The formation in these two areas shows a near-shore, shallow facies in contrast with that on the eastern wing of the Ikushumbetsu-Sorachi anticline, and is intercalated with some seams of coaly shale. The Mikasa Formation in the Yubari area is quite similar to that in the southernmost part of the Ikushumbetsu anticline, coming to show a relatively offshore facies eastwards.

The Mikasa Formation in the Ikushumbetsu area is classified into four facies (α, β, γ and δ) according to its remarkable lateral variation of rock-facies (Fig. 5). The formation of facies α on the east wing of the Ikushumbetsu anticline is stratigraphically divisible into four units (Table 1). The lower member, Tb, contains a large number of neritic shells such as trigonians and not a few ammonoids. The formation of facies β on the western wing of the anticline is thinner and coarser grained than that of facies α on the eastern wing, and is intercalated with several oyster beds. It is stratigraphically divisible into the following four units in ascending order: Twa (80 m; fine-grained sandstone), Twb (90 m; coarse-grained sandstone with subordinate conglomerate, carrying several thin seams of coaly shale), Twc (25 m; fine-grained sandstone) and Twd (105 m; medium- to coarse-grained sandstone with frequent intercalation of conglomerate). The formation of facies γ in the southernmost part of the anticline consists chiefly of coarse- to medium-grained sandstone. The formation of facies δ in the southernmost part of the western wing of the anticline, though its lower and upper limits are not observable in the field, is estimated at about 180 m in thickness and is very similar in rock-facies to the formation of facies β and γ.

II. 3 Upper Yezo Group

The Upper Yezo Group is represented by a comparatively monotonous sequence of rather massive siltstone and mudstone containing fossiliferous calcareous concretions. It ranges from Upper Turonian to Lower Campanian in age. The sediments are coarser grained in the lowermost and uppermost parts than in the main part. Fossils such as ammonoids and inocerami are abundant throughout.

The Upper Yezo Group in the northern part of the eastern wing of the Ikushumbetsu anticline, though its upper limit is not observable in the field, is some 500 m thick and is considerably thin in comparison with the 850 m thick equivalent on the eastern wing of the Sorachi anticline where the group has a total thickness up to about 1,100 m. The group on the east wing of the Sorachi anticline is characterized by the frequent intercalation of thin sandstone in some parts in addition to the Tsukimi Sandstone Member, the middle part of the group. The Tsukimi Member is nearly 150 m thick and made up predominantly of tuffaceous sandstone in its eastern facies and rich in pebbly mudstone in its western. Unlike the group in other areas of the coal-field, the group on the eastern wing of the Sorachi anticline begins with the Cenomanian Stage. The Upper Yezo Group on the western wing of the Ikushumbetsu anticline is very similar to that on the eastern wing in many respects, but the lowermost part, approximately 130 m thick, is much thicker than its eastern equivalent, which is nearly 30 m thick. The group on the western wing of the Sorachi anticline differs largely from that on the eastern wing in many respects, while it fairly resembles the group in the main part of the Ikushumbetsu area. Actually, glauconitic sandstone occurs as intercalations at some levels, especially in the lower half of the group on the eastern wing of the Ikushumbetsu anticline and the western wing of the Sorachi anticline. As to the Upper Yezo Group in the southernmost part of the Ikushumbetsu anticlinal area, the lower limit is at a considerably higher horizon than that of the group in the northern part and the thickness is 70 m or so, being no more than one fourth of that of the northern equivalent. Here, at least part of the group shows a comparatively near-shore, shallow facies as evidenced, for example, by the occurrence of an oyster bed. The group in the Yubari area is quite similar in rock-facies and thickness to that in the southernmost part of the Ikushumbetsu anticlinal area.

The Upper Yezo Group in the northern part of the eastern wing of the Ikushumbetsu anticline is stratigraphically divisible into thirteen units (Table 1). The lower half (Ua-Uf) consists mostly of fine-sandy siltstone; the upper half (Ug-Um) is made up chiefly of mudstone. The group on the east wing begins at a higher horizon and is more deeply eroded away before the deposition of the Ishikari Group in the south than in the north. Thus the group in the southernmost part of the anticline is referred to the sequence of the upper part of unit Ub to unit Ui in the north. The group on the western wing of the Ikushumbetsu anticline corresponds to the sequence of the upper part of unit Ub to unit Ug on the eastern wing. Here, the equivalent of the upper part of Ub is called unit Ub′.

II. 4 Hakobuchi Group

The Hakobuchi Group is neritic, partly littoral sediments consisting predominantly of sandstone with subordinate conglomerate and siltstone. It ranges from Upper Campanian to Maastrichtian in age. Marine molluscan fossils are found in several places, though very rarely. The group is distributed only in the Sorachi anticlinal area and in several thrust sheets on the eastern outer side of the Ikushumbetsu anticline. The group on the eastern limb of the Sorachi anticline ranges from 150 to 300 m in thickness and is intercalated with some seams of coaly shale. On the other hand, the group on the western limb, about 100 m thick, is much richer in conglomerate than that on the eastern.

III. Lithology

As is generally known, the Cretaceous sequence in the meridional folded zone of Hokkaido in which the Ikushumbetsu area is included is part of geosynclinal sediments of the syn-orogenic or pre-paroxysmal stage of the Hidaka orogeny (MINATO *et al.*, 1965). Actually, in the main part of the Middle Yezo Group in the studied area sandstone and shale* are frequently interbedded with each other in various thicknesses and proportions. Such deposits are referred to as a flysch facies (for definition of flysch, see KSIAZKIEWICZ, 1954; SUJKOWSKI, 1957; DZULYNSKI and SMITH, 1964; SEILACHER, 1967a). According to SEILACHER's definition of flysch facies (SEILACHER, 1967a), the flysch sediments in the Ikushumbetsu area are a "genuine" or "true" flysch. The great majority of the sandstone beds display various sedimentary attributes of turbidites which are described in many publications (KUENEN, 1951, 1953; KUENEN and CAROZZI, 1953; DZULYNSKI *et al.*, 1959; TEN HAAF, 1959b; BOUMA, 1962; POTTER and PETTIJOHN, 1963; KUENEN, 1964; MCBRIDE, 1966; POTTER, 1967). In some parts the flysch sequence under discussion is a series of massive or poorly bedded sandstone showing little, if any, sedimentary features typical of turbidites. In other parts it is associated with a series of shale which is not even interlaminated with sandstone and exhibits nothing of typical turbidite aspects. Tuff or tuffite beds with insignificant thicknesses are found at some levels. Furthermore, it should be noted that conglomerate occurs as very minor constituents and occurrence of slump beds also is of no importance throughout the flysch sequence.

III. 1 Sandstones

The sandstones of the Cretaceous flysch range from laminae a fraction of a centimetre thick to beds as thick as several metres. These sandstones fall into five groups in terms of their mode of occurrence: massive sandstone, bedded sandstone, sandstone rhythmically interbedded with shale, sandstone sporadically intercalated in shale and sandstone frequently interlaminated with shale, the third of which is most widespread.

Massive sandstone

Massive sandstone in which pelitic rock between is either absent or as thin as mere partings is prevalent in Member Mc of facies β and γ and in Member Me of facies α, β and γ. Sandstones of this type are grey, bluish grey or greenish grey in colour and are generally medium-grained, but occasionally

* Shale, unless otherwise stated, is to be used in this paper as a general term for various types of indurated pelitic rocks. There are, however, few true shales in the studied area, although many of the pelitic rocks are well laminated.

coarse-grained. They are on an average coarser grained, less muddy and better sorted than other types of sandstones to be mentioned below. Graded bedding and clear current sole markings cannot be detected at all in such sandstones. Moreover, the massive sandstone is in some cases crudely laminated, but it does not exhibit large-scale cross-bedding. It seems possible, therefore, that most, if not all, of the massive sandstones are interpreted not as inshore, shallow-sea deposits, but as fluxoturbidites (DZULYNSKI *et al.*, 1959; UNRUG, 1963; KUENEN, 1964) or as sand-flow deposits (DZULYNSKI and WALTON, 1965).

Bedded sandstone

Bedded sandstone that is as a general rule thickly bedded is widespread especially in Member Mc of each facies (Plate I-2). In such sandstones bedding planes occur at intervals of 0.3 to 1 m, occasionally up to 2 m, and the shale interbeds are commonly silty and interlaminated with sandstone, ranging from mere partings to beds nearly 5 cm thick.

The sandstone here referred to as bedded sandstone is similar in colour and grain size to the massive sandstone mentioned above. On the other hand, it is generally thicker bedded, coarser grained and less muddy than the sandstone rhythmically interbedded with shale mentioned below. Graded bedding is well developed in some sandstones, but imperceptible in others. Repeated graded bedding and intra-stratal wash-outs are occasional. Laminations are poorly developed on the whole. The base of the sandstone beds usually shows a sharp boundary with the underlying shales; directional sole markings are commonly found, but many of them are not conspicuous. In some sandstones contemporaneous breccias of shale occur in abundance. No autochthonous macrofossils of shallow-sea habitat are found in the sandstone or in the shale interbed. Furthermore, it is noted that beds of pebbly mudstone containing displaced shallow-sea shells occur in a certain bedded sandstone sequence.

It seems probable that all the sandstones of this category were deposited in relatively offshore, deep-sea environments. From the above sedimentary features, then, it may be concluded that some of the sandstones are interpreted as turbidites, but others as fluxoturbidites or sand-flow deposits.

Sandstone rhythmically interbedded with shale

Sandstone frequently and regularly interbedded with shale is one of the most characteristic rocks of the flysch succession in the studied area. It is the rule in particular for Member Mb of each facies and Member Me of facies δ (Plate I-1).

The sandstone ranges from 3 to 100 cm in thickness, being mostly grey to dark grey in colour and fine- to medium-grained. The interbedded shale is variable in thickness from 1 to 30 cm and commonly interlaminated with sandstone. Each sandstone layer is well persistent without any remarkable change of thickness and is always sharply separated from the underlying shale with an erosional surface. Graded bedding and lamination are well developed in such sandstones. The sandstone occurring in alternating succession with shale is for the most part comparatively muddy and moderately or poorly sorted. Small-scale cross-lamination, current ripple lamination, convolute lamination and various kinds of directional sole markings such as flute casts and groove casts are ubiquitous sedimentary structures. Current ripple marks also are occasional. However, neither wave ripple marks nor large-scale cross-bedding do occur in such sandstones. Furthermore, there are never found any other sedimentary structures as shallow-sea indicators. Sandstones of this type occasionally include contemporaneous breccias of shale. Autochthonous fossils are absent in the sandstone. However, in some of the shale interbeds there are found thin-shelled, weakly ornate, coiled ammonoids such as desmoceratids and gaudryceratinids*. Organic hieroglyphs, if present, are commonly found on the sole of relatively thin, fine-grained sandstones. The thicker sandstones (30 to 100 cm thick) tend to be better graded and less laminated and cross-laminated than the thinner ones (less than 30 cm thick).

From all the available data it is concluded that the sandstone under discussion is of relatively offshore, deep-sea deposition and is interpreted as turbidite.

Sandstone sporadically intercalated in shale

Sandstones of this type are usually, though not always, less than 30 cm thick and invariably show a sharp boundary with the shale above and below. Some are almost structureless, but others are distinctly graded and/or laminated.

Sandstone frequently interlaminated with shale

Sandstones of this type occur as laminae, a fraction of a centimetre thick, in shale interbeds between the aforesaid types of sandstones or in thick sequences of laminated sandy mudstone to be described later. Further remarks are reserved, because explanation of such sandstones will be given in reference to the laminated sandy mudstone.

To sum up, it can be pointed out that these different types of sandstones come to have a more offshore (or off-source), deeper facies in the order of the massive sandstone, bedded sandstone and sandstone rhythmically interbedded with shale.

Petrographic characters of the sandstones

Preliminary notes on the petrographic characters of the sandstones in the Cretaceous flysch are here briefly cited from FUJII's (1958) and OKADA's (1965) works, so as to supplement the megascopic features of the sandstones described above.

The sandstones of the flysch sequence are referred to the subgreywacke and the greywacke clans of PETTIJOHN's scheme of classification (PETTIJOHN, 1957). The majority of the sandstones of Member Me of facies α belong to the greywacke clan (clay matrix: about 35 per cent of the total); the sandstones of the sequence lower than Member Me are represented by the subgreywacke clan (clay matrix: 5 to 15 per cent of the total), which may be regarded as washed greywacke, a product of current agitation at or near the site of deposition. The general roundness of sand grains is not so good in either case, because it falls in the subangular class of PETTIJOHN's scale (PETTIJOHN, 1957). The mineral composition of the sandstones is represented by quartz, feldspar and rock fragments with lesser amounts of heavy minerals. The mineralogical maturity index expressed by the ratio of quartz plus chert/feldspar plus rock fragments shows the values ranging from 0.56 to 2.79, averaging about 1.3.

* The lower part of the graded part within a certain sandstone layer of this type in unit Mb_1 is made up mainly of redeposited shell sands. Impressions of ammonites on the underside of sandstones of this group are casts of the remains on the mud substratum.

In the sandstones of the flysch series rock fragments are in many cases much more predominant over feldspar, the former being composed of older sedimentary rocks, such as chert, sandstone and slate, and subordinate igneous rocks (e.g. andesite). The sandstone tends to be more or less calcareous. In particular, the subgreywacke sandstone has often more calcite cement than does the greywacke one. The quartz is for the most part of igneous origin. The heavy mineral content is 0.03 to 0.09 weight per cent, and prominent are zircon, garnet and minor tourmaline and biotite in addition to abundant iron minerals (pyrite and leucoxene). Furthermore, it draws one's attention that spherular authigenic pyrite replacing microfossils is of common occurrence in the flysch sequence, but very rare in the overlying neritic Mikasa Formation. Another matter to be noted is that authigenic marcasite is detected in a certain sample from Member Mc.

III. 2 Shales

The shales of the Ikushumbetsu flysch are classified into the following five categories according to their lithological features: siltstone, sandy mudstone*, laminated sandy mudstone, laminated mudstone and massive mudstone. Among the most widespread pelitic rocks is laminated sandy mudstone. These argillaceous rocks are occasionally more fissile along lamination planes until their fissility becomes so high that the rocks may be regarded as shales.

Siltstone

Siltstone occurs as thick sequences on the one hand and on the other it constitutes the lower part of shale layers frequently alternating with sandstone layer. It is dark grey in colour and rather massive or structureless, becoming occasionally fine-sandy.

Sandy mudstone

In some cases sandy mudstone is associated with thick sequences of laminated sandy mudstone; in others it occupies the lower part of shale layers frequently interbedded with sandstone layer. The sandy mudstone is represented by dark grey silty mudstone in which sand grains are disseminated or sandstone laminae, if present, are very thin and discontinuous.

Laminated sandy mudstone

Laminated sandy mudstone is prevalent not only as thick sequences but also as the middle or main part of shale layers frequently alternating with sandstone layer. It is laminated mudstone as defined below, very frequently interlaminated with sandstone and usually has a markedly striped appearance. The sandstone laminae involved are on occasion ripple cross-laminated or current ripple marked, thus forming discontinuous lenses along level surfaces.

Laminated mudstone

Laminated mudstone, usually shaly, constitutes thick sequences or the upper part of shale layers frequently alternating with sandstone layer. It is composed of interlaminated more dark clayey mudstone and less dark silty mudstone

* The term *mudstone* in this paper means indurated, rather clayey rock which is composed of mixtures of clay and silt grades and does not split easily along lamination planes. Mudstone is classified into clayey mudstone and silty mudstone, discriminating the former from claystone and the latter from siltstone.

both of which are as thin as several milimetres or less, thus having an appreciable striped appearance.

Massive mudstone

Massive mudstone, where preserved, usually occupies the uppermost or upper part of shale layers in alternating sequence of sandstone and shale; it does not occur as any thick sequence. In general, mudstones of this category are dark grey to blackish grey in colour, structureless and homogenous. They are represented chiefly by silty mudstone which grades upwards into clayey mudstone, if present.

In all the aforesaid types of shales calcareous concretions and marine macrofossils are very scarce on the whole, but rather common in some limited parts of laminated sandy mudstone sequences. The common molluscan fossils contained are thin-shelled, weakly ornate, comparatively inflated coiled ammonoids such as *Ammonoceratites, Anagaudryceras* and *Desmoceras,* subordinate strongly ornamented, coiled ammonoids such as *Mortoniceras* and thin-shelled pelecypods such as *Inoceramus, Propeamusium* and *Solemya* (TANAKA *in* MATSUNO *et al.*, 1964, table 3). The foraminiferal assemblages in the argillaceous sediments of the flysch formation are dominated by arenaceous benthonic forms such as *Bathysiphon* and *Haplophragmoides.* Calcareous benthonic forms such as *Dentalina, Lenticulina, Saracenaria* and *Gyroidina* also are common. Hence, it will be inferred that the argillaceous deposits indicate comparatively deep-water environments. These different types of shales come to show a more offshore (or off-source), deeper facies in the order of the siltstone, sandy mudstone, laminated sandy mudstone and laminated mudstone.

When the lithological features and mode of occurrence of the aforementioned distinct types of sandstones and shales are integrated, the following suites can be discriminated: (1) massive sandstone-siltstone and sandy mudstone, (2) bedded sandstone-sandy mudstone and laminated sandy mudstone, (3) sandstone rhythmically interbedded with shale-laminated sandy mudstone and laminated mudstone, and (4) sandstone frequently interlaminated with shale-laminated mudstone.

III. 3 Conglomerates

The conglomerates of the flysch deposits under consideration are of three types: petromict conglomerate, intraformational conglomerate and paraconglomerate.

Petromict conglomerate

Petromict conglomerate (PETTIJOHN, 1957), the matrix of which is sandy, occurs at two levels within Member Mc in the form of pebble- or granule-bearing sandstone, several decimetres thick. The gravels involved are rounded and comparatively well sorted, their kinds being rocks of exotic origin such as older sedimentary rocks (sandstone, slate and chert), volcanic rocks (andesite and rhyolite) and hornfels.

Intraformational conglomerate

Intraformational conglomerate (PETTIJOHN, 1957) with a general thickness of several centimetres is met with in the massive or graded part of sandstone layers. In sandy matrix of these conglomerates many thin or tabular pieces of contemporaneous shale are embedded.

Paraconglomerate

Referred to paraconglomerate (PETTIJOHN, 1957) or conglomeratic mudstone (PETTIJOHN, 1957) is the pebbly mudstone (CROWELL, 1957) that occurs at a certain level within unit Ma_2 of facies β and Member Mc of facies α (Plate II-1; see Fig. 20B, TANAKA *in* MATSUNO *et al.*, 1964, plate 1). These pebbly mudstones, 1 to 1.5 m thick, are structureless, very ill-sorted rocks originating from chaotic mixtures of silt and sand. They contain randomly distributed, angular or twisted lumps of the intra-basinal rocks such as sandstone, shale and calcareous rocks in addition to rounded pebbles of exotic rocks. The pebbly mudstone occasionally shows internal folds due to slumping. In accordance with CROWELL's opinion (CROWELL, 1957) the probable origin of such sediments may be ascribed largely to subaqueous mudflows abounding in pebbles and flowing into a relatively deep-sea. Further details will be given in the description of the slump structures later.

III. 4 Other Rocks

As minor constituents of the flysch formation tuff and calcareous and carbonaceous rocks are found.

Tuff and tuffaceous rocks

Tuff, tuffaceous sandstone or tuffaceous shale is usually a few centimetres to several decimetres, exceptionally up to a few metres, in thickness. Some beds are structureless; others are well laminated and/or distinctly graded. The tuff is greenish grey or greyish white in colour, comparatively fine-grained and is referred to vitric crystal tuff or vitric tuff. Some contain quartz, feldspar (mostly andesine) and biotite, thus being of probable dacitic nature; others comprise feldspar (mostly labradorite and betwynite), pyroxene and minor, if any, biotite, thus being of probable andesitic nature.

Calcareous rocks

Calcareous rocks occur as sporadic concretions, several centimetres to several decimetres across, in the argillaceous rocks. They are lithologically referred to calcareous shale or marlstone, being ellipsoidal or flattish particularly in the laminated mudstone and laminated sandy mudstone. Some of them include fossils such as ammonites and inocerami.

Carbonaceous rocks

Carbonaceous rocks do not occur as distinct layers or beds. Laminae or fragments of coal (0.1 m thick and 0.2 m long in maximum size) are contained, though locally, in some sandstone layers.

IV. Graded Units

The Ikushumbetsu Cretaceous flysch is dominated by alternating graded sandstone and shale. Any component sedimentation unit or stratal unit in such alternating sequence is termed here a graded unit. A single standard graded unit is defined as including the whole sequence of lithological units from the base of one coarse phase up to the base of another coarse phase at the upper level, being in the present case composed of sandstone (or rarely very sandy, coarse siltstone*) below and shale above. In reference to the sedimentary attributes of the graded units to be described, the lithological data obtained from the statistical analysis and part of the detailed stratigraphical columns of some selected sections are given in Table 2 and Fig. 6 respectively**. Similar statistical investigations on lithological aspects of some other flysch or turbidite sequences have already been made by BOUMA (1959, 1962), MCBRIDE (1962, 1966), TANAKA (1965) and WALKER (1967).

IV. 1 Unit Types

Sedimentation units as represented by graded units have been classified, as an example of their subdivision, into several groups according to their thickness (DOTT, 1963). However, the graded units in the studied area were classified on the basis of both unit thickness and sandstone percentage which is calculated from the proportion of sandstone layer in each graded unit (Table 3) as in the case of the Izumi Group (TANAKA, 1965).

Table 3. Classification of graded units based on their thickness and sandstone percentage

Unit type	Thickness (in cm)	Sandstone percentage (%)	Remarks
0	>300	>80	Thickness: generally less than 500cm.
I	100–300	>80	
II	60–100	>80	
III	30–60	>50	
IV	10–30	>50	
V	0–10	>10	Thickness: generally more than 0.5cm.
VI	10–30	10–50	
VII	30–60	10–50	
VIII	60–100	10–50	
IX	100–300	10–50	
X	60–100	50–80	
XI	100–300	50–80	

As will be seen from Fig. 7, the distribution of unit types thus distinguished shows a unimodal pattern with the primary mode of type IV or V except for unit Mb_2 of facies α, in which the distribution is polymodal and has the primary mode of type III. The unimodal distribution exhibits a much stronger mode in unit Mb_1 of facies α and γ and Member Me of facies δ than in other sequences.

* Very sandy, coarse siltstone layers are to be dealt with as sandstone layers for the statistical analysis of the graded units, because the former also exhibit some of the sedimentary features characteristic of the latter.

** In addition, statistical analysis of sedimentary features was attempted for the following two sections: (1) about 8 m sequence of sandstone and shale in alternation (number of graded units: 72), lower part of unit Mb_1 of facies α, Takambetsu; (2) about 20 m sequence of bedded sandstone (number of graded units: 32), lower part of unit Mb_2 of facies α, Ikushumbetsu Valley. The data from the former section are not included in Tables 5, 6 and 7 and Figs. 8, 9, 10, 11 and 20.

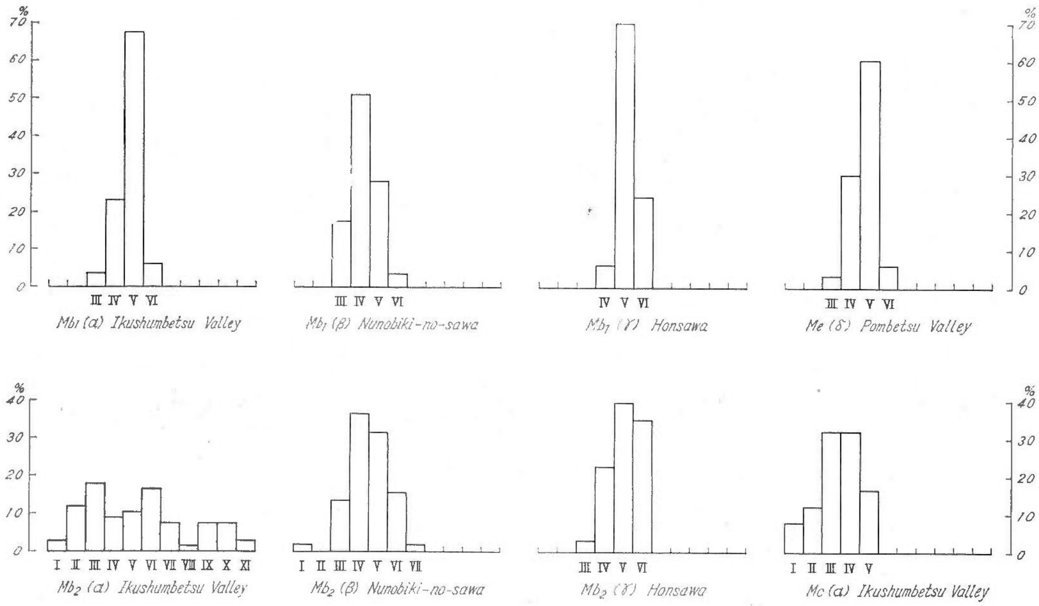


Fig. 7. Distribution of unit types.

IV. 2 Sequence Types

The graded units in the flysch series vary in degree of vertical change of their lithological features. To the ideal sequence of internal structures of the graded units in the studied area BOUMA's model of fivefold subdivision (BOUMA, 1962) can be applied with a slight terminological modification as follows:

From the top downwards

Shale layer

(e) Massive mudstone

(d) Laminated sandy mudstone

Sandstone layer

(c) Cross-laminated sandstone

(b) Laminated sandstone

(a) Graded sandstone

General account of the sedimentary features of the graded units is given in the lines to follow. To begin with, division *a* usually concentrates the coarsest grains at or near its base and occasionally contains contemporaneous shale fragments at any level, especially in its relatively upper part. Where materials are well sorted throughout, graded bedding is hardly visible in this division. Graded bedding, if still present, is finely developed in division *b* into which division *a* ordinarily grades. Below division *a* is rarely found a thin laminated part. Division *b* is characterized by parallel lamination throughout. Both division *b* and division *c* are finer grained than division *a*, the boundary between the former two divisions being often clear-cut. Division *c* occasionally shows current ripple lamination in association with cross-lamination and in some cases ends with current ripple marks. Convolute lamination is occasional in division *c* as well as in division *b*. Transition from division *c* into division *d* is gradual, but less commonly rapid. Division *d* consisting of siltstone which grades upwards into silty mudstone is commonly laminated, and graded though not distinctly. This division is interlaminated with very fine-grained sandstone which decreases upwards in frequency and thickness. In division *d* it is noticeable that, in addition to parallel lamination, cross-lamination and/or ripple cross-lamination is commonly developed; this division is equivalent to BOUMA's upper interval of parallel lamination (BOUMA, 1962), though the latter is devoid of cross-lamination. A similar situation is found in some other flysch deposits (BALLANCE, 1964; SNAVELY *et al.*, 1964; HUBERT, 1967). Thus the sandstone laminae in this division occasionally exhibit flaser structure. Division *e*, having a gradual boundary with the underlying division, consists of clayey mudstone showing no visible structures. Under the microscope, however, faint laminations can be occasionally observed in the division *e*. Furthermore, marlstone or clayey marlstone occurs, though only locally, as laminae or thin layers in shale layers constituting the graded units.

An ideal vertical sequence of internal structures of a single graded unit as mentioned above has been ascribed to waning velocity of a turbidity current by various authors, but is now more appropriately interpreted as reflecting change of flow regime represented by the integrated resultant of all variables (HARMS and FAHNESTOCK, 1965; WALKER, 1967). This is equally true of the Ikushumbetsu flysch. Concerning shale layers alternating with graded sandstones in many flysch deposits, a seemingly overwhelming opinion now is that shale layers are composed of turbidite sediments below and pelagic sediments above (CROWELL, 1955; DZULYNSKI *et al.*, 1959; NEDERLOF, 1959; UNRUG, 1963; SCOTT, 1966; WALKER, 1967). Actually, the shale layers constituting the graded units of the Ikushumbetsu flysch commonly exhibit a gradual transition from the underlying turbidite sandstone layers. Hence it is plausible that such shale layers, at least their lower parts, are of turbidity current origin. However, the occasional occurrence of thin-shelled, weakly ornated, comparatively inflated coiled ammonites in the shale layers may suggest the presence of some pelagic or hemi-pelagic sediments.

Considerable variation of sequence type, i.e. sequence of internal structures, is noticed in the graded units of the Cretaceous flysch formation (Table 4). Taken altogether, the graded units begin most commonly with division *a*. This situation is strikingly different from the distribution of sequence types in the flysch sediments of the Peïra-Cava area, Alpes Maritimes, France (BOUMA, 1962) in which the majority of the graded units begin with division *c*, although the thickness distribution of graded units is remarkably similar between the two cases (Table 5*). In addition, unlike BOUMA's sequence types (BOUMA, 1962, figs. 8, 9, 10, 11), the graded units in the studied area are occasionally lacking one or more intervening divisions. Similar occurrence was reported from the Upper Carboniferous turbidite formation of northern England in which division *d* is always absent (WALKER, 1966). Where division *a* is considerably thick division *c* is commonly lacking or very poorly developed as exemplified by the case of Member Mc of facies *α*, Ikushumbetsu Valley.

The distribution of the sequence types varies largely with stratigraphical unit and facies type (Table 4). For example, graded units beginning with division *a* are especially widespread in unit Mb_2 of facies *α* and Member Mc of

* From BOUMA's data sequences Td-e and Te (approximately 14.2 per cent of the observed cases) are omitted.

Table 4. Distribution of sequence types of graded units

For divisions a, b, c, d and e in graded units see text. For example, a graded unit of type abc consists of divisions a, b and c in ascending order.

Sequence type	Mb_1			Mb_2			Mc	Me of facies δ		
	Facies α	Facies β	Facies γ	Facies α	Facies β	Facies γ	Facies α	Division B	Division E	Division F
	Iku-shum-betsu Valley	Nuno-biki-no-sawa	Hon-sawa	Iku-shum-betsu Valley	Nuno-biki-no-sawa	Hon-sawa	Iku-shum-betsu Valley	Pombetsu Valley		
abcde	15.1	22.8	18.8	12.1	15.7	12.1	1.1	15.7	13.9	8.6
abcd	5.8	28.1	8.8	22.7	17.6	10.6	14.3	30.6	9.9	18.5
abce	2.3	5.3	—	3.0	2.0	1.5	—	—	5.0	3.7
abc	—	—	—	—	—	—	1.1	—	—	—
abde	—	3.5	2.5	10.6	13.7	—	1.1	4.5	3.0	9.9
abd	—	5.3	2.5	27.3	19.6	13.6	29.7	6.0	3.0	16.0
abe	—	—	—	—	—	—	—	—	1.0	4.9
ab	—	—	—	—	—	—	19.8	—	1.0	—
acde	—	—	1.3	—	—	—	—	0.7	1.0	1.2
acd	—	1.8	—	—	2.0	6.1	—	6.7	2.0	—
ace	—	—	—	—	—	—	—	—	2.0	—
ade	1.2	—	—	1.5	7.8	1.5	2.2	—	—	3.7
ad	—	1.8	—	10.6	3.9	—	13.2	0.7	1.0	6.2
ae	—	—	—	1.5	—	—	1.1	—	—	3.7
a	—	—	—	—	—	—	12.1	—	—	—
bcde	26.7	12.3	23.8	3.0	—	24.2	—	0.7	10.9	4.9
bcd	12.8	7.0	7.5	—	—	9.1	3.3	8.9	21.8	3.7
bce	8.1	3.5	—	—	—	—	—	—	6.9	2.5
bc	—	—	—	—	—	—	1.1	—	—	—
bde	3.5	1.8	10.0	3.0	—	1.5	—	—	3.0	—
bd	4.7	3.5	6.3	1.5	2.0	4.5	—	1.5	1.0	2.5
be	1.2	—	1.3	—	—	—	—	—	—	—
cde	8.1	1.8	11.3	—	2.0	10.6	—	2.2	6.9	3.7
cd	2.3	1.8	5.0	3.0	9.8	4.5	—	21.6	5.9	6.2
ce	8.1	—	1.3	—	3.9	—	—	—	1.0	—
Total	99.9	100.3	100.4	99.8	100.0	99.8	100.1	99.8	100.2	99.9
Beginning with a	24.4	68.4	33.7	89.4	82.4	45.5	95.6	64.9	42.5	76.5
Beginning with b	57.0	28.1	48.8	7.6	1.9	39.4	4.4	11.2	43.6	13.6
Beginning with c	18.6	3.5	17.5	3.0	15.7	15.1	—	23.9	13.9	9.9
Ending with e	74.4	50.9	70.0	34.8	45.1	51.5	5.5	23.9	54.5	46.9
Ending with d	25.6	49.1	30.0	65.2	54.9	48.5	60.4	76.1	44.5	53.1
Total number of graded units	86	57	80	66	51	66	91	134	101	81

Table 5. Comparison of thickness and sequence type of graded units from the Ikushumbetsu area with those from the Peira-Cava area, Alpes Maritimes

The data are given in percentages. For divisions a, b and c see text.

	Ikushumbetsu area	Peira-Cava area, Alpes Maritimes
Thickness (in cm)		
0–2	0.9	0.1
2–4	11.6	6.6
4–10	33.4	34.7
10–20	26.6	21.8
20–40	14.7	12.0
40–100	10.1	9.6
100–200	2.4	7.6
200–400	0.2	4.8
>400	—	2.9
Total	99.9	100.1
Sequence beginning with		
Division a	62.6	14.1
Division b	24.9	10.5
Division c	12.5	75.4
Total	100.0	100.0
Total number of graded units	850	910

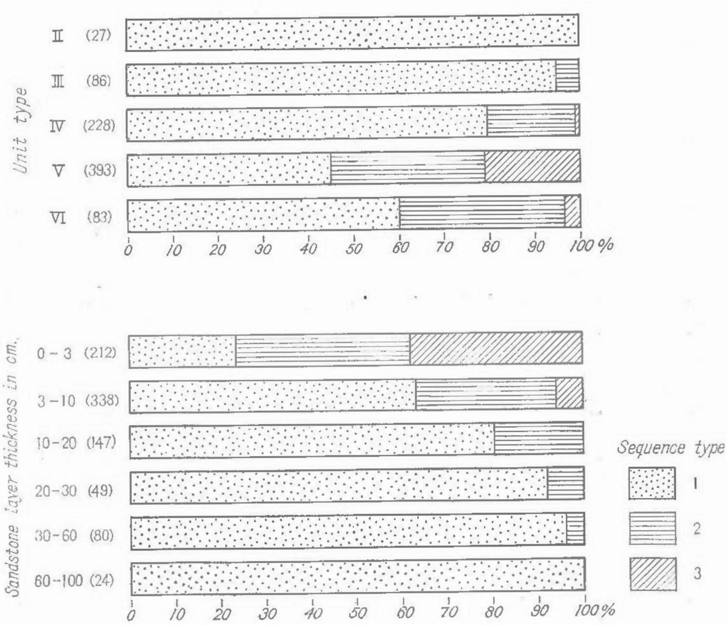


Fig. 8. Relation between unit type, sandstone layer thickness and sequence type.

1: graded units beginning with graded sandstone division.
2: graded units beginning with laminated sandstone division.
3: graded units beginning with cross-laminated sandstone division.
Numerals in parentheses are the number of graded units or sandstone layers in each class.

facies α in both of which the sandstone is comparatively thick and poorly laminated. In this connection, it is noteworthy that only a few units end with division *e* in Member Mc of facies α. On the contrary, in unit Mb_1 of facies α and γ which is dominated by thin, well-laminated sandstone the graded units begin more commonly with division *b* and end with division *e* than in other sequences. After all, from such striking contrasts of sequence types between Mb_1 of facies α and γ and Mc of facies α it may be suggested that the eroding power of turbidity currents was generally stronger and the sand-depositing currents were of higher velocity for Mc of facies α than for Mb_1 of facies α and γ. The graded unit in the laminated sandy mudstone sequences is, of course, commonly composed of divisions *d* and *e*. Furthermore, there is a definite correlation between the sequence type, unit type and sandstone layer thickness. That is to say, graded units beginning with division *a* decrease in abundance in the order of unit types II, III, IV and V and with decreasing thickness of sandstone layers (Fig. 8).

IV. 3 Some Notes on the Sedimentary Features

Each of the graded units constituting the flysch sequence shows usually, but not always, a sharp bottom contact which is undulating in varying degree, due to the presence of many kinds of sole markings, though occasionally even. The undulation of the lower contact of a sandstone layer against the underlying shale layer falls into three orders of magnitude according to its general amplitude which is given in parentheses: strongly undulating (more than 3 cm),

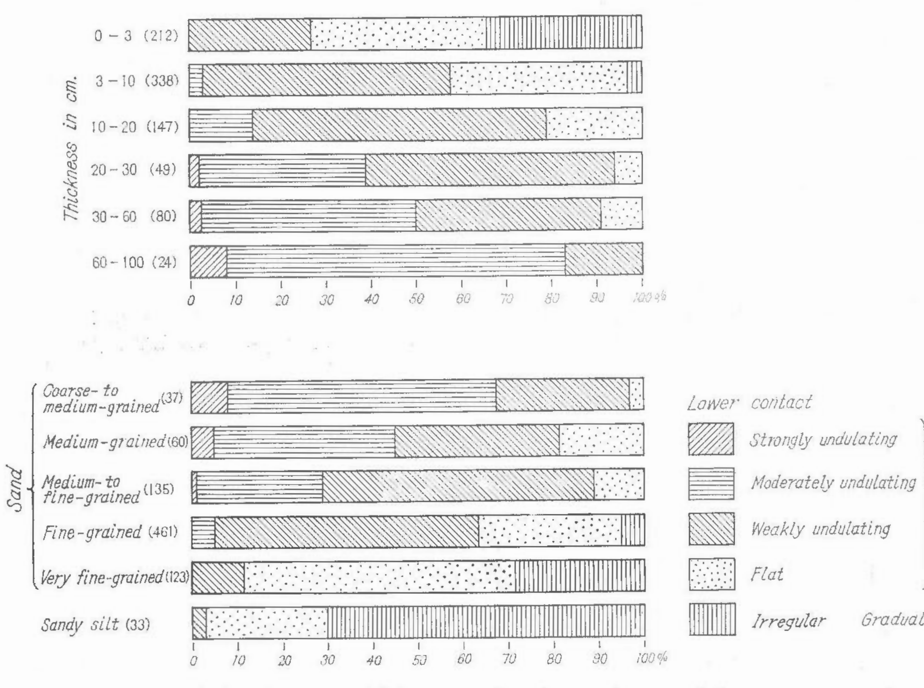


Fig. 9. Relation between thickness, grain size at base and lower contact of sandstone layers.

Numerals in parentheses are the number of sandstone layers in each class.

moderately undulating (1 to 3 cm) and weakly undulating (less than 1 cm). The underside of very thin sandstones occasionally exhibits irregular pattern, where the bed contact is gradual. Undulation of the lower contact has a marked tendency to become stronger with increasing thickness and grain size at the base of sandstone layers (Fig. 9). This trend is in harmony with the case of the Izumi Group (TANAKA, 1965). It may imply that swift currents depositing thick, coarse sandstones roughly eroded the mud substratum which, in turn, was subjected to intense load deformation due largely to rapid deposition of a series of such sandstones. However, in Member Mc of facies α along the Ikushumbetsu Valley the bottom contact is often weakly undulating in spite of the predominance of relatively thick, coarse-grained sandstone (Table 2). A probable explanation of this fact may be that the shale layers (mud floors) of this member were in some cases rather smoothed in erosion by fast currents and in other cases the layers were too thin and/or firm to suffer load deformation.

Passage from sandstone below to shale above is rapid in some graded units, but gradual in many others. In the former case the bounding surface is occasionally ripple marked; this point indicates that the top part of turbidite sandstone layers was reworked and sorted by bottom currents. Gradual transition tends to become more frequent in the order of unit types III, IV and V and with decreasing thickness and coarseness of sandstone layers. The higher

Table 6. Relation between unit type, sequence type, grain size at base and thickness of sandstone layers and gradual passage from sandstone layer to overlying shale layer in graded units The data are given in percentages. Numerals in parentheses are the number of graded units or sandstone layers in each class.

Unit type			
III	IV	V	VI
(76)	(216)	(388)	(83)
48.7	59.7	74.7	68.7

Basal division of graded units		
Graded sandstone	Laminated sandstone	Cross-laminated sandstone
(510)	(204)	(71)
58.8	68.1	88.6

Grain size at base of sandstone layers					
Sand					Sandy silt
Coarse- to medium-grained	Medium-grained	Medium- to fine-grained	Fine-grained	Very fine-grained	
(29)	(46)	(132)	(455)	(123)	(33)
55.2	47.8	43.9	65.5	84.5	100.0

Thickness of sandstone layers (in cm)					
0–3	3–10	10–20	20–30	30–60	60–100
(210)	(327)	(141)	(47)	(68)	(21)
78.1	67.2	53.8	53.2	45.5	42.8

the division where the graded units begin, the more prevalent becomes the gradational upper contact (Table 6).

Concerning the sandstone layers constituting the graded units, the following positive correlation is found between thickness, grain size at the base and thickness of graded division. The proportion of graded division to sandstone layer is extremely high in Member Mc of facies α, Ikushumbetsu Valley which is dominated by relatively thick, coarse-grained sandstone; it is exceedingly low in unit Mb_1 of facies α, Ikushumbetsu Valley which consists mostly of relatively thin, fine-grained sandstone (see Tables 2, 8). The thicker the sandstone layers, they become coarser grained at the bottom (Fig. 10) and the proportion of graded division to sandstone layer is higher (Fig. 11). These trends pertain largely to the velocity of the sand-depositing currents. A positive correlation between thickness and coarseness of sandstone layers is found also in the Izumi Group (TANAKA, 1965).

The shale layer of the graded unit is occasionally traversed by sand-filled burrows (exichnial burrow casts, MARTINNSON, 1965) and the sandstone laminae involved are disturbed thereby. Massive mudstone division is present in some graded units, but in others it, though originally deposited, is now missing

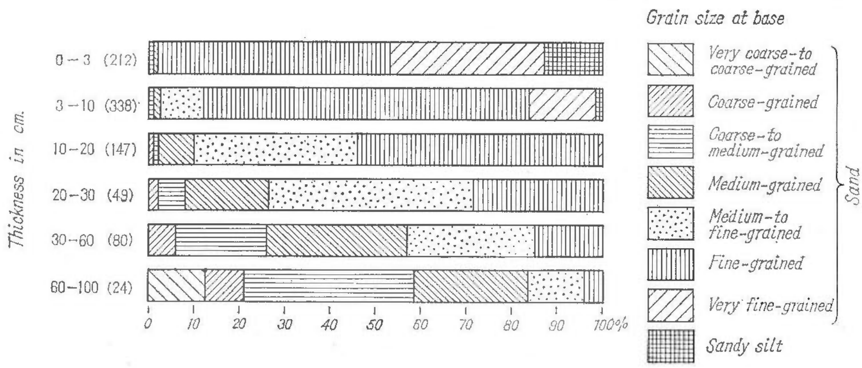


Fig. 10. Relation between thickness and grain size at base of sandstone layers.
Numerals in parentheses are the number of sandstone layers in each class.

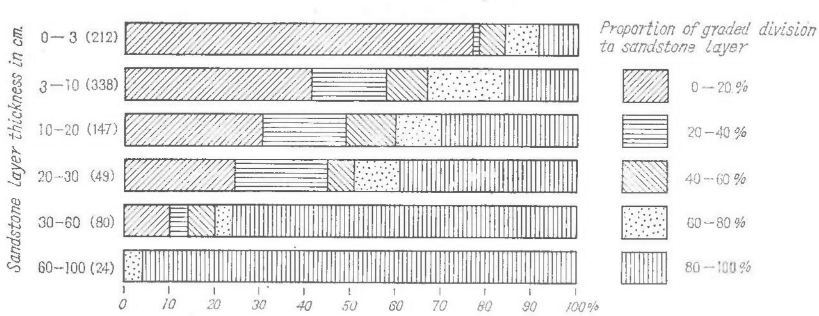


Fig. 11. Relation between sandstone layer thickness and proportion of graded division to sandstone layer.
Numerals in parentheses are the number of sandstone layers in each class.

Table 7. Relation between thickness of shale layers, grain size at base and thickness of overlying sandstone layers and presence of massive mudstone division at top of graded units

The data are given in percentages.

	Number	Presence of massive mudstone division
Thickness of shale layers (in cm)		
0–3	433	38.5
3–6	173	64.1
6–10	76	64.5
10–20	58	43.1
Grain size at base of overlying sandstone layers		
Coarse- to medium-grained sand	32	3.1
Medium-grained sand	50	28.0
Medium- to fine-grained sand	128	36.7
Fine-grained sand	441	40.1
Very fine-grained sand	121	56.2
Sandy silt	33	75.7
Thickness of overlying sandstone layers(in cm)		
0–3	194	50.5
3–10	334	46.2
10–20	145	37.2
20–30	46	19.6
30–60	69	26.1
60–100	20	5.0

Table 8. Thickness data from some selected sections in the
The standard deviations are given in parentheses.

	Mb_1			
	Facies α Ikushumbetsu Valley	Facies α Takambetsu	Facies β Nunobiki-no-sawa	Facies γ Honsawa
THICKNESS OF THE SECTION (IN M)	9.10	7.91	9.99	7.13
NUMBER OF GRADED UNITS	86	72	57	80
AVERAGE THICKNESS (IN CM)				
Graded unit	10.6(9.2)	11.0(10.4)	17.5(11.7)	8.9(4.7)
Sandstone layer	6.2(6.2)	8.5(10.1)	14.5(10.8)	3.9(2.3)
Shale layer	4.4(5.1)	2.5(1.7)	3.0(2.2)	5.0(3.7)
Graded sandstone division	0.4(0.7)	1.1(2.8)	5.2(6.4)	0.6(0.9)
Laminated sandstone division	3.7(4.8)	4.7(7.9)	7.8(7.0)	1.9(1.7)
Cross-laminated sandstone division	2.1(2.1)	2.7(2.0)	1.5(2.9)	1.4(1.1)
Laminated sandy mudstone division	2.2(4.0)	2.0(1.5)	2.1(2.0)	4.1(3.9)
Massive mudstone division	2.2(1.7)	0.5(0.9)	0.9(1.3)	0.9(0.9)
MAXIMUM THICKNESS (IN CM)				
Graded unit	57.0	56.0	53.0	28.0
Sandstone layer	29.0	49.0	50.0	12.0
Shale layer	28.0	7.0	10.0	20.0
AVERAGE SANDSTONE PERCENTAGE	54.5(18.3)	67.4(19.8)	78.1(15.6)	46.7(20.0)
AVERAGE DIVISION PERCENTAGE				
Graded sandstone division	3.0(7.5)	4.9(9.2)	26.7(24.9)	15.1(13.1)
Laminated sandstone division	28.7(20.1)	24.7(25.8)	34.3(24.2)	22.5(18.6)
Cross-laminated sandstone division	22.8(14.5)	38.2(23.4)	16.9(15.8)	17.5(16.0)
Laminated sandy mudstone division	21.6(19.3)	27.5(19.5)	15.0(13.4)	39.1(24.4)
Massive mudstone division	23.5(20.0)	4.8(7.9)	6.7(9.5)	11.4(10.5)

because of the erosion before the deposition of the overlying sandstone. Occurrence of this division tends to become commoner as the overlying sandstone layer decreases in thickness and grain size at the base (Table 7). A similar conclusion applies to the turbidite sequence of the Izumi Group (TANAKA, 1965). The shale layers in Member Mc of facies α, Ikushumbetsu Valley are mostly lacking in massive mudstone division, whereas those in unit Mb_1 of facies α, Ikushumbetsu Valley in the majority of cases are provided with this division (Table 2). Such a striking contrast depends largely on the before-mentioned distinct differences between the two sequences in thickness and coarseness of sandstone layers. Hence, it may be suggested that the turbidity currents from which relatively thin, fine-grained sandstones were deposited had a relatively small ability of scouring the pelitic substratum.

IV. 4 Thickness

The thickness data on the graded units from each member or unit in the Ikushumbetsu flysch sequence are given in Table 8. As to the thicknesses of the graded units, sandstone and shale layers and individual divisions within the graded units, generally speaking, the average values vary in accordance with the maximum ones, and the standard deviations are considerably large. The standard deviations are invariably smaller than the average values for the unit thicknesses. They are more commonly below the average values for the sandstone and shale layer thicknesses than for the division thicknesses. The standard

Cretaceous flysch sequence of the Ikushumbetsu area

Mb_2			Mc	Me		
Facies α Ikushumbetsu Valley	Facies β Nunobiki-no-sawa	Facies γ Honsawa	Facies α Ikushumbetsu Valley	Facies δ Pombetsu Valley		
				Division B	Division E	Division F
40.17	10.87	8.14	36.74	10.71	14.32	8.63
67	52	66	91	134	105	81
52.2(46.0)	20.9(20.0)	12.3(7.4)	40.4(36.5)	8.0(7.9)	13.6(9.3)	10.7(7.1)
30.8(27.1)	15.0(19.2)	5.7(5.4)	38.6(36.2)	6.5(7.4)	9.0(7.8)	8.4(6.4)
21.4(33.7)	5.9(5.7)	6.6(4.4)	1.8(2.6)	1.5(1.4)	4.6(3.6)	2.3(2.3)
26.6(27.3)	9.6(15.5)	0.9(1.4)	36.0(33.8)	3.7(2.4)	1.9(3.0)	4.6(4.5)
3.4(2.9)	4.1(6.6)	2.9(4.0)	2.2(3.1)	1.3(5.9)	5.1(6.5)	2.8(4.2)
0.8(1.1)	1.3(1.7)	1.9(1.8)	0.4(1.0)	1.5(1.2)	2.0(1.9)	1.0(1.2)
19.9(12.5)	4.9(5.8)	5.9(4.3)	1.7(2.6)	1.3(1.7)	3.8(3.5)	1.8(2.1)
1.5(2.7)	1.0(1.3)	0.7(0.8)	0.1(0.4)	0.2(0.3)	0.8(1.4)	0.5(0.7)
220.0	130.0	44.0	170.0	34.5	43.0	32.0
105.0	126.0	33.0	170.0	39.0	37.0	30.0
175.0	35.0	19.0	160.0	13.0	18.0	12.0
57.6(29.5)	65.1(21.2)	47.4(20.0)	91.5(13.2)	77.6(10.3)	63.1(20.6)	77.2(15.0)
44.9(29.7)	34.8(26.3)	9.1(13.6)	79.2(25.4)	29.6(26.9)	13.7(21.1)	39.1(28.7)
9.1(12.7)	16.4(16.9)	19.4(17.0)	10.0(16.1)	19.9(22.5)	30.8(28.9)	23.9(23.5)
2.8(5.0)	11.9(20.2)	16.2(13.6)	2.3(6.2)	28.0(25.5)	21.5(18.2)	14.1(21.7)
38.0(27.8)	28.9(21.5)	47.0(22.3)	8.0(12.0)	20.0(13.5)	28.5(20.1)	17.3(15.6)
4.9(10.0)	8.6(12.1)	5.4(6.6)	0.7(3.3)	2.2(4.7)	8.0(10.8)	5.9(7.1)

deviations of the layer and division thicknesses also tend to vary with the mean thicknesses and maximum ones. Furthermore, the standard deviations of the sandstone percentages together with those of the division percentages show comparatively high values. The former are always much smaller than the average values, while the latter occasionally exceed the average values.

Thickness distribution

The thickness distribution of graded units in any member or unit within the flysch deposits can roughly be deduced from the distribution of unit types classified in terms of both thickness and sandstone percentage of graded units (see Fig. 7). The thickness distribution of the sandstone layers shows a wider spread than does that of the shale layers with some minor exceptions (Figs. 12, 13). The distribution approaches a normal distribution in sequences consisting chiefly of thin sandstone layer (e.g. unit Mb_1 of facies γ and Member Me of facies δ), and seems to display a polymodal pattern in sequences dominated by relatively thick sandstone layer (e.g. unit Mb_2 of facies α and Member Mc of facies α). The histograms of the thickness distribution of both sandstone and shale layers tend to be skewed towards the greater thickness values. The skewed shapes of thickness distribution demonstrate that the sedimentary process of the flysch succession under consideration had a tendency to deposit more thin beds than thick.

The histograms of the shale thickness distribution are found to be more skewed than those of the sandstone thickness distribution if compared on the same scale. The probable explanation for this is that as already pointed out by KOLMOGOLOV (see NEDERLOF, 1959, fig. 7), owing to erosion by the turbidity currents depositing the interbedded sandstones the original thickness distribution of shale layers, which in an ideal case is expected to be a normal distribu-

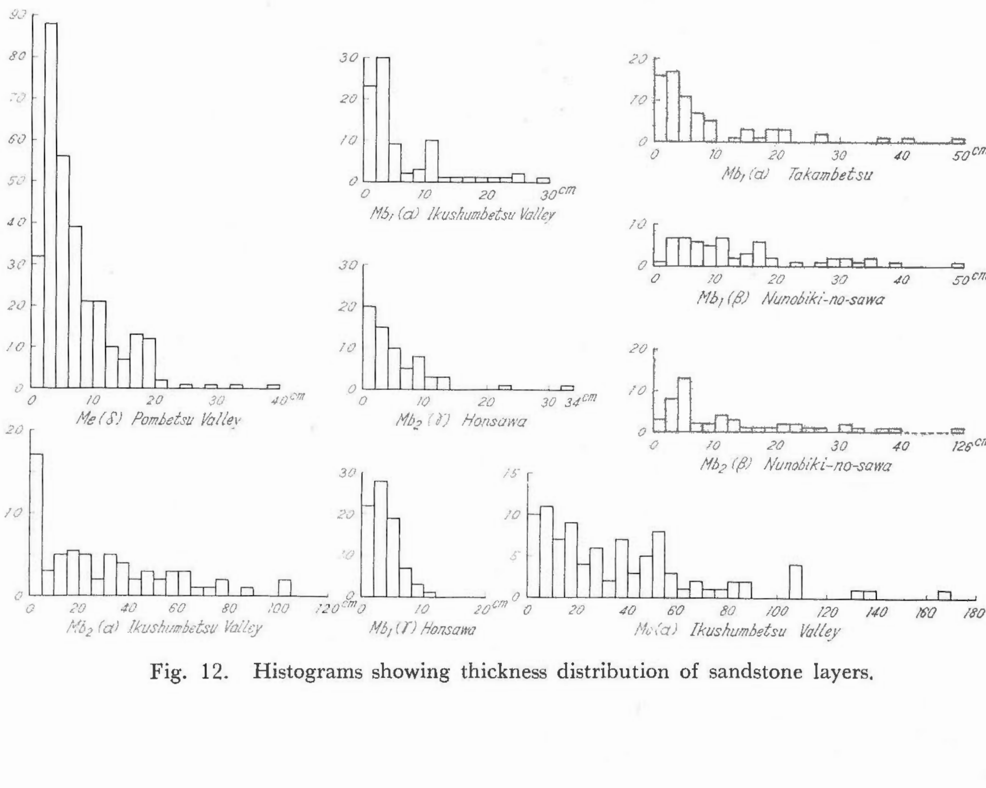


Fig. 12. Histograms showing thickness distribution of sandstone layers.

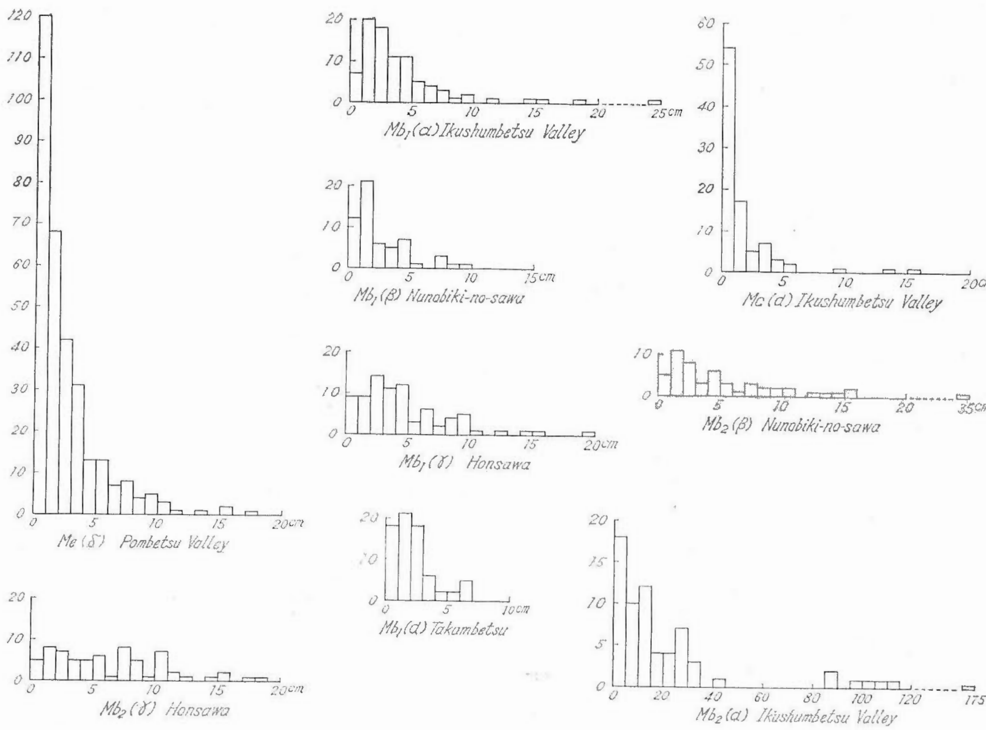


Fig. 13. Histograms showing thickness distribution of shale layers.

tion, was transformed towards the smaller thickness values. Thus, extremely skewed patterns of shale thickness distribution, as would be expected, result from frequent complete absence of shale layers due to erosion by turbidity currents. The best example will be the very strongly skewed shape for Member Mc of facies α, Ikushumbetsu Valley in which the shale layers end with massive mudstone division only in about 7 per cent of the observed cases and are often even missing between the successive sandstone layers. A similar, but less skewed distributional pattern is recognized also in Member Me of facies δ, Pombetsu Valley in which the shale layers have massive mudstone division in some 40 per cent of the observed cases. On the contrary, the thickness distribution of shale layers is similar to a normal one for unit Mb_1 of facies α, Ikushumbetsu Valley and that of facies γ, Honsawa. In the shale layers of these two sequences, massive mudstone division exists in about 70 per cent of the observed cases. An intermediate pattern is displayed in unit Mb_1 of facies β, Nunobiki-no-sawa in which this division is present in nearly 50 per cent of the observed cases. Similarly, the histogram of the shale thickness distribution in division E of Member Me of facies δ along the Pombetsu Valley shows a distribution close to a normal one in comparison with the cases of divisions B and F in which the graded units end less commonly with massive mudstone division than in division E (see Fig. 32; Table 2). From these facts described above, it may be considered that there is a close relationship between the distributional pattern of shale thicknesses and the presence of massive mudstone division and that the shale thickness distributions become closer to a normal distribution with increasing occurrence of massive mudstone division.

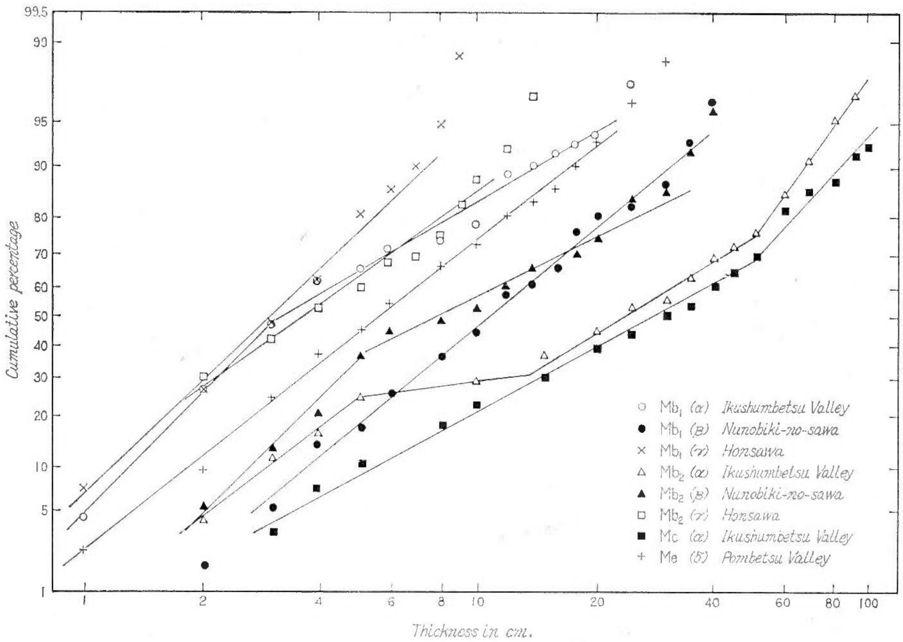


Fig. 14. Logarithmic probability distribution of sandstone layer thicknesses.

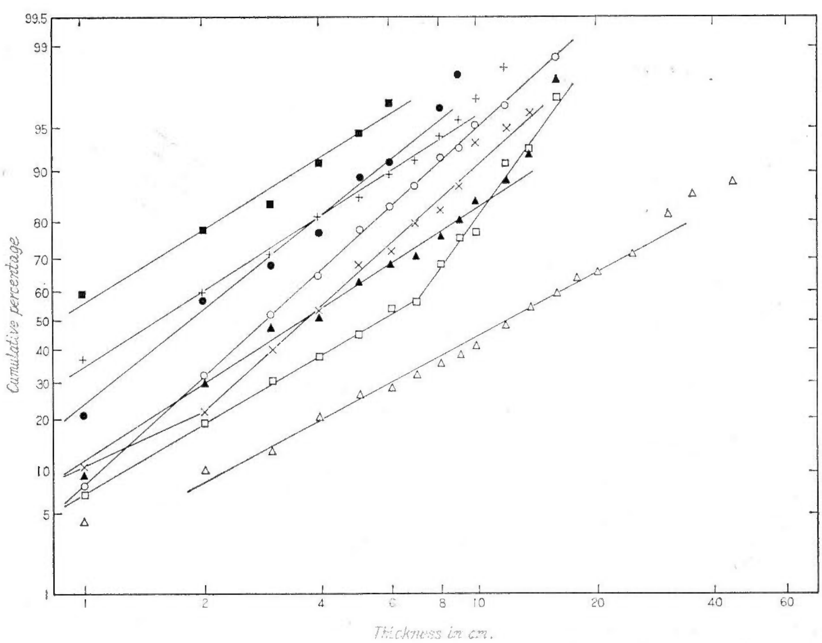


Fig. 15. Logarithmic probability distribution of shale layer thicknesses.
For legends see Fig. 14.

The cumulative frequency of the sandstone and shale thicknesses plotted on the logarithmic probability paper tends to show a log normality which is confirmed by an almost straight line (Figs. 14, 15). A similar relationship was noted for many other flysch-type deposits or turbidite sequences (BOKMAN, 1953; PETTIJOHN, 1957; NEDERLOF, 1959; WEBBY, 1959; MCBRIDE, 1962; DOTT, 1963; HIRAYAMA and SUZUKI, 1965; TANAKA, 1965; SCOTT, 1966). Such a log normal distribution may demonstrate that the sandstone and shale layers of any member or unit within the flysch series in question were deposited respectively from currents of similar origin. For thicker layers the plots of both sandstone and shale layers often exhibit a systematic deviation. This is interpreted as meaning that thicker layers occur at a frequency greater than could be expected if the distribution perfectly followed the log normality. While the data of the Izumi Group (TANAKA, 1965, figs. 8, 10) also displays a similar systematic deviation of sandstone and shale thicknesses, the reverse is the case with the data of the Carboniferous flysch of northern Spain (NEDERLOF, 1959, figs. 8, 9). The lowermost part of the plots also exhibits slight deviations from the log normality.

Some of the plots of sandstone and shale thicknesses are found to comprise two or more straight lines, thus indicating a mixture of two or more log normal populations. This point pertains to polymodal distribution of thicknesses. For instance, the plot of sandstone thicknesses for unit Mb_2 of facies α and Member Mc of facies α is broken at about 50 cm, thus consisting of two straight lines in its upper part. As would be expected, this results probably from differences

Table 9. Relation between grain size at base, type of graded bedding and thickness of sandstone layers in unit Mb_2 of facies α and Member Mc of facies α along the Ikushumbetsu Valley

The data are given in percentages. For types of graded bedding see text.

Grain size at base	Type of graded bedding	Mb_2		Mc	
		Thickness (in cm)		Thickness (in cm)	
		0-50	>50	0-50	>50
Very coarse- to coarse-, coarse- and coarse- to medium-grained sand	1	5.8	6.7	9.4	29.6
	2	—	—	6.3	—
	3 and 4	3.8	20.0	3.1	37.0
	5	—	—	—	—
Medium-grained sand	1	7.7	6.7	1.6	3.7
	2	—	—	3.1	—
	3 and 4	9.6	20.0	21.9	14.8
	5	1.9	—	—	—
Medium- to fine-, fine- and very fine-grained sand	1	19.3	6.7	12.5	—
	2	—	—	—	—
	3 and 4	36.6	13.3	28.1	—
	5	11.5	26.7	14.1	—
Sandy silt	4	3.8	—	—	—
Number of layers		52	15	64	27

in mode of deposition between the sandstones 50 cm thick or less and those more than 50 cm thick. That is to say, the sandstones of the latter group are coarse-grained and poorly graded in comparison with those of the former group (Table 9). Several other plots of sandstone thicknesses, on the other hand, are broken at certain small values such as 3 cm and 5 cm. The main, if not the only, reason for this is that the thinner sandstone beds may have been different from the thicker ones in mode of emplacement as inferred from, for example, the fact that the thinner beds begin much more commonly with laminated or cross-laminated division or show much lower percentage of graded division than do the thicker beds. The plot of sandstone thicknesses for unit Mb_2 of facies α indicates an abnormal shape in its lower part. This may be attributed to the small number of thickness samples in addition to the above-mentioned difference in mode of deposition. While the plot of sandstone thicknesses inclines gently in Mb_2 of facies α and Mc of facies α in which the sandstones over 50 cm thick are left out of consideration, it tends to incline steeply in some other sequences. This contrast implies that the sandstone thickness distribution of the former two sequences has a very wide spread about the mean. Furthermore, the steepest inclination of the plot of sandstone thicknesses for unit Mb_1 of facies γ indicates that the thicknesses are closely grouped about the mean as evidenced by the smallest value of standard deviation (Table 8).

The plot of shale thicknesses for unit Mb_1 of facies α is most steeply inclined and much more ideal than that for other sections, thus approaching a perfect log normality. The probable explanation for this is that the original thickness distribution of the shale layers was not so strongly transformed because of the small erosive power of the turbidity currents depositing the interbedded sandstones, as inferred from the most common occurrence of massive mudstone division. On the contrary, the most gentle inclination of the plot of shale thicknesses is found in unit Mb_2 of facies α whose thickness distribution is very wide about the mean. The plots of shale thicknesses for certain sections are broken at certain small thickness values.

The thickness of each division in the graded units was plotted on the logarithmic probability paper (Fig. 16*). Any division which occupies the uppermost part of a given graded unit is ignored, because it does not indicate the original thickness owing to erosion before the deposition of the overlying graded unit. The plots for the individual divisions have a tendency to exhibit an essentially log normal distribution as defined by an almost straight line. A similar relationship is recognized in Prealpine flysch of Switzerland (HUBERT, 1967). The plots for the studied area, however, occasionally show deviations from the log normality in their lowermost and uppermost parts. In addition, it is found that the plots for graded sandstone division in unit Mb_2 of facies α and Member Mc of facies α are found to comprise two straight lines joined at a certain large value of thickness. Such a pattern is closely similar to the aforesaid pattern of cumulative frequency of the sandstone layer thicknesses in these two sections, because the proportion of graded division to sandstone layer is very high.

Sandstone-shale thickness correlation

Some correlation in thickness is occasionally found between the sandstone

* The data based on a small number of thickness samples are omitted from Fig. 16.

Table 10. Thickness correlation of sandstone and shale layers
Numerals in brackets are the number of sandstone or shale layers.

			Upper limit of thicknesses dealt with (in cm)		Correlation coefficient	
			sand-stone	Shale	Sandstone-overlying shale	Sandstone-underlying shale
Mb_1	Facies α Ikushumbetsu Valley		15	10	0.498 (P<0.001) [74]	−0.208 [73]
	Facies α Takambetsu		15	10	0.292 (0.05>P>0.02) [60]	−0.019 [58]
	Facies β Nunobiki-no-sawa		15	10	−0.164 [37]	−0.087 [37]
	Facies γ Honsawa		15	10	0.023 [75]	0.202 [74]
Mb_2	Facies α Ikushumbetsu Valley		70	40	−0.048 [53]	0.035 [53]
	Facies β Nunobiki-no-sawa		25	15	0.126 [41]	0.072 [42]
	Facies γ Honsawa		15	15	0.108 [60]	0.419 (0.01>P>0.001) [59]
Mc	Facies α Ikushumbetsu Valley		60	6	−0.257 (0.05>P>0.02) [72]	0.003 [71]
Me	Facies δ Pombetsu Valley	Division B	15	10	0.424 (P<0.001) [114]	0.125 [112]
		Division E	15	10	0.218 (0.05>P>0.02) [83]	0.053 [80]
		Division F	15	10	0.234 [67]	−0.163 [67]

layer and the overlying or underlying shale layer (Table 10). No systematic relation is recognized between the correlation coefficient for sandstone-shale thickness, the average sandstone thickness, the average sandstone percentage and the presence of massive mudstone division in shale layer. However, Member Mc of facies α with the largest average value of sandstone thicknesses and sandstone percentages shows a markedly negative correlation between the sandstone thickness and the overlying shale thickness. In strong contrast with this member, units Mb_1 and Mb_2 of facies γ, both being characterized by the smallest average value of sandstone thicknesses and sandstone percentages, have comparatively high positive values for sandstone-underlying shale thickness correlation. On the other hand, high positive values of sandstone-overlying shale thickness correlation are found in unit Mb_1 of facies α and Member Me of facies δ which are extremely similar to each other in sedimentary aspects. These values are considerably high in comparison with the data of the Cretaceous flysch of southern Chile (SCOTT, 1966). It may be possible to distinguish Mb_1 of three separate facies from one another in terms of the values of correlation coefficient for sandstone-shale thickness. Furthermore, for certain three divisions within Member Me of facies δ the sandstone-overlying shale thickness correlation has much higher positive values than do the sandstone-underlying shale thickness correlation.

IV. 5 Lithological Classification based on Types of Graded Units

The flysch and associated deposits in the studied area are lithologically classified into various types according to their component unit types as in the case of the Izumi Group (TANAKA, 1965). The lithological types thus discriminated are shown in Table 11.

Table 11. Lithological classification of flysch and associated sediments according to unit type

Lithological division			Symbol	Graded units	
				Principal type	Subordinate type
Sandstone and shale in flysch-type alternation and associated sediments	Massive sandstone		S_0 S_1	0	I
		Very thick-bedded sandstone	S_2	I	II
		Thick-bedded sandstone	S_3	II	I and III
	Sandstone being predominant	Sandstone and shale in medium-bedded alternation	SM_1	III	II and IV
		Sandstone and shale in thin-bedded alternation	SM_2	IV	III, V and VI
		Sandstone and shale in very thin-bedded alternation	SM_3	V	IV and VI
	Shale being predominant or both being equal in amount	Shale and sandstone in thin-bedded alternation	MS_1	VI	IV, V and VII
		Shale and sandstone in medium-bedded alternation	MS_2	VII	VI and VIII
		Shale and sandstone in thick-bedded alternation	MS_3	VIII	VII and X
		Shale and sandstone in very thick-bedded alternation	MS_4	IX	VIII and X
	Sandstone being predominant	Sandstone and shale in thick-bedded alternation	Sm_1	X	VIII and IX
		Sandstone and shale in very thick-bedded alternation	Sm_2	XI	IX and X
	Shale		M	Thin beds or layers of sandstone are sporadically intercalated. Sandstone percentage is less than 10 per cent.	

Among the lithological types sm_1 and sm_2 which belong to sandy flysch* occur only in a very limited amount throughout the flysch formation in the present area. Sandy flysch-type sediments (S_1, S_2 and S_3) are widespread in Member Mc of every facies and Member Me of facies α, β and γ. In general, the sandstones of S_1 and S_2 types are comparatively coarse-grained and show no or little

* Flysch deposits are divided into three types of facies on the basis of their sandstone-shale ratio: sandy, normal and shaly flysch (VASSOEVIC, 1957).

graded bedding and lamination both of which are in a greater or lesser degree developed in the sandstones of S_3 type. The sandstones that are referred to as the bedded sandstones mentioned before are of S_2 and S_3 types. Normal flysch-type deposits are indicated by SM_1, SM_2 and part of SM_3. SM_1 is characteristic of unit Mb_2 of facies α and Member Mc of facies α, and SM_2 is typical of unit Mb_1 of facies α and Member Me of facies δ in particular. In the sandstones constituting SM_1 and SM_2 graded bedding and lamination are the most common internal structures. In addition, the sandstones of SM_2 are in some cases characterized by the exclusive occurrence of lamination as in those of SM_3 which are generally fine-grained. Referred to shaly flysch-type sediments are MS_1, MS_2, MS_3, MS_4 and part of SM_3 the first of which is most prevalent. MS_3 and MS_4 are uncommon throughout the flysch sequence. MS_1 is dominant in unit Ma_3 of facies α and Md_3 of facies δ. In the normal flysch-type deposits some sandstones are well laminated, but others are poorly laminated.

V. Inorganic Sedimentary Structures

The sandstone layers of the Ikushumbetsu flysch abound in various types of inorganic sedimentary structures which are characteristic of, but not always restricted to, turbidite sandstones. These structures observed fall into three

Table 12. Distribution of inorganic and biogenic sedimentary structures

Double circles: abundant, very frequent or very well developed; open circles: common, frequent or well developed; open triangles: scarce, occasional or poorly developed; crosses: rare, very occasional or very poorly developed. Local occurrence is given in parentheses. α, β, γ and δ show types of facies.

Sedimentary structures	Ma_3			Mb_1			Mb_2			Mc			Md		Me		
	α	β	δ	α	β	γ	α	β	γ	α	β	γ	α	δ	α	γ	δ
Flute casts	×	×	×	○	○	○	◎	○	○	◎	×	×	×	△	×		◎
Longitudinal furrows and ridges				×			×										×
Groove casts	×	×		×	×	×	◎	×		×	×	×		×			×
Bounce casts					×		△			×					×		×
Prod casts							×			×							×
Brush casts														×			×
Striation casts	×	×		△	△	△	◎	△	△	○	×			△			○
Frondescent casts							×										
Load casts	×	×		△	△	×	◎	△	×	△				△			○
Graded bedding	×	○	×	△	◎	×	◎	△	×	○	(×)	(×)	×	×	(×)	(×)	△
Parallel lamination	○	○	○	◎	◎	◎	△	○	◎	×	(×)	(×)	×	○	(×)	(×)	◎
Cross-lamination	○	○	○	◎	◎	◎	△	○	◎	×	(×)	(×)	×	○	(×)	(×)	◎
Current ripple lamination		×		△	△	×	△	×	×	×				×		(×)	×
Wavy lamination				×	×	×	×	×	×	×				×			△
Convolute lamination				×	△	×	×	×	△	×				×		(×)	×
Parting lineation				○	○	△	×	○	×					×			◎
Slump structures										×							×
Current ripple marks				△	×		×	×		×							△
Tracks and burrows	◎			○			△			△			○		◎		

groups: sole markings, internal structures and top surface structures. Distribution of the sedimentary structures, whether inorganic or biogenic, vary with lithofacies or properties of sandstone layers from member to member and from place to place (Tables 2, 12).

V. 1 Sole Markings

The sole markings on the bottom surface of the sandstone layers in the flysch series include a wide variety of pre-depositional to post-depositional casts*. Among the most prevalent sole structures are flute casts and load casts. Striation casts and groove casts also are common. Any member or unit is dominated by certain types of sole markings which have characteristic sizes and shapes, although larger or smaller variation occurs from sole to sole.

Flute casts

Flute casts are elongated ridges which have a relatively rounded or bulbous termination upstream and fade away downstream (Plate III-1; TANAKA *in* MATSUNO *et al.*, 1964, plate 3). These casts are widespread in unit Mb_2 of facies α and Members Mc of facies α and Me of facies δ. Flute casts become abundant in occurrence as the thickness of sandstone layers increases. They are rare on sandstones less than 3 cm thick. The structures described here are more

Table 13. Relation between thickness, grain size at base and type of graded bedding of sandstone layers and presence of sole markings

The data are given in percentages. Numerals in parentheses are the total number of sandstone layers with each type of sole markings. For types of graded bedding see text.

	Number of soles exposed	Flute casts	Groove casts	Striation casts	Load casts
Thickness (in cm)					
0–3	49	2.0	2.0	—	2.0
3–10	148	19.0	3.4	11.5	17.6
10–20	84	29.8	6.0	20.3	31.0
20–30	31	38.7	6.5	16.1	51.6
30–60	54	35.2	25.9	16.7	38.9
60–100	20	40.0	20.0	15.0	55.0
		(93)	(31)	(51)	(100)
Grain size at base					
Coarse- to medium-grained sand	29	20.7	24.1	10.3	48.3
Medium-grained sand	35	31.4	25.7	14.3	37.2
Medium- to fine-grained sand	89	37.1	10.1	15.7	39.4
Fine-grained sand	213	18.3	3.3	12.7	18.8
Very fine-grained sand	16	—	—	—	—
		(89)	(32)	(49)	(102)
Type of graded bedding					
1	64	32.8	23.4	23.4	
2 and 3	80	35.0	10.0	10.0	
4 and 5	246	17.9	3.7	10.2	
		(93)	(32)	(48)	

* Although the objects on sandstone sole should be called *moulds* (DZULYNSKI and WALTON, 1965), the term *casts* that is very commonly used in the literature is employed here in the terminology of sole markings.

commonly developed on the bottom surface of relatively coarse-grained or well-graded sandstone beds than on that of relatively fine-grained or poorly graded ones (Table 13). They are occasionally met with on the sole of sandstones which are more than 1 m thick and coarse-grained or very coarse-grained at the base.

As to the shapes of the flute casts of the Ikushumbetsu area, they are of four basic types in plan view: linguiform (Plate III-I), spatulate-shaped (comparable to elongate-symmetrical type), fan-shaped (comparable to conical or triangular type) and bulbous (cf. DZULYNSKI and WALTON, 1965, fig. 27), the last type being very rare. Linguiform and spatulate-shaped casts are generically called here elongated forms. Linguiform casts are by far the most dominant type. The shape of the flute casts seems to bear no definite relation to the thickness and coarseness of the sandstone layers under which the casts occur (Fig. 17). It, however, may be pointed out that the flute casts are apt to be linguiform or spatulate-shaped where sandstones carrying the structures are comparatively thick, say, 60 to 100 cm or coarse- to medium-grained at the

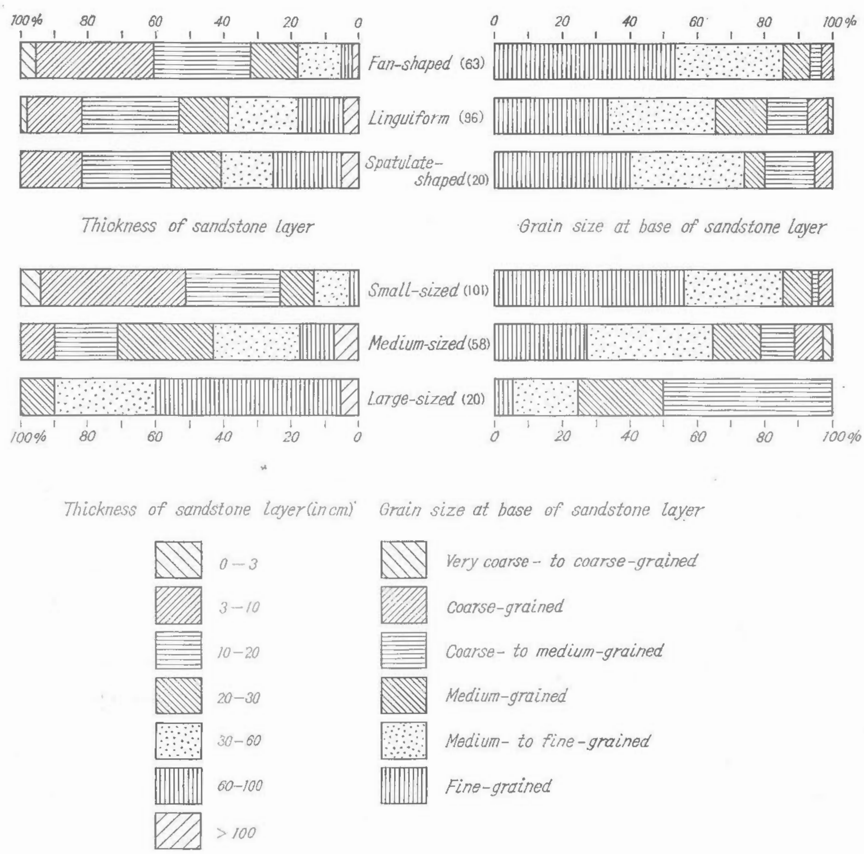


Fig. 17. Relation between shape and average size of flute casts and thickness and grain size at base of sandstone layers.

Very large-sized casts are included in large-sized ones.
Numerals in parentheses are the number of sandstone layers with flute casts.

base (Fig. 17). Elongated forms are widespread in Mb_2 and Mc of facies α in comparison with Mb_1 of facies α and Me of facies δ in which flat, fan-shaped casts are predominant. The casts in unit Mb_2 of facies α are commonly of cork-screw type, showing spiral twisting at the up-current end. Superimposed casts that show closely spaced overlapping arrangement occur generally on the soles of relatively thick, coarse-grained sandstones.

The size of the flute casts of the studied area varies over a wide range, thus falling into five classes as follows (the length is given in parentheses): giant- (more than 30 cm), very large- (10 to 30 cm), large- (5 to 10 cm), medium- (2 to 5 cm) and small-sized (less than 2 cm; more than 0.5 cm). The ratio of width to length is, roughly speaking, 1 : 4 (or 5) to 1 : 1. Small-sized forms are most dominant. The smaller flute casts tend to occur on the bottom of relatively thin, fine-grained sandstone layers, while the larger casts on the bottom of relatively thick, coarse-grained ones (Fig. 17). A quite similar situation is found in other flysch sediments (McBRIDE, 1962). The maximum size of flute casts is 5 cm for unit Mb_1 of facies α, 20 cm for unit Mb_2 of facies α, 15 cm for Member Mc of facies α and 8 cm for Member Me of facies δ. Thus, it is evident that the maximum size is larger in sequences dominated by relatively thick, coarse-grained sandstone than in sequences consisting chiefly of relatively thin, fine-grained sandstone. Actually, large- and very large-sized casts also are characteristic of Mb_2 of facies α.

In the light of the result of RÜCKLIN's experiments (RÜCKLIN, 1938) it may be suggested that the aforesaid difference in size and shape or features of the flute casts depends largely on the flow conditions, e.g. velocity and turbulence of the sediment-laden turbidity currents and the consistency and cohesion of the mud floor on which the flutes were cut. On the assumption that the eroded mud substratum was uniform, the large elongated forms of the Ikushumbetsu area are regarded as having been produced by fast, strongly turbulent currents which had great erosive power. However, it seems that the shape of the flute casts was not so largely influenced by the flow conditions as was the size. Similarly, it is considered by DZULYNSKI and SANDERS (1962) that flow conditions were responsible largely for the kinds of current marks and the type of mud bottom secondarily influenced the shape of marks.

Longitudinal furrows and ridges

Longitudinal furrows and ridges are composed of closely spaced, continuous ridges separated by furrows. They are occasional in the flysch sequence. The structures described here are of two types: one is referred to as furrow casts which grade into furrow flute casts (McBRIDE, 1962; Plate VI-1), and the other to as ridge casts (BOUMA, 1962; Plate III-2).

Some show parallel patterns in which up-current bifurcation of the ridges is uncommon and its angle is generally some 10 degrees; others show distinct dendritic patterns, their bifurcating angle occasionally attaining to about 30 degrees (Plate III-2). The ridges range from 0.3 to 2.5 cm in width; the furrows in between are one to several milimetres in width. The sandstone layers under which these structures occur are 30 to 60 cm thick and medium-grained or medium- to fine-grained at the base. The relatively small-scale structures with ridges less than 1 cm wide are found restricted to the underside of sandstones which are comparatively fine-grained at the base. The structures described here occasionally occur in association with small- to medium-sized flute casts or groove casts on the same sole. It is accordingly conceivable that the flow conditions (e.g. velocity and turbulence) were quite similar for the formation of the structures in question and the small- to medium-sized flute casts and groove casts.

Groove casts

Groove casts are rectlinear ridges of slight relief which are parallel to the current (Plate IV-2; TANAKA *in* MATSUNO *et al.*, 1964, plate 4). They are particularly widespread in unit Mb_2 of facies α. Groove casts are more dominant on the base of relatively thick, coarse-grained sandstone layers than on that of relatively thin, fine-grained ones as is the case with the flute casts (Table 13). However, so far as the available data from the flysch sequence studied are concerned, the groove casts are found to have a stronger tendency to occur on relatively thick, coarse-grained sandstone beds than the flute casts (Table 13). The tendency just referred to is not in accord with some author's views that flute casts in general were produced by a faster current flow than groove casts (HSU, 1959; MCBRIDE, 1962, 1966). This discrepancy may depend largely on the thickness distribution of the sandstone layers investigated and the size distribution of the flute casts and groove casts observed. Nevertheless, it should be noted here that as far as the studied area is concerned, unlike the flute casts, the groove casts do not occur on the sole of sandstones which are more than 100 cm thick or coarse- and very coarse-grained at the base. In addition, groove casts are more commonly met with on well-graded sandstones than on poorly graded ones (Table 13). They exhibit a marked tendency to occur on well-graded sandstones in comparison with the flute casts (Tables 13, 14). A similar conclusion was offered by some authors (HSU, 1959, 1960; PLESSMANN, 1961).

Table 14. Relation between sandstone layers with flute casts, those with groove casts and type of graded bedding of sandstone layers

The data are given in percentages. For types of graded bedding see text.

	Number	Type of graded bedding		
		1	2 and 3	4 and 5
Sandstone layers with flute casts	179	15.1	31.3	53.6
Sandstone layers with groove casts	51	33.3	27.4	39.2

Groove casts are crowded or closely spaced on the lower bedding plane of some sandstones (Plate IV-2). These structures in unit Mb_2 of facies α are commonly marked with longitudinal ridges and striations throughout the length (Plate IV-2). Groove casts rather commonly occur in association with flute casts on the same sole. However, there seem to be no cases where groove casts of closely spaced type and superimposed flute casts coexist with one another on the same sole. The groove casts on occasion form two, exceptionally three, sets intersecting at an acute angle up to about 30 degrees, of which one is parallel to the flute casts indicating the primary orientation on the same sole. In a few cases groove casts are cut by flute casts, which means that the former was formed earlier than the latter. A similar age relation of groove casts and flute casts has already been noted by KUENEN (1957a) and TEN HAAF (1959a).

The size of the groove casts observed varies over a wide range, thus falling into five classes as follows (l, length; w, maximum width): giant- (l, several metres or more; w, more than 10 cm; not yet found in the studied area), very large- (l, several metres; w, 5 to 10 cm), large- (l, several metres; w, 1 to 5 cm), medium- (l, 30 cm to several metres; w, 0.1 to 1 cm) and small-sized (l, 3 to 30 cm; w, 0.1 to 1 cm). The height ranges from 0.1 to 1 cm or more, in some cases as much as several centimetres being accentuated by subsequent load casting. Small-sized casts are found most commonly in the flysch series; large- and very large-sized casts are characteristic of unit Mb_2 of facies α. The maximum width of the casts is 0.2 cm for unit Mb_1 of facies α, 7 cm for unit Mb_2 of facies α, 1 cm for Member Mc of facies α, and 0.3 cm for Member Me of facies δ. There is a marked tendency that the smaller casts occur on relatively thin, fine-

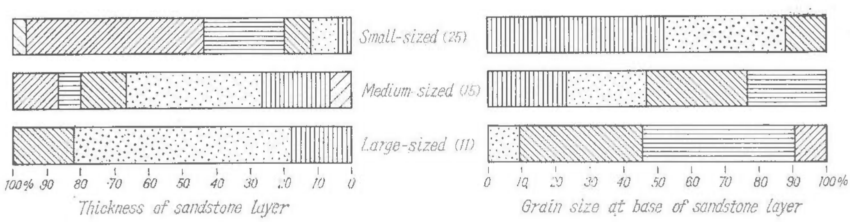


Fig. 18. Relation between average size of groove casts and thickness and grain size at base of sandstone layers.

For legends see Fig. 17.
Very large-sized casts are included in large-sized ones.
Numerals in parentheses are the number of sandstone layers with groove casts.

grained sandstone beds and the larger casts on relatively thick, coarse-grained sandstone beds (Fig. 18). As mentioned before, such a positive correlation between the size of the casts and the thickness and coarseness of the sandstone layers concerned is recognized in the flute casts as well. Thus, we reach a conclusion that both flute casts and groove casts of the same order of size are apt to occur on sandstones having similar thicknesses and grain sizes.

Bounce casts

Bounce casts are short ridges, parallel to the current, which fade away in both up-current and down-current directions (Plate V-1). Apart from minute casts, less than 1 cm long, that constitute striation casts to be described later, they are not common throughout the flysch sequence in this area. The bounce casts in some cases are associated with groove casts of a small size on the same sole.

These structures are as a general rule less than 3 cm, but exceptionally attain to 5 cm in length and range from 0.2 to 1 cm in width. The longer, more slender forms bear a close resemblance to short groove casts in appearance and grade into the latter. The sandstone layers carrying bounce casts, as is generally the case, are less than 20 cm thick and fine-grained or fine- to medium-grained at the base. The small-sized groove casts mentioned before are also most common on similar sandstone layers. These facts may suggest that the bounce casts, roughly speaking, were formed under the flow condition similar to that producing the small-sized groove casts.

Prod casts

Prod casts are short ridges running parallel to the current. They deepen downstream and abruptly disappear upstream, in contrast to flute casts (Plate V-2). In the great majority of cases they are slightly curved sideways at the downstream end. These casts are occasional in the studied area. The structures to be described are generally 3 to 5 cm in length and 0.3 to 0.6 cm in width, but an exceptionally large form attains to 15 cm long and 3.5 cm wide.

The prod casts tend to occur on the sole of sandstone layers that are less than some 20 cm thick and medium- to fine-grained or fine-grained at the base. Accordingly, it can be pointed out that the sandstones with such structures are quite similar in thickness and coarseness to those with bounce casts or small-sized groove casts. This conclusion demonstrates a similarity of flow condition for the formation of these three types of structures. Furthermore, minute forms, several milimetres long, together with bounce casts of such a scale, occur in myriads all over the sole, thus constituting striation casts described below.

Brush casts

Brush casts are short ridges with crescent depressions at the down-current end (Plate VI-1). They are scarce in this area and are 1.2 to 3 cm long and 0.7 to 2 cm wide near the down-current extremity.

Striation casts

Striation casts*, parallel to the current, consist of minute bounce casts, prod casts and allied structures, occurring in groups over the entire bottom surface. They are of common occurrence in the flysch succession. The individual structures constituting the striation casts are represented by faint scratches which are less than 1 cm long and less than 0.1 cm wide. Striation casts occur in common association with small-sized flute casts and groove casts on the same sole.

There is no systematic relation between the occurrence of the striation casts and the thickness and grain size of the sandstone layers, although prominent casts are not developed on very thin, very fine-grained sandstones (Table 13). Flute casts and groove casts coexisting with striation casts, however, are commonly of small size. Therefore, it can be pointed out, as would be expected, that the sandstone layers with striation casts are apt to be thinner and finer grained than those carrying flute casts or groove casts in general (Table 13). Furthermore, striation casts more commonly occur on the underside of well-graded sandstones than on that of poorly graded ones (Table 13).

Frondescent casts

Frondescent casts consist of a group of crowded ridges which are elongated, bifurcated downstream and crenulated at the edge, thus presenting an appearance of large leaves (Plate VI-2). They are encountered on only one sandstone sole, having a length of some 20 cm. The structures to be described are associated with flute casts on the same sole and are elongated in the direction

* The term *striation casts* (PETTIJOHN, 1957) was abandoned by DZULYNSKI and WALTON (1965) but has been adopted in some works (BOUMA, 1962; POTTER and PETTIJOHN, 1963; PETTIJOHN and POTTER, 1964).

of the latter. Hence, it may be supposed that the frondescent casts were largely of pre- to syn-depositional formation rather than post-depositional formation, although the casts have somewhat higher relief than the associated structures.

Load casts

Load casts are irregularly shaped swellings formed by differential downward sagging of sediment (e.g. sandstone) into the underlying sediment (e.g. shale). Load casts are one of the most widespread sole markings throughout the flysch series of the Ikushumbetsu area. They are well developed in unit Mb_2 of facies α in which the shale layers as well as the sandstone layers are comparatively thick. Load casts are not common where sandstones are thin, say, less than 10 cm or fine-grained at the base (Table 13).

In some cases load folds (SULLWOLD, 1959), load waves (SULLWOLD, 1959) and deformed internal structures (e.g. laminations) in load pockets (SULLWOLD, 1959) are well developed as outstanding phenomena resulting from load casting (Figs. 19, 22). The load waves (or flame structures) oriented in the same preferred direction as the current marks on the same or adjacent sandstones

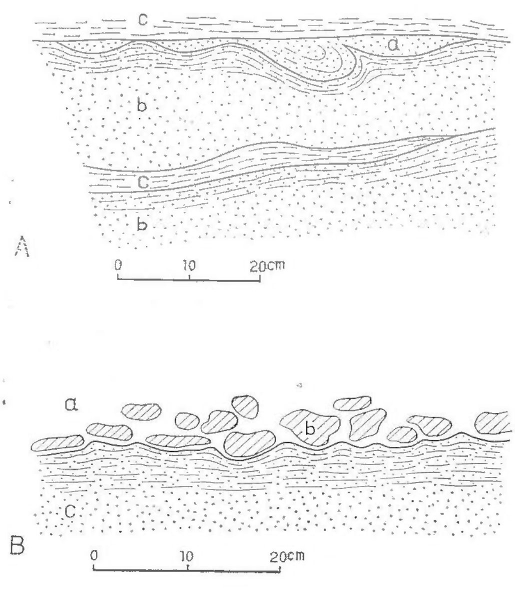


Fig. 19. Rough sketches of load casting.

A. Load casting at the base of a sandstone layer. Unit Ma_3 of facies β, Middle Yezo Group, Nunobiki-no-sawa.

a: sandstone.
b: sandstone (upper part being laminated).
c: laminated sandy mudstone.
The sole markings on adjacent sandstones indicate currents from right to left.

B. Load casting at the base of a pebbly mudstone bed. Unit Ma_2 of facies β, Middle Yezo Group, Nunobiki-no-sawa.

a: chaotically mixed sandy siltstone containing pebbles of exotic origin.
b: reworked calcareous siltstone which originally occurred somewhere as concretions.
c: sandstone (upper part being laminated).

indicate lateral displacement due to curernt drag (Figs. 19A, 22). The load casts observed differ greatly in size and shape from sole to sole, but are much the same on the same sole. They are of two types. One is pure load casts that are not connected with earlier sole markings, thus indicating no preferred orientation; the other is load casts produced from directional current marks as indicated by flute-load-casts and groove-load-casts (KELLING and WALTON, 1957) which are common in unit Mb_2 of facies α. It, however, is a matter of course that there are a variety of intermediate forms. For example, the finely-textured, oriented load casts in Member Me of facies δ, Pombetsu Valley (Plate VII-2) may have owed their origin to pre-existent flute casts, although they cannot be clearly referred to as typical flute-load-casts.

Marks of unknown origin

Sole markings of a peculiar kind are found on only one sandstone sole (Plate VII-1). The structures observed consist of crowded, small circular pits with a minute projection at the centre. The pits are 1 to 2 mm across and 0.5 to 1 mm deep. The described structures are suggested to be casts of mounds with a central pit which were produced on a soft mud floor by gas escaping thereform. If so, the structures may be referred to pit and mound structures (SHROCK, 1948).

Notes on the relation between the properties of sandstone layers and the occurrence of sole markings

Table 15. Relation between distribution of sole markings and thickness and grain size at base of sandstone layers

Triple asterisk: dominant, double asterisk: fairly dominant, single asterisk: present (not common). Striation casts coexisting with other types of sole markings on the same sole are omitted here.

		Thickness (in cm)				Grain size at base			
		0–10	10–30	30–60	60–100	Fine-grained sand	Medium- to fine-grained sand	Medium-grained sand	Coarse- to medium-grained sand
Flute casts	In general	**	***	***	***	**	***	***	**
	Large- to medium-sized	**	**	***	***	**	***	***	***
	Small-sized	***	***	**	**	***	***	**	**
Longitudinal furrows and ridges			*	*			*	*	
Groove casts	In general	**	**	***	***	**	**	***	***
	Large- to medium-sized	**	**	***	***	**	***	***	***
	Small-sized	***	***	**	**	***	***	**	**
Bounce casts		*	*			*	*		
Prod casts		*	*			*	*		
Striation casts		*	*			*			

The distribution of the individual types of sole markings with respect to the properties of sandstone layers is summarized in Table 15. First of all, it is readily seen that the flute casts as a whole occur dominantly on the sole of thinner or finer-grained sandstone layers than do the groove casts. However, the above-mentioned two kinds of structures display a quite similar occurrence according to their size. In this connection, it is noteworthy that the width of the flute casts is, roughly speaking, 1 to 5 cm for the large- to medium-sized forms and a few to ten milimetres for the small-sized ones as in the case of that of the groove casts, although the two kinds of structures are quite different in shape and origin. Concerning both the flute casts and the groove casts, the large- to medium-sized forms have a strong tendency to be well developed on relatively thick, coarse-grained sandstone beds in comparison with the small-sized ones. The longitudinal furrows and ridges having 0.3 to 2.5 cm ridge width occur in common association with small- to medium-sized flute casts or groove casts on the same sole. As would be expected from the above fact, actually the sandstone layers carrying longitudinal furrows and ridges generally have the properties intermediate between the sandstones with large- to medium-sized flute casts and those with small-sized ones.

The bounce casts and prod casts observed are generally several milimetres to one centimetre in width as in the case of the small-sized groove casts of similar origin and the small-sized flute casts of quite different origin. In harmony with such a similarity of sizes (widths), the sandstone layers with bounce casts and prod casts usually resemble those with small-sized flute casts or small-sized groove casts in thickness and coarseness. Occurrence of the striation casts not accompanied by any other prominent current marks on the same sole is restricted to relatively thin, fine-grained sandstones as in the case of the bounce casts and prod casts.

To sum up, a conclusion presented here is that the size (or width, to be more precise) of the current marks is closely related to the properties (e.g. thickness and grain size at the base) of the sandstone layers. That is to say, the larger forms are well developed on the underside of relatively thick, coarse-grained sandstones, while the smaller ones are dominant on the underside of relatively thin, fine-grained sandstones. This positive correlation, together with the general consistency of the directions of sole markings and those of internal structures in the same sandstone layer (see p. 80 of this paper), may suggest continuity of the eroding currents forming current marks on the mud floor and the sand-depositing currents. Assuming that the properties (e.g. consistency and cohesion) of the mud bottom were uniform, the larger forms are thought to have been produced by faster, more turbulent currents than for the smaller ones. It should be added here that the current marks of similar sizes (widths), regardless of their types, tend to occur on sandstone layers with similar thicknesses and grain sizes. Another point of interest is that the general correlation between the four classes of thickness and those of grain size at the base of the sandstone layers is demonstrated by the relationship between the distribution of current marks and the thickness and grain size of the sandstone layers with current marks (Table 15). That is to say, class 0–10 cm is correlated with the class of very fine- to fine-grained sand, class 10–30 cm with the class of fine- to medium-grained sand and so on. This positive correlation is confirmed by Fig. 10 as well.

V. 2 Internal Structures

Among the most widespread internal structures in the sandstone layers of the Cretaceous flysch formation are graded bedding, parallel lamination and cross-lamination all of which are ubiquitous in turbidite sandstones. Current ripple lamination, wavy lamination and convolute lamination also occur in common association with the above-mentioned two types of laminations. In addition, parting lineation is one of the intrastratal structures prevailing in well-laminated sandstones. Slump structures are of no important occurrence in the present area.

Graded bedding

Graded bedding is well developed in many of the sandstone layers, particularly in unit Mb_1 of facies β, unit Mb_2 of facies α and Member Mc of facies α. A typical graded bedding observed presents an upward decrease of the mean as well as the maximum grain size from bottom to top. The sandstone layers of the flysch sequence as a general rule show single grading. The single grading observed is classified into the following five descriptive types.

Type 1 (distinct): grading continuous throughout; upper part generally gradational to overlying shale layer.

Type 2 (rather distinct): grading indistinct in main part, but distinct in both lower and upper parts; upper part generally gradational to overlying shale layer.

Type 3 (rather indistinct): grading indistinct in main part, but distinct in lower part; upper part gradational or not gradational to overlying shale layer.

Type 4 (rather indistinct): grading indistinct in main part, but distinct in upper part; upper part generally gradational to overlying shale layer; corresponds to "delayed" grading (KUENEN, 1953, fig. 1E; KSIAZKIEWICZ, 1954, fig. 1b; SCOTT, 1966, p. 80, type 2).

Type 5 (indistinct): little or no grading detected throughout; upper part gradational or not gradational to overlying shale layer.

The sandstones showing graded bedding of type 1 are generally poorly laminated, while those showing graded bedding of type 5 are in many cases well laminated almost throughout the thickness. Of the above-mentioned types, type 4 is the most common, and is much predominant over type 3 where thin, well-laminated sandstone is widespread; these two types are nearly equal in abundance where thick, poorly laminated sandstone is dominant (Table 16). As far as the sandstone layers less than 100 cm thick are concerned, they become better graded with increasing thickness (Fig. 20).

Graded bedding is repeated in some of the sandstone layers. Thus a given layer is to be made up of two or more superposed graded units. The repeated graded bedding is classified into two types according to the mode of the contact of two successive graded units: *multiple* graded bedding (multiple bed, WOOD and SMITH, 1959; multiple grading, BALLANCE, 1964, fig. 5A; composite bed in part, DZULYNSKI and SLACZKA, 1958, figs. 3, 6; complex bed, UNRUG, 1963, fig. 8; KUENEN, 1953, figs. 1C, H) and *composite* graded bedding (composite bed, WOOD and SMITH, 1959; composite grading, BALLANCE, 1964, fig. 5B; multiple graded bedding and pen-symmetrical graded bedding, KSIAZKIEWICZ, 1954, figs. 2A, D, E; recurrent grading, KUENEN, 1953, fig. 1D). Where a single

Table 16. Distribution of types of graded bedding

The data are given in percentages.

Type of graded bedding	Mb_1			Mb_2			Mc	Me of facies δ		
	Facies α	Facies β	Facies γ	Facies α	Facies β	Facies γ	Facies α	Division B	Division E	Division F
	Iku-shum-betsu Valley	Nuno-biki-no-sawa	Hon-sawa	Iku-shum-betsu Valley	Nuno-biki-no-sawa	Hon-sawa	Iku-shum-bestu Valley	Pombetsu Valley		
1	1.2	33.3	2.5	29.9	13.5	—	26.4	11.2	6.3	6.2
2	4.7	7.0	—	—	9.6	—	11.0	0.7	1.0	1.2
3	13.9	3.5	—	23.9	3.8	1.5	29.7	9.7	3.1	2.5
4	65.1	49.2	72.5	29.9	48.1	74.3	23.1	41.0	60.4	77.7
5	15.2	7.0	25.0	16.4	25.0	24.2	9.9	37.3	29.2	12.4
Total	100.1	100.0	100.0	100.1	100.0	100.0	100.1	99.9	100.0	100.0
Total number of sandstone layers	86	57	80	67	52	66	91	134	96	81

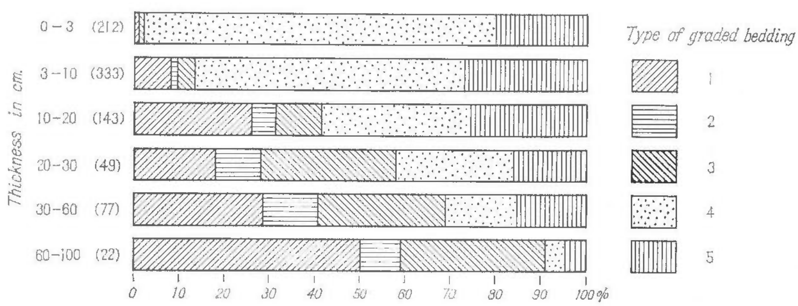


Fig. 20. Relation between sandstone layer thickness and type of graded bedding in sandstone layers.

For types of graded bedding see text.
Numerals in parentheses are the number of sandstone layers in each class.

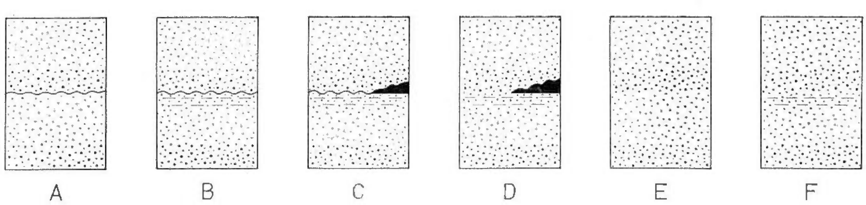


Fig. 21. Schematic diagrams showing some selected types of repeated graded bedding.

A, B, C and D: multiple graded bedding, E and F: composite graded bedding.

sandstone layer displays composite grading, the two successive graded units involved are bounded with a welded contact, not with a horizontal joint, and no intervening shale layer is found throughout the length of the outcrop (Figs. 21E, F). On the other hand, where sandstone layers show multiple grading, the boundary between the two successive graded units therein is represented by a visible horizontal joint with occasional load casts or a discontinuous shale layer is preserved at the boundary (Figs. 21A, B, C, D; 22A). In Member

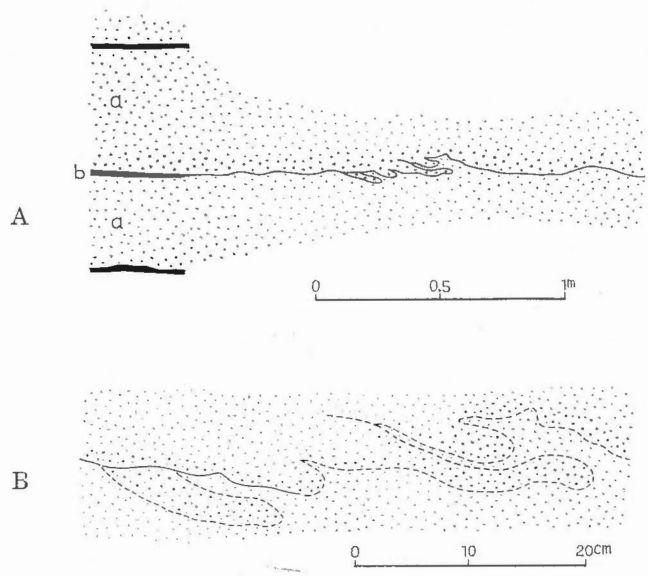


Fig. 22. Rough sketches of multiple graded bedding. Unit Mb_2 of facies α, Middle Yezo Group, right bank of the Ikushumbetsu.
A. Two successive graded sandstones (a) are bounded with a visible horizontal joint on the right and left sides, but with a welded contact accompanied by load waves (or flame structures) in the middle. A discontinuous shale layer (b) is preserved at the boundary.
B. The middle of the upper figure (A) is magnified. The solid line indicates a visible horizontal joint and the broken lines indicate a welded contact. The sole markings on adjacent sandstones indicate current flows from right to left.

Mc of facies α multiple grading is fairly common and composite grading is occasional. A possible explanation of the origin of these two types of repeated graded bedding may be presented in the lines to follow, according to some authors' views (BOUMA, 1962; UNRUG, 1963; BALLANCE, 1964). Concerning the multiple grading, it is suggested that a later turbidity current had an erosive power strong enough to remove the pre-deposited shale layer or a later turbidity current arrived so soon after the preceding one that a shale layer was not deposited at all. In the case of the composite grading, two phases of a single turbidity current arrived at a given depositional site with a very short time-interval, thus any shale layer or even the upper finer part of a sandstone layer could not be deposited.

Furthermore, even in some of the shale layers graded bedding is perceptible which is shown typically by an upward decrease in grain size from siltstone through silty mudstone to clayey mudstone. By way of example, graded bedding in shale layers can be clearly detected in 34 cases, some 56 per cent of the 61 cases in unit Mb_1 of facies α, Ikushumbetsu Valley.

Parallel lamination

Parallel lamination is prevalent in common association with cross-lamination in the sandstone layers especially of unit Mb_1 of each facies, unit Mb_2 of facies γ and Member Me of facies δ (Plate VIII-1). The parallel laminations observed are most commonly manifested by flat-lying carbonaceous flakes and occasionally by an alternation of thicker coarse and thinner fine material or selective iron oxides staining. The laminae are generally less than several milimetres thick. The laminations described here are of two types: internal gradation is present in one type, but absent in the other. In a single sandstone layer these laminations are normally overlain by cross-laminations. They, moreover, are well developed in the laminated sandy mudstone division of graded units.

Cross-lamination

Cross-lamination is well developed in the thin sandstone layers constituting Mb_1 of each facies, Mb_2 of facies γ and Me of facies δ. The cross-lamination is best shown by carbonaceous flakes like other types of laminations. Being occasionally accompanied by current ripple lamination and convolute lamination, the structure to be described is underlain by parallel lamination in some sandstones, but in others it is developed throughout the thickness. Cross-laminations, moreover, are occasionally detected in sandstone laminae constituting laminated sandy mudstone.

The cross-laminations observed are either of tabular type or trough type, although intermediate types are also common. The thickness of individual sets of the cross-laminations ranges from 0.5 to 3 cm, mostly 0.5 to 1 cm. The general dip of the foreset laminae is less than 15 degrees. Such is the case with unit Mb_1 of facies α (a relatively distal facies), but in unit Mb_1 of facies β (a relatively proximal facies) the foreset laminae commonly incline at an angle up to approximately 30 degrees where the sandstone layers are thicker and coarser grained on an average than those of Mb_1 of facies α. Taking into consideration that the inclination of foreset laminae tend to become steeper with decreasing velocity of the currents (McKee, 1957) and that the general velocity of sand-depositing currents is supposed to have been swifter for facies β than for facies α, it is evident that the facts just referred to contradict themselves. In Mb_1 of facies β, however, the cross-laminations often suffered convoluions in a greater or lesser degree and the resulting conspicuous convolute laminations are occasionally found. Therefore, it is natural and reasonable to interpret the steep inclination of the foreset laminae in Mb_1 of facies β as a result of oversteepening caused by load casting effect or soft-sediment deformation. Furthermore, ripple cross-laminations produced by migrating current ripple are commonly developed in very thin interbeds or interlaminae of sandstone within laminated sandy mudstone.

Current ripple lamination

Current ripple lamination that is comparable to lamination forming current ripples is found in common association with cross-lamination (Plate VIII-1). This structure is seldom in sandstone layers less than 5 cm thick. The current ripple laminations in plan view exhibit linear pattern with relatively straight, continuous crests or linguoid (or cuspate) pattern with notably curved, discontinuous crests. In a certain example of current ripple lamination from Member Me of facies δ, the carbonaceous flakes are observed to be oriented perpendicular to the axis on the ripple crests but parallel to the axis in the ripple troughs. The current ripple laminations in the present area are classified into large-sized (wave length, 10 to 30 cm; amplitude, 2 to 5 cm) and small-sized forms (wave length, less than 10 cm; amplitude, less than 2 cm), the latter being dominant over the former. In some cases, however, they are convoluted and deformed by load casting, thus the amplitude being exaggerated.

Wavy lamination

Wavy lamination is a kind of stratification in which the lower and upper limits of the laminae are weakly undulating. It occurs within the laminated division of sandstone layers but are very rare in sandstones less than 5 cm thick. The wavy pattern of these laminations is not so regular in both wave length and amplitude as the current ripple laminations mentioned above. The structure here referred to as wavy lamination is one to several decimetres in wave length and less than 1.5 cm in amplitude. The wavy laminations may be of various origins. Actually, they generally grade vertically or laterally into parallel laminations, and occasionally into current ripple laminations. It is accordingly conceivable that some wavy laminations owe their origin to rippling. In other cases, however, the wavy laminations are quite similar in appearance to or perhaps identical with incipient convolute laminations originating from parallel laminations; the two structures may be genetically closely related to each other.

Convolute lamination

Convolute lamination is characterized by syngenetic intricate corrugations of laminations which are normally composed of narrow peaked anticlines and broad rounded synclines and die out both downwards and upwards (Plate VIII-2). The convolute laminations in the studied area originated from parallel lamination, cross-lamination and current ripple lamination, showing various degrees of corrugation. Convolute laminations exhibiting moderately or strongly contorted patterns are occasionally, if not commonly, found in the sandstone layers especially of units Mb_1 of facies β and Mb_2 of facies γ. They seldom occur in sandstone beds less than 5 cm thick. However, incipient forms, which are not dealt with in Tables 2 and 12, are not uncommon. The conspicuous convolute laminations normally range from 10 to 20 cm in wave length and from 3 to 8 cm in amplitude.

The convolute laminations observed are simple as a rule. A very complicated form in division A of Member Me of facies δ, Pombetsu Valley (Plate VIII-2), however, is referred to as *corrugate lamination* of Davies (1965) which is distinguished from typical convolute lamination by the absence of contortions of an overall anticline-syncline morphology. Furthermore, it is to be noted that in all of the convolute laminations the corrugation of laminations dies out both downwards and upwards within the sandstone layer involved and the convolute lamination is overlain by undeformed laminations, being not truncated by the superjacent erosion surface. This fact, therefore, strongly demonstrates that such laminations were of syn-depositional origin. Some of the convolute laminations pass downwards into current ripple laminations, showing remarkable serial overturning in a down-current direction. Such forms are suggested to have been produced in a close relation to current-rippling.

Parting lineation

Parting lineation is manifested by a group of parallel ridges and hollows of low relief (usually less than one milimetres) on the upper surface of laminae constituting sandstone layers. It is widespread in unit Mb_1 of facies α and Member Me of facies δ where the sandstone is well laminated (Plate IX-1). This structure is restricted to the laminated division within sandstone layers. The sandstone layers showing parting lineation are 10 to 30 cm thick and fine-grained. It is well known that ridges and hollows in parting lineation depend for their origin on the preferred orientation, parallel with the current flow, of the component elongated clastics of sandstone layers in which this structure occurs. Actually, the preferred orientation of carbonaceous flakes or plant fragments in the sandstone layers is found to be nearly parallel to that of parting lineation with respect to a given bedding surface (see Fig. 40).

Clast lineation

Clast lineation is a kind of internal structure of sandstone layers which is represented by a preferred orientation of elongated clastic components on the bedding plane of sandstones (CROWELL, 1955; McBBRIDE, 1962). The elongated clastic components in the clast lineation of the flysch sandstones in the studied area are carbonaceous flakes or plant fragments and contemporaneous breccias of mudstone. Carbonaceous flakes tend to exhibit a preferred orientation nearly parallel with the orientation of parting lineation in the same or adjacent sandstone layers as is often the case with Member Me of facies δ (see Fig. 44). This is equally true of flattened elongated shale fragments (see Figs. 41A, 44).

Slump structures

Slump structures which were formed in poorly consolidated sediments owing to gravity-generated downslope movement are characterized by the occurrence of folded structures such as slump overfolds and spiral slump balls and chaotic mixture of sediments. Apart from the occasional incipient slump structures as shown by pull-apart structures, simple, weak folds and so forth, noticeable slump beds are associated with local extension and have insignificant thicknesses at several horizons in the flysch succession of the present area. One or more sedimentation units are involved in the slumping. Among these slump deposits, the chaotic masses of silt and sand are usually accompanied by some angular or twisted fragments of sandstone and shale, a single unit being 1 to 1.5 m thick.

The slump sediments in unit Ma_2 of facies β, Nunobiki-no-sawa are composed of two units of chaotic mass separated by a graded sandstone layer, about 30 cm thick, the upper unit including a number of reworked calcareous concretions and not a few molluscan fossils such as *Natica* (*Lunatia*), *Dentalium* and bivalves (Fig. 19B; TANAKA *in* MATSUNO *et al.*, 1964, plate 1). The base of the

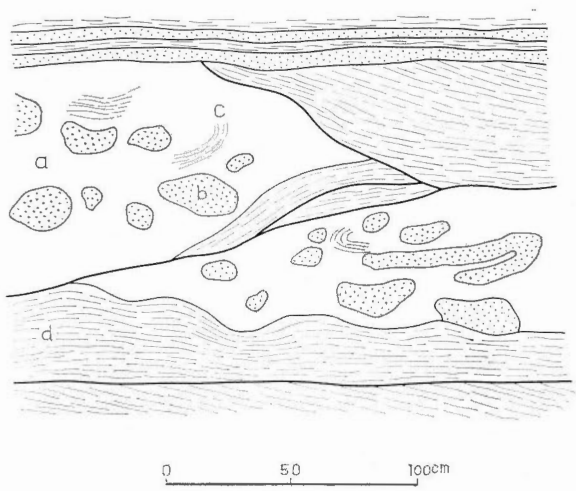


Fig. 23. Rough sketch of slump structure. Division F, Member Me of facies δ, Middle Yezo Group, left bank of the Pombetsu.

a: chaotically mixed sandy siltstone.
b: sandstone.
c: visible internal folded structure.
d: laminated sandy mudstone.
The heavy lines indicate contemporaneous faults.

slump bed described here is marked by conspicuous load casts. The slump deposits in Member Mc of facies α, Ikushumbetsu Valley are divided into three units; the lower and upper units are characterized by chaotic masses with some bent slabs of laminated sandy mudstone and displaced molluscan fossils (Plate II-1); the middle unit consists of sandstone and pebble-bearing shale in thin-bedded alternation, showing folded structures due to movements of décollement type. Since the above-mentioned chaotically mixed sediments in both Ma_2 and Mc contain many pebbles of exotic origin, they are referred to as pebbly mudstone (CROWELL, 1957) the origin of which can be ascribed to submarine mudflow. The chaotic mass in division A of Member Me of facies δ, Pombetsu Valley is nearly 10 cm thick and is rich in fragments of contemporaneous tuffaceous rocks and other intra-basinal rocks such as sandstone and shale. The slump deposits in division F of Member Me, Pombetsu Valley are accompanied by a bed of chaotic sediments showing slump overfolds and some other internal folded structures. This chaotic mass, together with the superjacent and subjacent argillaceous beds, is deformed by slumping and contemporaneous faults, and is overlain by normally bedded younger strata (Fig. 23). In the division another slump bed, about 1 m thick, is found which is characterized by folded structures resulting from slumping of décollement type.

V. 3 Top Surface Structures

Ripple marks

Unlike current ripple laminations, a kind of intrastratal structure, ripple marks occur on the upper surface of sandstone layers, although the two structures have identical features except for their modes of occurrence (Plate VIII-1, IX-2). Ripple marks are occasional, if not common, throughout the flysch formation and are generally found on narrowly exposed top surfaces of sandstone layers. Only one noticeable example of ripple marks is seen on the wide bedding surface of a sandstone bed in Member Mc of facies α on the right bank of the Ikushumbetsu near the Katsurazawa Electric Station (Plate IX-2).

All the ripple marks observed belong to current ripples. They are of two types; one is referred to linguoid (or cuspate) ripples with markedly curved, discontinuous crests, and the other is relatively straight crested forms, the former being commoner than the latter. The internal ripple laminae, when viewed in vertical sections parallel to the currents, are truncated at the upper extremity and thus the foreset laminations dipping to one side are developed internally. The crests have an asymmetrical profile with a rounded top; the troughs in between are flattened. The current ripples are 6 to 18 cm in wave length, 1 to 1.5 cm in amplitude and 6 to 12 in ripple index. As to the aforementioned spectacular ripple marks of Member Mc, the crests are 20 to 50 cm long, the longer and the shorter in alternation and more or less curved, the shorter being more curved than the longer.

VI. Biogenic Sedimentary Structures

Biogenic sedimentary structures found in the Ikushumbetsu flysch sequence are various types of animal tracks and burrows on many sandstone soles and less commonly on the top surface and in the interior of sandstone layers. These sedimentary structures of organic origin fall into two categories, pre-depositional and post-depositional, depending on whether they were formed before or after the deposition of the sandstone layers on which the structures occur. Taken altogether, pre-depositional structures are much predominant over post-depositional ones, although exposures of the latter are not sufficient.

VI. 1 Pre-depositional Biogenic Sedimentary Structures

The pre-depositional sedimentary structures due to organisms in the studied area are sole impressions of animal tracks and burrows, represented mostly by narrow, variously sinuous casts of marks. In general, they are preserved on the underside of sandstone layers as convex (or positive) hyporeliefs (SEILACHER, 1964) or hypichnial casts (MARTINSSON, 1965). These structures are particularly abundant in Member Me of facies δ. No case is found in which the sandstone layers of the flysch sequence are internally burrowed by organic sole markings.

The pre-depositional biogenic sedimentary structures are found on the bottom of sandstone layers of any thickness and coarseness. However, the sandstones carrying such structures tend to be comparatively thin and fine-grained (Table 17). This tendency just referred to becomes more pronounced by examining the sandstone soles on which pre-depositional sedimentary structures of organic origin do not coexist with current marks (e.g. flute casts and groove casts). Thus, it can be pointed out that such sandstone layers in the majority of cases are less than 10 cm thick and fine-grained at the base (Table 17). In view of the general tendency described above, it is suggested, as would be expected, that the current flows producing small-sized current marks and

Table 17. Relation between presence of pre-depositional biogenic sedimentary structures and thickness and grain size at base of sandstone layers

The data are given in percentages.

	Number of soles exposed	Soles with pre-depositional biogenic structures	Soles with pre-depositional biogenic structures coexisting with no current marks
Thickness (in cm)			
0–3	49	12.5	17.4
3–10	148	22.3	43.4
10–20	84	23.8	23.9
20–30	31	3.2	6.5
30–60	54	11.1	8.7
60–100	20	5.0	—
			Total 99.9
Grain size at base			
Coarse-grained sand	—	—	2.2
Coarse- to medium-grained sand	29	3.4	2.2
Medium-grained sand	35	5.7	4.3
Medium- to fine-grained sand	89	22.4	21.7
Fine-grained sand	213	20.7	69.5
Very fine-grained sand	16	—	—
			Total 99.9
Total number		67	46

Table 18. Relation between presence of flute casts and groove casts and that of pre-depositional biogenic sedimentary structures

The data are given in percentages.
Numerals in parentheses are the number of soles.

A. Pre-depositional biogenic structures-bearing soles (91)	
Flute casts present	41.7
Groove casts present	8.1
Flute casts and groove casts absent	48.8
B. Flute casts-bearing soles (177)	
Pre-depositional biogenic structures present	21.5
Pre-depositional biogenic structures absent	78.5
Groove casts-bearing soles (47)	
Pre-depositional biogenic structures present	14.9
Pre-depositional biogenic structures absent	85.1
C. Flute casts coexisting with pre-depositional biogenic structures (38)	
Small-sized	73.7
Medium-sized	26.3
Groove casts coexisting with pre-depositional biogenic structures (7)	
Small-sized	85.7
Medium-sized	14.3

subsequently depositing thin, fine-grained sandstone layers were too small in erosive power to completely wash out tracks on the mud floor or burrows disclosed there. Nevertheless, these organic hieroglyphs are not common on the sole of sandstone layers which are less than 3 cm thick or very fine-grained at the base (Table 17). This fact implies that the turbidity currents depositing such sandstones had not enough eroding ability to reveal burrows, if present, in the underlying shale layer.

The pre-depositional sedimentary structures of organic origin are commonly associated with current marks on the same sandstone sole (Table 18A). However, the vast majority of the soles carrying flute casts or groove casts are not provided with such organic hieroglyphs (Table 18B). Actually some pre-depositional biogenic structures are partially obliterated by current marks, particularly flute casts. In this connection, it is to be noted that flute casts or groove casts are in many cases small-sized where they coexist with pre-depositional biogenic sedimentary structures on the same sole (Table 18C). A most probable explanation of this is that pre-depositional biohieroglyphs were apt to be spoiled to a great degree by strong current flows producing large-sized flute casts or groove casts than by weak current flows producing small-sized casts. A further point which draws one's attention is that current marks were cut, though very rarely, by animal tracks before the deposition of the overlying sandstone layer, thus the latter being younger than the former (Plate IV-1).

VI. 2 Post-depositional Biogenic Sedimentary Structures

The post-depositional biogenic sedimentary structures of the flysch succession are represented by variously sinuous or branching burrows which occur as concave (or negative) epireliefs (SEILACHER, 1964) or epichnial grooves (MARTINSSON, 1965) on the top surface of sandstone layers and less commonly in the interior of sandstones as full reliefs (SEILACHER, 1964) or endichnial burrows (MARTINSSON, 1965).

These structures are especially widespread in the upper part of unit Mb_1 of facies α, Ikushumbetsu Valley, where the sandstones are mostly less than 5 cm thick. In fact, most of about fifty sandstone layers in a 2 m sequence therein have such structures all over the top surface. It should be noted that in many cases the post-depositional biogenic sedimentary structures on the top surface of sandstone layers occur uniformly over a wide area in contrast to the pre-depositional ones on the soles. The sandstone layers carrying post-depositional structures due to organisms are usually, but not always, less than 10 cm in thickness, while those with pre-depositional biohieroglyphs have a much wider range of thickness and are generally thicker than the former (Table 17). A similar tendency was noted in the flysch sediments of northern Spain (SEILACHER, 1962). The post-depositional biogenic sedimentary structures inside sandstones are represented mostly by burrows filled with muddy material.

VI. 3 Assemblages of Trace Fossils

Many different kinds of biogenic sedimentary structures in the Cretaceous flysch sequence of the studied area are regarded as tracks and burrows of sediment-eating animals. The prevalence of such organic structures indicates that various kinds of bottom dwellers (presumably annelids and gastropods) thrived during the deposition of the flysch formation in spite of the uncommon occurrence of shell fossils such as ammonites and other molluscs. It attracts one's attention that these tracks and burrows are very abundant in Member Me of facies δ on the western wing of the Ikushumbetsu anticline. On the other hand, they are sporadic in unit Mb_1 of facies α on the eastern wing which closely resembles the above sequence in lithological features. This point, together with many other available sedimentological data to be mentioned later, suggests that the depositional site of Member Me of facies δ was in relatively shallow-sea environments in comparison with that of unit Mb_1 of facies α.

Among the biogenic sedimentary structures, there are trace fossils of which nine genera and ten species have been identified as will be described on another occasion (Table 19). There are many other undeterminable forms including excrements of unknown animals and bores and casts of worms. Of these trace fossils listed in Table 19, one genus, *Anapaleodictyon* (Plate X-1), and two species are new to science and four genera, *Anapaleodictyon, Chondrites*

Table 19. List of trace fossils from the Cretaceous flysch sequence of the Ikushumbetsu area

Double asterisks indicate abundant occurrence.

	Ikushumbetsu Valley			Pombetsu Valley		
		Mb_1				
	Ma_3 Facies α	Lower part Facies α	Upper part Facies α	Md_2 Facies δ	Md_3 Facies δ	Me Facies δ
Pre-depositional trace fossils						
Anapaleodictyon irregulare n. gen. and n. sp.	*				*	**
Helminthoida japonica n. sp.		*				**
Helminthopsis akkeshiensis (MINATO and SUYAMA)		*				*
Lorenzinia (?) sp.						*
Paleodictyon sp. α (regular type)	**	*				**
Paleodictyon sp. β (irregular type)			*			*
Spirorhaphe (?) sp.					*	*
Post-depositional trace fossils						
Chondrites sp.			*			
Neonereites aff. *uniserialis* SEILACHER		*	**	**		**
Polydora (?) sp.	*		**	**	*	*

(Plate XII-1), *Lorenzinia* (?) and *Neonereites* (Plate XI-2) have not been hitherto reported from the Cretaco-Palaeogene in the Shimanto terrain of Southwest Japan and Okinawa (KORIBA and MIKI, 1939; KATTO, 1960a, 1960b, 1964; KONISHI, 1963; HARATA, 1965; HARATA *et al.*, 1967). *Anapaleodictyon* is closely allied to *Protopaleodictyon* (KSIAZKIEWICZ, 1958, pl. 2, fig. 1; 1960, p.

745–746, pl. 1, fig. 5, text-fig. 1) from the Eocene of Poland. *Helminthopsis akkeshiensis* (MINATO and SUYAMA, 1949, p. 277–279, pl. 11, figs. 1, 2; Plate XII-2) was reported from the Upper Cretaceous of eastern Hokkaido. Some forms of *Paleodictyon* with regular meshes (Plates XI-1, XII-2) resemble *P. majus* MENEGHINI (KORIBA and MIKI, 1939, pl. 4, fig. la-g) from the Palaeogene of the Kii Peninsula. *Paleodictyon* with irregular meshes is to some extent similar to *Paleodictyon* of irregular type figured by SEILACHER (1962, fig. 1). *Neonereites* aff. *uniserialis* (Plate XI-2) is closely similar to *Neonereites uniserialis* (SEILACHER, 1960, p. 48, pl. 2, fig. 1, text-fig. 3) from the Lower Jurassic of Germany.

Among the most common pre-depositional trace fossils from the flysch formation are *Helminthoida japonica* (Plate X-2) and *Paleodictyon* of regular type. *Spirorhaphe* (?) also is one of the representative forms of the pre-depositional trace fossils. The most prevalent of the post-depositional trace fossils is *Neonereites* aff. *uniserialis* and *Polydora* (?) sp. All the pre-depositional trace fossils are feeding trails or burrows, i.e. "Pascichnia" (SEILACHER, 1964), produced by animals creeping and grazing on the mud floor. Many of the post-depositional trace fossils, on the other hand, are referred to "Pascichnia" and feeding burrows, "Fodinichnia" (SEILACHER, 1964) formed by sediment-eating animals. In this manner, it is evident that the assemblages of trace fossils from the flysch series under discussion are fundamentally characterized by feeding trails and feeding burrows, and are lacking in resting tracks, "Cubichnia" (SEILACHER, 1964) and undoubted dwelling burrows, "Domichnia" (SEILACHER, 1964) made up of U-shaped or vertical tunnels. Therefore, we are led to a conclusion that the trace fossil communities of the Ikushumbetsu flysch clearly correspond to the *Nereites* facies (SEILACHER, 1964) characteristic of geosynclinal areas or flysch facies. In connection with this, it should be added here that some recent representatives of the *Nereites* community are found on the deep-sea floor of about 3,000 m and 4,700 m depth (SEILACHER, 1967b). This fact is suggestive of a considerable depth for the Ikushumbetsu Cretaceous flysch basin.

VII. Sedimentary Facies

VII. 1 Sedimentary Facies in General

In the Cretaceous flysch of the Ikushumbetsu area the individual members or units show lateral variations in lithological aspects, so that several facies (e.g. α, β, γ and δ) can be discriminiated (Figs. 4, 5). As mentioned before, the sandstones of the flysch sequence fall into the following groups in terms of their mode of occurrence: sandstone, either massive or bedded, sandstone frequently interbedded with shale (sandstone and shale in alternation) and sandstone frequently interlaminated with shale (laminated sandy mudstone). On the other hand, according to the mode of deposition of the sandstones involved the flysch deposits are to be classified into four principal types of sediments: fluxoturbidite (or sand-flow deposits), turbidite A, turbidite B and laminite* facies (Table 20;

* The term *laminite* in this paper is for convenience used as a descriptive name for a particular stratum that is lithologically referred to part of LOMBARD's laminites of second order (LOMBARD, 1963) without respect to the origin. Some of such sediments, however, are regarded as having been deposited from slow, dilute turbidity currents.

Table 20. Comparison of facies in the Cretaceous flysch sequence of the Ikushumbetsu area

		Fluxoturbidite facies	Turbidite A facies	Turbidite B facies	Laminite facies
Sandstones	Layer thickness	Generally less than 3m, more than 1m.	Less than 3m, commonly less than 1m and more than 3cm.	Generally less than 30cm, more than 1cm.	Less than 1cm.
	Bedding	Graded bedding absent or indistinct. Multiple graded bedding common. Lamination occasional.	Graded bedding commonly distinct. Multiple or composite graded bedding occasional. Lamination common. Graded sandstone division predominant over laminated sandstone to cross-laminated sandstone divisions.	Graded bedding commonly indistinct. Lamination well developed. Laminated sandstone to cross-laminated sandstone divisions predominant over graded sandstone division.	Graded bedding usually imperceptible or absent. Lamination exclusively well developed.
	Grain size	Comparatively well sorted. Coarse- to medium-grained. Pebble-sized at maximum.	Comparatively poorly sorted. Coarse- to fine-grained at base. Granule-sized at maximum.	Comparatively poorly sorted. Fine- to very fine-grained at base.	Comparatively well sorted. Very fine-grained.
	Lower contact	Sharp, undulating.	Sharp, undulating.	Sharp, comparatively undulating, occasionally flat.	Sharp or gradual. Flat or irregular.
	Upper contact	Sharp or gradual.	Commonly sharp.	Commonly gradual.	Commonly gradual.
	Directional sole markings	Uncommon.	Common.	Rather common.	Almost absent.
Interbedded shales		Siltstone and laminated sandy mudstone. Usually thinner than 5cm. Occasionally absent.	Laminated sandy mudstone. Commonly thinner than 10cm.	Laminated sandy mudstone. Commonly thinner than 30cm.	Laminated mudstone.
Corresponding lithology in general		Massive sandstone and bedded sandstone.	Bedded sandstone and alternating sandstone and shale.	Sandstone and shale in thin-bedded alternation.	Laminated sandy mudstone.

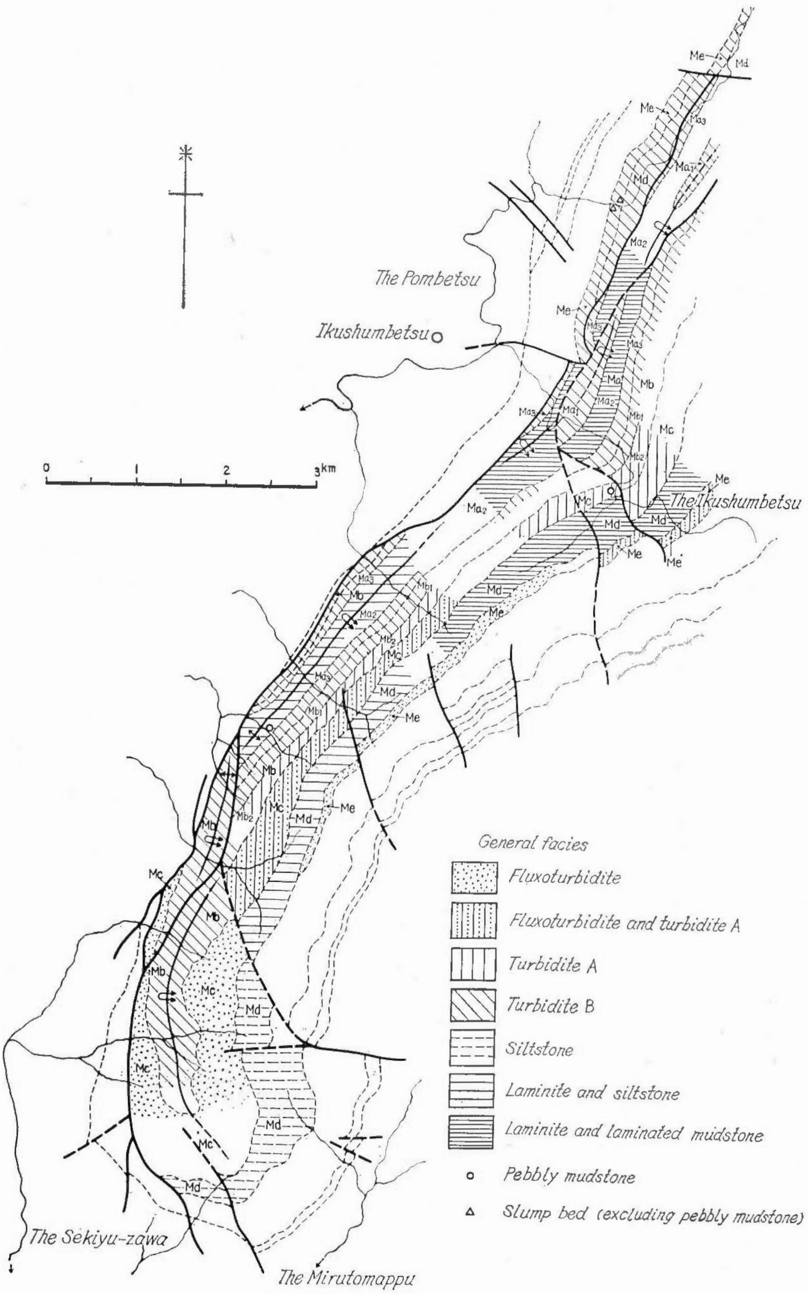


Fig. 24. Geological map showing the facies distribution in the main part of the Middle Yezo Group in the Ikushumbetsu area.

Figs. 24, 25). Roughly speaking, the fluxoturbidite facies is characterized by sandy flysch, the turbidite A facies by sandy flysch and normal flysch, the turbidite B facies by normal flysch and shaly flysch, and part of the laminite facies by shaly flysch.

Brief comments are given on the above-mentioned types of facies. On the whole, the sandstones of the fluxoturbidite facies are less muddy than those of the turbidite A facies. In the turbidite B facies are commonly developed equivalents of LOMBARD's laminites of first order (LOMBARD, 1963). On the other hand, the sandstone laminae in the laminite facies correspond exclusively to part of LOMBARD's laminites of second order. The proportion of laminated division–cross-laminated division to sandstone layer increases in the order of the fluxoturbidite, turbidite A, turbidite B and laminite facies. Furthermore, sole markings tend to become larger and more commonly load casted in the turbidite A and fluxoturbidite facies than in other facies. As contrasted with the above various types of flysch deposits, a neritic sandstone facies as represented by the Mikasa Formation covering the flysch sequence is marked especially by the abundance of shallow-sea bivalves inclusive of trigonians and glycimerids, among others, by the absence of graded bedding and directional sole markings, and by the predominance of comparatively well-sorted sediments.

VII. 2 Lateral Variation of the Sedimentary Facies

Large-scale lateral variation of the sedimentary facies

The sandy sequences represented by Members Mc and Me on the eastern wing of the Ikushumbetsu anticline change from the turbidite A to fluxoturbidite facies southwards. The fluxoturbidite facies of Member Me, in turn, passes southwards even into the trigonians-bearing neritic sandstone facies which is referred to the lowermost part of the Mikasa Formation. In this way, the sandy sequences become less stratified and poorer in shale interbed from north to south. Member Me thins southwards; Member Mc thickens in the same direction. In Members Ma and Md dominated by muddy sequence laminated mudstone facies is widespread in the north, while massive siltstone facies is predominant in the south. Thus, in these members the argillaceous rocks themselves become generally coarser grained and less stratified to the south. Moreover, Member Md decreases in thickness southwards and in the southernmost siltstone facies area it thins westwards as well as southwards.

In the northern part of the west wing of the Ikushumbetsu anticline, the middle part of Member Md (Md_2) of facies δ and Member Me of facies δ principally exhibit the turbidite B facies and the upper part of Member Ma (Ma_3) of facies δ is richer in sandstone than that of facies α on the east wing. From the facies distribution together with the current directions to be mentioned later, it is evident that facies δ on the western wing of the anticline is developed independently of the particular facies change in the N-S direction of both the sandy and the muddy sequences on the eastern wing of the anticline.

The lateral facies variation in Member Mb which consists of alternating sandstone and shale is more complicated than the aforesaid tendency of facies variation in the N-S direction of the sandy and the muddy sequences. That is to say, the lower part of Member Mb (Mb_1) changes southwards from the turbidite B facies through the turbidite A-like facies of relatively thick sandstones to the turbidite B facies. In the upper part of Member Mb (Mb_2) the turbidite A facies is dominant in the north, while the turbidite B facies prevails in the south.

To sum up, the flysch deposits and associated beds on the east wing of the

Ikushumbetsu anticline come to have a near-source (or proximal) facies from north to south. The lateral variation in lithology and thickness in Member Md suggests that the source area was situated probably to the west of the Cretaceous outcrop area during the Md period. The lateral change in facies from the near-source (or proximal) to off-source (or distal) facies falls into the following three principal, though somewhat idealized, types (facies which is not developed in the field is marked with an asterisk): (1) in the sandy sequences, neritic sandstone facies → fluxoturbidite facies → turbidite A facies → turbidite B facies*; (2) in the alternating sandstone and shale sequences, laminite facies → turbidite B facies → turbidite A facies → turbidite B facies → laminite facies; (3) in the muddy sequences, massive siltstone facies → laminated siltstone (or mudstone) facies → laminite facies → laminated mudstone facies. In each case a more proximal or a more distal facies is unknown for the lack of field evidence.

Lateral variation of the sedimentary facies in Member Mb

Member Mb is dominated by alternating sandstone and shale and is divided into facies α, β and γ. In the lower part of the member, Mb_1 which consists mostly of sandstone and shale in thin-bedded alternation, facies β is clearly distinguished in many respects from facies α and γ which are slightly or little different from each other; facies α is more similar to facies β than is facies γ (Tables 2, 4, 8, 16). The graded units in facies β, as compared with those in facies α and γ, begin commonly with graded sandstone division, and the proportion of graded division to sandstone layer is generally larger and the sandstone layers are on the whole coarser grained at the base and less cross-laminated. These differences may signify that the sand-depositing currents had a generally higher velocity for facies β than for other facies. In this connection, graded units ending with massive mudstone division are fewer in facies β than in the others. Assuming that any shale layer was originally occupied by massive mudstone division at its top and had the same degree of compaction and plasticity, it may be suggested that the turbidity currents flowing on the muddy bottom had a greater erosive power, i.e. higher speed, for facies β than for facies α and γ. It is added here that the general rate of sedimentation of the sandstones may have been greater for facies β than for the others. This will be inferred from the larger mean thickness of sandstone layers, smaller mean thickness of shale layers, higher sandstone percentage and more common occurrence of markedly undulating soles due to load deformation. Furthermore, graded bedding is better developed and thicknesses of sandstone layers show a greater distributional spread for facies β than for facies α and γ.

The lateral variation in sedimentary aspects presented here is a variation along the general trend of the strata. Judging from the regional current pattern (see Figs. 37, 38), it may be safely said that the above-mentioned lateral change of sedimentary attributes reflects the lateral change along the axial part of the gross sedimentary body of unit Mb_1. Thus facies α, β and γ are denominated here the distal, medial and proximal facies respectively. From Figs. 26 and 27 it is readily seen that the lateral variation from facies β to facies α in unit Mb_1 is more gradual than from facies β to facies γ. Facies β, viz., the medial facies, is developed in the extremely posterior part of the sedimentary body under consideration. In relation to the aforementioned lateral change in facies it may be remarked here that the total thickness of unit Mb_1 is greater in facies β (the medial facies) than in facies α (the distal facies) and probably in facies γ (the proximal facies). In other words, the total thickness of this sequence varies with the total thickness of the sandstone layers therein. Another interesting fact is that the correlation coefficient for sandstone-shale thickness clearly differs among facies α, β and γ (see Table 10). That is to say, in regard to facies α the thickness of the sandstone is positively correlated with that of the overlying shale, whereas it is negatively correlated with the thickness of the underlying shale. Facies γ, on the other hand, shows a positive value of correlation coefficient for sandstone-underlying shale thickness. In the case of facies β, however, no strong correlation of thickness is found be-

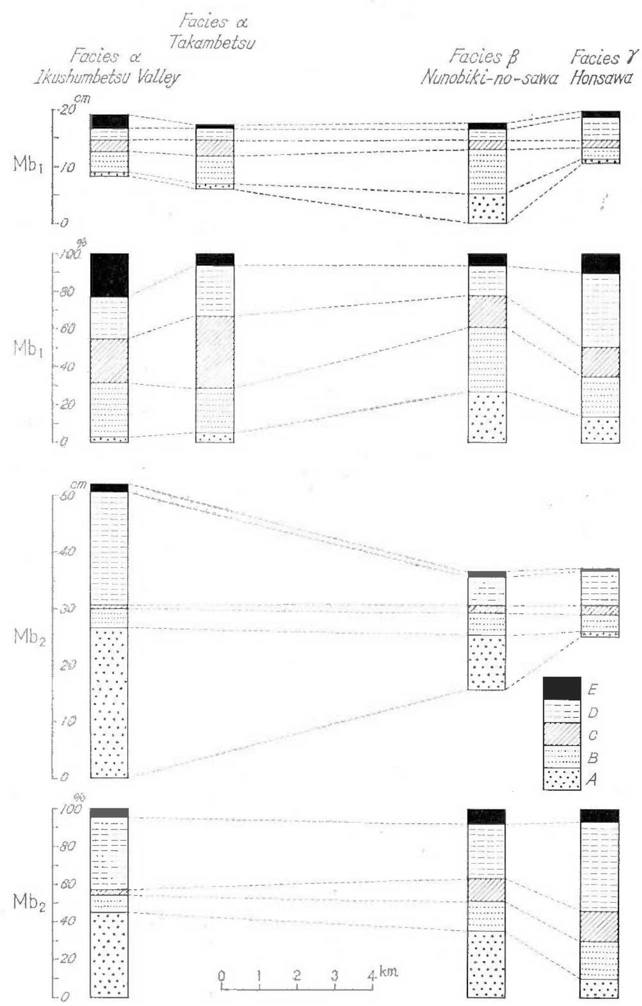


Fig. 26. Diagrams showing the lateral variation in average thickness and average division percentage of graded units in units Mb_1 and Mb_2.

A: graded sandstone division.
B: laminated sandstone division.
C: cross-laminated sandstone division.
D: laminated sandy mudstone division.
E: massive mudstone division.

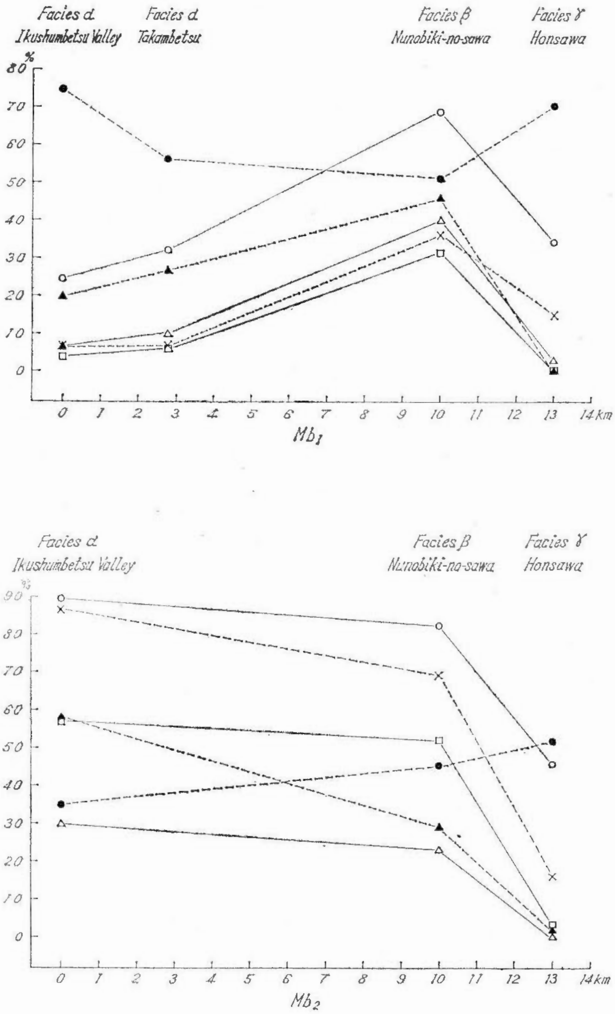


Fig. 27. Diagrams showing the lateral variation in sedimentary features of graded units in units Mb_1 and Mb_2.

Open circles: graded units beginning with graded sandstone division, solid circles: graded units ending with massive mudstone division, crosses: average proportion of graded division to sandstone layer, open squares: moderately undulating bottom surface of sandstone layer, solid triangles: graded units beginning with grain sizes coarser than fine-grained sand, open triangles: distinct and rather distinct graded bedding. The average proportions of graded division to sandstone layer are given in percentages and other sedimentary parameters are given in percentage frequencies.

tween sandstone and overlying shale or underlying shale.

The upper part of the member, Mb_2 is dominated by sandstone and shale in alternation. From Tables 2, 4, 8 and 16 and Figs. 26 and 27 it may be seen that the sedimentary features tend to change in a definite direction, i.e. from facies α through facies β to facies γ or from north to south. The lateral facies variation from facies α to facies γ is indicative of the facies variation along the axial part of the gross sedimentary body of unit Mb_2 as in the case of unit Mb_1 and is nearly in harmony with the general tendency of lateral variation from facies β to facies γ in unit Mb_1. Therefore, as to unit Mb_2, facies α should be close to the medial facies* and facies γ is referred to as the proximal facies. There are, however, some exceptions to the rule of the lateral variation in sedimentary aspects in unit Mb_2. Such is the case particularly with the average value for shale thicknesses and average proportion of shale layer to graded unit. In reality, the average thickness of shale layers is much greater for facies α than for facies β and γ. This implies that in the relatively distal facies area laminated sandy mudstone division within graded units, together with underlying sandstone layer, was extraordinarily thickly deposited by waning turbidity flows. Furthermore, unit Mb_2 of facies γ is quite similar in many respects to unit Mb_1 of facies γ (Tables 2, 4, 8; Fig. 26). Their similarity is exemplified by the values of correlation coefficient for sandstone-shale thickness (see Table 10).

For both unit Mb_1 and unit Mb_2 the average thickness of sandstone layer and graded sandstone division, the average proportion of graded sandstone division to graded unit (or sandstone layer) and the thickness ratio of mean level of graded sandstone division to laminated and cross-laminated sandstone divisions all increase from the proximal to medial facies (Fig. 26). Nevertheless, there are some distinct differences between Mb_1 and Mb_2 in the general tendency of lateral variation in the same direction. From the proximal to medial facies, the average thickness of laminated and cross-laminated sandstone divisions in unit Mb_1 markedly increase, while that of unit Mb_2 shows little change. The average proportion of laminated sandstone division plus cross-laminated sandstone division to graded unit becomes higher in the same direction for unit Mb_1; it decreases considerably for unit Mb_2. In addition, the average thickness of graded sandstone division increases from the proximal to medial facies at a greater rate in Mb_2 than in Mb_1.

Closely related to the aforementioned types of lateral variation in sedimentary aspects of unit Mb_2 are the differences in features of sole markings among facies types. The flute casts in the sediments of facies α (the medial facies) are in the great majority of cases medium- and large-sized, occasionally even very large-sized, as contrasted with the generally small-sized forms in the sediments of facies β and γ (the proximal facies). Fan-shaped casts are dominant over linguiform ones in facies β and γ; in facies α the reverse takes place and even spatulate-shaped casts are occasionally found. Groove casts are very common, many of them being medium- to large-sized in facies α; they are scarce and small-sized in the other facies. From these differences it follows that the turbidity currents producing current marks had a higher velocity and a greater eroding power for facies α than for facies β and γ.

Lateral variation of the sedimentary facies in Member Mc

Member Mc consists chiefly of sandstone throughout. The lateral facies variation of this member is examined along the trend of the strata roughly parallel with the long axis of the gross sedimentary body (Figs. 28, 29). In this member three relatively coarse-grained horizons are discerned which are called here C_1, C_2 and C_3 in ascending order (Fig. 29).

Unit C_2, as compared with unit C_1, is coarser grained and extends more

* Sandstone decreases along the upper valley of the Pombetsu (see Fig. 45) north of the Ikushumbetsu Valley.

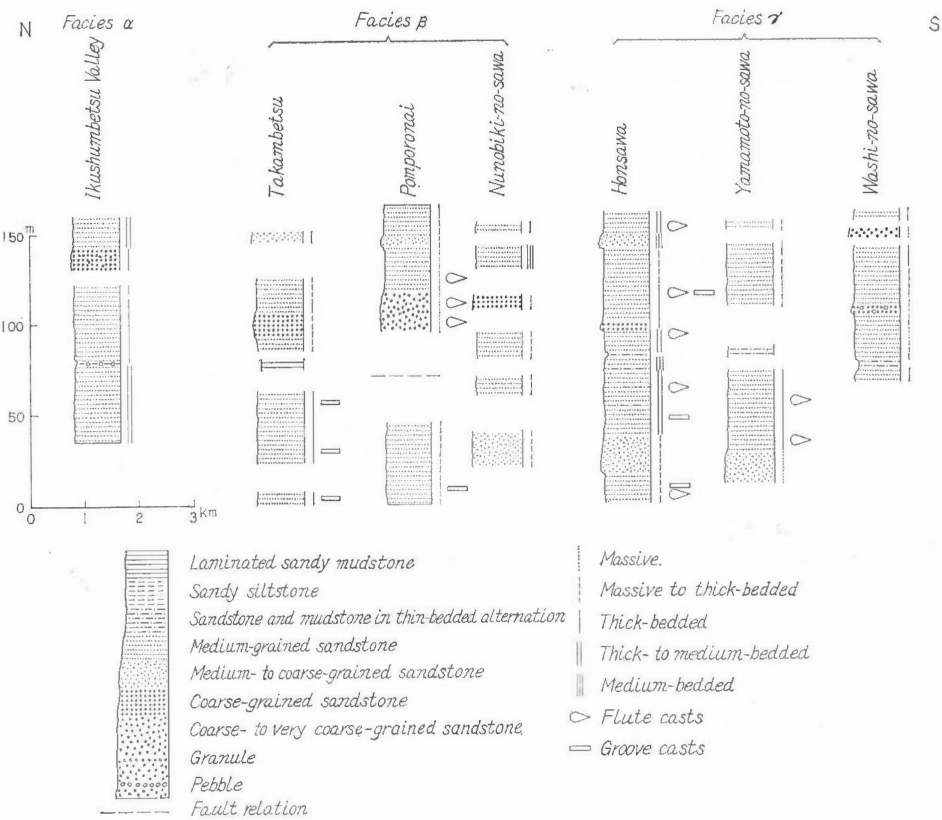


Fig. 28. Columnar sections of Member Mc along some selected routes.

The horizons of flute casts and groove casts are omitted from the Ikushumbetsu section because of the ubiquitous occurrence of these casts.

northwards than the latter. It is coarsest in the southern part of facies γ area, becoming pebbly there. Unit C_2 much thickens in facies β area where the sediments are coarser grained and more thickly bedded in the medial part than in the proximal and distal parts. In this manner, the lenticular profile of the sedimentary body and the lateral variation of the sedimentary features in unit C_2 of facies β remind us of those in unit Mb_1. Taking into consideration the extension and coarseness of units C_1 and C_2 as well as the lateral change in frequency of bedding in the lower and middle parts of the member, it may be suggested that the facies advanced northwards farther for unit C_2 than for unit C_1 or farther for the middle part than for the lower part. The northward advance of facies with time may be ascribed largely to increasing uplift of the source area and resultant increasing supply of materials.

The uppermost coarse horizon, C_3, becomes finer grained from facies γ to facies β, i.e. northwards. It, however, becomes coarser grained again in facies α in the northernmost part. Unit C_3 of facies β and γ is finer grained than unit C_2 of the same facies. Furthermore, it should not be overlooked that as will be mentioned later unit C_3 is characterized exclusively by southeastward, lateral

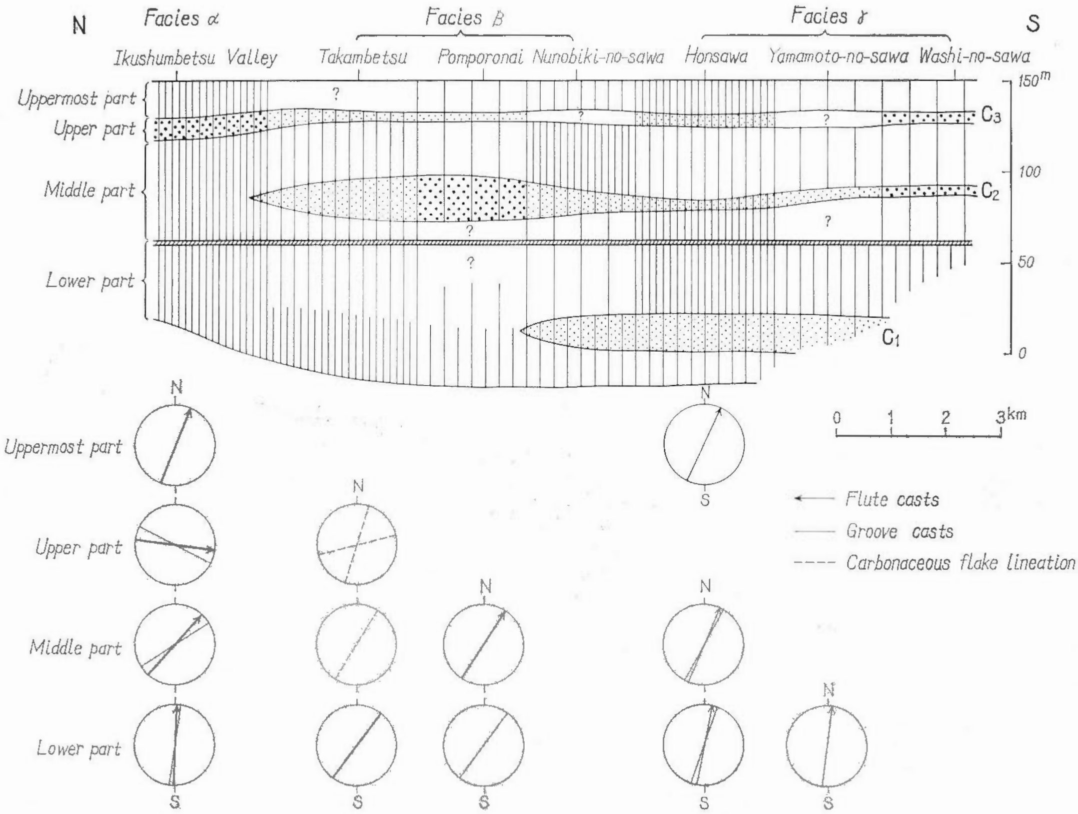


Fig. 29. Diagrammatic section showing the facies distribution and current data of Member Mc.

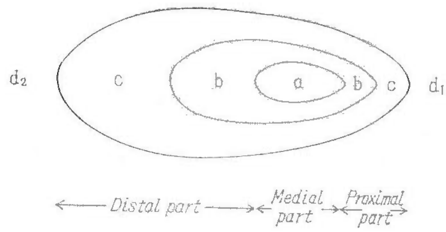
Fine dots: relatively coarse-grained zones (C_1, C_2 and C_3), coarse dots: coarsest part within relatively coarse-grained zones, inclined lines: argillaceous sediments at the top of the lower part.
Density of lineation is directly proportional to relative frequency of bedding. Heavy symbols for current directions indicate three or more readings.

currents in facies α area where unit C_2 is not developed. Hence, it may be concluded that during the C_3 period the coarse-grained facies advanced southeastwards in the northern part of the studied area but retreated southwards in the southern part.

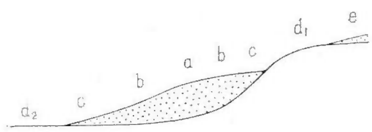
Summary of the lateral facies variation in the flysch sequence

The general lateral variation in sedimentary aspects in the Ikushumbetsu Cretaceous flysch is of two types as in the case of the Izumi Group (TANAKA, 1965): one is observed in lenticular sedimentary bodies, and the other in wedge-shaped ones.

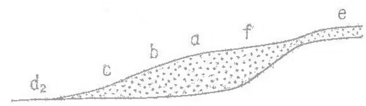
Lateral variation in sedimentary features in a lenticular body is best exemplified by unit Mb_1 (Fig. 26). It is a matter of course that the lateral change of mean level in thickness of a group of graded units in unit Mb_1 is correlative to a general lateral variation in thickness of a single graded unit which itself forms a lenticular sedimentary body. Thus, a model of lenticular



A



B



C

Fig. 30. Schematic, greatly fore-shortened diagrams showing model of basin-filling by flysch (or turbidite) sediments. The vertical scale and slopes are greatly exaggerated.
A and B: lenticular sedimentary body; A, plan; B, section.
C: wedge-shaped sedimentary body, section.
Typical examples of facies distribution: a, turbidite A facies; b, turbidite B facies; c, laminite facies; d_1, massive siltstone facies; d_2, laminated mudstone facies; e, neritic sandstone facies; f, fluxoturbidite facies.

body (Fig. 30A, B) is presented with some minor but significant modification of BOUMA's model of the deposition cone of a turbidity current (BOUMA, 1962, fig. 25A; EINSELE, 1963, fig. 6). The model presented here, on the other hand, is the same as that of the Izumi Group (TANAKA, 1965, fig. 22). In the lenticular body under discussion the proximal, medial and distal facies (or parts) are recognized. The medial facies is thicker and coarser grained than the others, being developed in the posterior (up-current) part within the sedimentary body, but not at the proximal extremity of the body. In this way the lenticular sedimentary body is very asymmetrical lengthwise. A similar situation is found in MEISCHNER's model of allodapic limestones referred to turbidites (MEISCHNER, 1964, fig. 2) and the Neogene graded sandstone layers in the Boso Peninsula, southeast of Tokyo (HIRAYAMA and SUZUKI, 1968). In BOUMA's model, however, the equivalent of the medial facies designated here is developed just at the proximal extreme part of his deposition cone of a turbidity current. Furthermore, it should be emphasized that the more proximal facies of a lenticular body or the much more proximal shale facies is occasionally accompanied by slump deposits as exemplified by the chaotically mixed sediments in unit Ma_3 of facies β. In an ideal case, the sedimentary features of the flysch deposits forming a lenticular body show the following significant changes from the medial to distal facies. With regard to a single layer of sandstone involved, the layer thickness and graded division thickness decrease, and the percentage of graded division becomes lower, while the percentage of laminated division plus cross-laminated division becomes higher. The sandstone layers become finer grained at the base, more weakly undulating on the bottom surface and less graded. In a sequence of graded sandstone frequently interbedded with shale, which corresponds to stratigraphical units like members, the following lateral variations from the medial to distal facies would be noticed in addition to the general tendencies described above. Graded units beginning with graded sandstone division decrease, but those ending with massive mudstone division increase. Composite graded bedding becomes less common. Thickness distribution of sandstone layers becomes narrower.

The general tendency of the lateral facies variation from the proximal to medial is opposed to that from the medial to distal. However, it can be pointed out that the lateral variation is much more gradual from the medial to distal facies than from the medial to proximal facies because of the extremely posterior position of the medial facies. It is also known that graded sandstone division occurs less commonly and is much thinner in the proximal and distal facies than in the medial facies, and that cross-laminated sandstone division becomes predominant over laminated sandstone division from the medial to distal facies and from the medial to proximal facies. These facts demonstrate that graded sandstone division comes to be progressively replaced by laminated sandstone division and then the latter, in turn, by cross-laminated sandstone division distally as well as proximally. Equally important is that the lateral variation of graded unit thickness is controlled fundamentally by that of sandstone thickness which, in turn, is ascribed to the lateral change of graded division thickness. Furthermore, it seems probable that massive mudstone division has a general tendency to increase its thickness from the proximal to distal facies despite that this division is usually eroded by the turbidity current depositing the overlying sandstone layer. However, the average thickness of the massive mudstone division in unit Mb_1 is smaller in facies α, Takambetsu, and in facies β than in facies α, Ikushumbetsu Valley, and in facies γ (Fig. 26). The main, if not the only, reason for this is that the division originally deposited in the former two facies was deeply eroded by turbidity currents.

In order to know whether any turbidite sequence exhibits a proximal facies or a distal facies, WALKER (1967) proposed the ABC index, P_1 that represents the proportion of layers in the group beginning with divisions *a*, *b* and *c* (see p. 17 of this paper) and is largely a function of proximality. The index is applicable to the lateral variation from the medial to distal facies, but not to the proximal to medial facies variation, in the lenticular body under consideration, and to the proximal to distal facies variation in the wedge-shaped body to be mentioned below. With unit Mb_1, this index gives 52.9 for the distal (α) facies, 82.5 for the medial (β) facies and 58.2 for the proximal (γ) facies. With unit Mb_2, the index changes from 65.2 through 83.4 to 91.7 from the proximal (γ) facies through facies β to the medial (α) facies.

An example of the distribution of unit types and sequence types is shown in Figs. 30A and B. As to the facies disposition of the flysch sequence, a lenticular body displays a generalized facies variation in the downstream direction as follows: laminite facies with slump beds→turbidite B facies→turbidite A facies→turbidite B facies→laminite facies (Fig. 30A, B). The proximal laminite facies is distinguished from the distal laminite facies by the predominance of inconspicuous or discontinuous sandstone laminae, and grades upcurrent into the massive siltstone facies that was deposited mainly on the continental shelf. Thus, it is worthy of mention that the lenticular turbidite facies characterized by redeposited sandstone is separated from the autochthonous sandstone facies in the marginal part of the basin by the massive siltstone facies (Fig. 30B).

Another type of lateral variation in the flysch sediments occurs in wedge-shaped sedimentary bodies. The lateral facies change from Member Me to the southern equivalent, the lowermost part of the Mikasa Formation on the east wing of the Ikushumbetsu anticline, is a case in point. The idealized facies variation from the proximal to distal facies is as follows: neritic sandstone facies →fluxoturbidite facies →turbidite A facies → turbidite B facies → laminite facies (Fig. 30C). In their relatively distal part, however, wedge-shaped sedimentary bodies occasionally have the same general tendency of lateral facies change as lenticular bodies. By way of example, the turbidite B facies is developed between the proximal, fluxoturbidite facies and the distal, turbidite A facies. Such is the case with the middle coarse horizon (C_2) of Member Mc (Fig. 29). It should be added here that any wedge-shaped sedimentary body tends to become thinner on the outer edge of the continental shelf.

The flysch sediments forming a wedge-shaped body display the following significant variations as the facies changes from proximal to distal: sandstone layers become thinner, more regularly bedded and finer grained; various kinds of laminations in sandstone layers become better developed; shale interbeds become more frequent and thicker, thus the sandstone percentage of graded units or the sandstone-shale ratio becoming lower. Graded bedding which is absent or little developed in the proximal, fluxoturbidite facies is well developed in the distal, turbidite A facies, but becomes imperceptible as the facies becomes more distal. Directional sole markings are uncommon in the proximal, fluxoturbidite facies, while they are widespread in the distal, turbidite A facies and then decrease in abundance and size towards a more distal facies.

Furthermore, it should be noted that the flysch deposits dominated by sandstone form wedge-shaped sedimentary bodies (tongues), whereas the deposits composed largely of alternating sandstone and shale occur in the form of lenticular bodies (lentils). Whether the flysch sediments in question are lenticular or wedge-shaped may depend on the conditions in and around the basin, properties of turbidity currents and so forth. Differing from the case of the flysch deposits forming wedge-shaped bodies, the deposition of the flysch deposits forming lenticular bodies may be ascribed largely to a rather small supply of coarse materials on account of a mild upheaval of the source areas and to a well-defined trough flanked with steep submarine slopes due to intensive subsidence of the basin. Furthermore, it may be suggested that the turbidity currents for the lenticular bodies were derived mainly from mudflows, whereas those for the wedge-shaped bodies were derived mainly from sand-flows.

Finally, a brief mention might be made of the relation between the lithofacies and the mode of occurrence of sole markings. For this purpose, Mb_1, Mb_2, Mc and Me of facies α on the eastern wing of the Ikushumbetsu anticline are to be compared with one another as the representatives of different types of facies in the flysch sequence under discussion (Table 21*). Directional sole markings, e.g. flute casts, groove casts and striation casts, are widespread in the turbidite A facies. In the fluxoturbidite facies, however, directional sole markings are few, if any. The flute casts of the turbidite A facies are as a general rule larger sized, more elongated, more commonly superimposed and more frequently

* In Member Me of facies α the subordinate turbidite A facies with some current marks is not included.

Table 21. Relation between sedimentary facies and mode of occurrence of sole markings

		Mb_1 (Facies α)	Mb_2 (Facies α)	Mc (Facies α)	Me (Facies α)
Lithology		Sandstone and shale in thin-bedded alternation.	Sandstone and shale in alternation.	Bedded sandstone.	Massive sandstone.
Facies interpretation		Turbidite B facies (normal flysch).	Turbidite A facies (normal flysch).	Turbidite A facies (sandy flysch).	Fluxoturbidite facies (sandy flysch).
Flute casts	Frequency	Common.	Abundant.	Abundant.	Not found.
	Size	Small-sized, occasionally medium-sized.	Medium- and large-sized.	Medium-sized, occasionally small- and large-sized.	
	Maximum length	5cm.	20cm.	15cm.	
	Shape	Linguiform, occasionally fan-shaped.	Linguiform, occasionally spatulate-shaped.	Linguiform, occasionally spatulate-shaped.	
	Arrangement	Individual.	Individual, occasionally superimposed.	Individual, occasionally superimposed.	
	Loading	Scarce.	Common.	Rather common.	
Groove casts	Frequency	Scarce.	Abundant.	Scarce.	Not found.
	Size	Small-sized.	Medium- and large-sized, occasionally small-sized.	Small- and medium-sized.	
	Maximum width	0.2cm.	7cm.	1cm.	
	Arrangement	Individual.	Closely spaced, occasionally individual.	Individual.	
	Loading	Scarce.	Common.	Rather Common	
Striation casts		Scarce.	Abundant.	Common.	Not found.

and strongly load-casted than those of the turbidite B facies. Groove casts also are of larger size in the turbidite A facies than in the turbidite B facies.

VII. 3 Vertical Variation of the Sedimentary Facies

Large-scale vertical variation of the sedimentary facies and sedimentary cycles

The Cretaceous formation in the meridional zone of Hokkaido shows in itself three major cycles of sedimentation (TANAKA, 1963). The flysch sequence in the Ikushumbetsu area is referred to the lower to middle parts of the second major cyclic sequence that is represented by almost the whole sequence of the Middle Yezo Group. It roughly indicates the Middle Albian (?) to Upper Albian age. The general rate of sedimentation of the flysch deposits may be at least about five times as large as that of the overlying Mikasa Formation and Upper Yezo Group. The second major cycle ranges from Middle Albian(?) to Upper Turonian in age, so the flysch formation marks the early stage of the cycle.

On the basis of the large-scale vertical variation of grain size from coarse to fine, it is noticed that the sediments of the flysch sequence present three minor cycles, which are, in ascending order, cycle I (more than 450 m thick) represented by Ma-Mb, cycle II (350 to 450 m thick) represented by Mc-Md, and cycle III (50 to 140 m thick) represented by Me, locally inclusive of Ta, the basal member of the Mikasa Formation (Fig. 25). In the southern part of the studied area cycle III is represented by the lowermost part of the Mikasa Formation. Since Member Me as cycle III is much thinner than the sequences of cycles I and II, it is alternatively referred to the upper, sandy part of cyclic sequence II which is dominated by argillaceous sediments. However, taking account of the vertical facies change in Member Me as will be mentioned later, it is natural and reasonable to regard the member as presenting a distinct cycle of the same order as cycles I and II.

The upward variation of the sedimentary facies in the minor cyclic sequences on the eastern wing of the Ikushumbetsu anticline is roughly as follows: cycle I (lower limit unknown), turbidite B facies→laminite facies with subordinate laminated mudstone facies→turbidite B facies→turbidite A facies; cycle II, local fluxoturbidite facies→turbidite A facies with local slump beds→ laminite facies with subordinate laminated mudstone facies→turbidite B facies; cycle III, fluxoturbidite facies→turbidite A facies→laminite facies→massive siltstone facies. Cyclic sequence III on the western wing exhibits an upward change from the turbidite A facies with a slump bed through the turbidite B facies to the turbidite A facies with slump beds. In short, the vertical facies variation is symmetrical (sequence: a→b→c→b→a) in cycle III on the western wing and in cycle I, but asymmetrical (sequence: a→b→c→a) in cycle II and in cycle III on the eastern wing. Transition from a given cycle to the succeeding cycle is generally rapid. Thus, an ideal minor cycle in the flysch sequence would display the following upward symmetrical changes in facies: fluxoturbidite facies →turbidite A facies→turbidite B facies→laminite facies→turbidite B facies→ turbidite A facies→fluxoturbidite facies at the beginning of the succeeding cycle.

Epicycles are superposed on the minor cycles described above; they are seven in cycle I, five in cycle II, three in cycle III on the east wing of the anticline and more than five in cycle III on the west wing (Fig. 25). The epicyclic sequences range generally from 20 to 130 m in thickness. Furthermore, it should be emphasized that acid tuff usually occurs in the lower or upper part of the epicyclic sequences, but never in the middle part (Fig. 25) as in the case of the minor cyclic sequences of the Izumi Group (TANAKA, 1965) which are comparable to the epicyclic sequences of the Ikushumbetsu area in time-space magnitude and mode of origin. Whenever tuff is found in the middle part of any epicyclic sequence, it actually occur in the lower and/or upper part of the constituent smaller-scale epicyclic sequences. A good example is presented in epicycle 7 within cycle I, Ikushumbetsu Valley.

Vertical variation of the sedimentary facies in Member Mb

The lower part of Member Mb (Mb_1) is mostly characterized by the turbidite B facies all over the area, while the upper part (Mb_2) shows the turbidite A facies (or in certain places the turbidite B facies) accompanied by the laminite facies. Unit Mb_1 and unit Mb_2 are compared in the following lines (see Tables 2, 4, 8, 16; Figs. 26, 27).

Concerning Member Mb of facies α, the average thickness of graded unit, sandstone layer and graded sandstone division and the average proportion of graded division to sandstone layer (or graded unit) are all much larger and the sandstones are much coarser grained in unit Mb_2 than in unit Mb_1. The graded units of Mb_2, as compared with those of Mb_1, begin much more commonly with graded sandstone division and end much less commonly with massive mudstone division. All these differences become smaller in the case of facies β. With respect to facies β, the sandstones of unit Mb_2 are generally fine-grained and poorly graded in comparison with those of unit Mb_1. Units Mb_1 and Mb_2 of facies γ are extremely similar to each other in many respects.

To sum up, it is concluded that the differences in sedimentary features between unit Mb_1 and unit Mb_2 become insignificant in the order of facies α, β and γ, i.e. from north to south. In this connection, the flute casts in Mb_1 of every facies are similar in size and shape to those in Mb_2 of facies β and γ. These casts are larger and more elongated in Mb_2 of facies α, in which many large-sized groove casts also occur, than in Mb_1 of the same facies. As previously mentioned, units Mb_1 and Mb_2 of facies γ exhibit the proximal facies. Unit Mb_1 of facies β is represented by the medial facies with the greatest total thickness of the unit. Unit Mb_2 of facies β shows an intermediate facies between the proximal and the medial facies. Facies α is comparable to the distal facies for Mb_1, while for Mb_2 it is regarded as the medial facies in which the thickness of the whole sequence becomes greatest. Hence, the difference between Mb_1 and Mb_2 in facies disposition, considered together with the aforesaid difference in sedimentary features between the two sequences, suggests that the facies and the centre of subsidence may have shifted northwards as the time lapsed from Mb_1 to Mb_2 owing to the increasing rate of uplift in the southwestern source area, thus supplying a larger amount of sediments into the basin, and to the increasing distance of sediment-transport by turbidity currents of higher speed and other conditions. A quite similar northward advance of facies took place during the deposition of Member Mc.

Vertical variation of the sedimentary facies in Member Me along the Pombetsu Valley

As was mentioned earlier in this chapter, Member Me of facies δ is regarded as showing a single minor cycle of sedimentation. This point, however, should be confirmed by more detailed investigation of the vertical variation of the sedimentary features. For this purpose, a statistical analysis was made of the sedimentary features of divisions B, E and F which were selected, for convenience' sake, to represent the lower, middle and upper parts of the member respectively (Tables 2, 4, 8, 16; Figs. 31,* 32, 33).

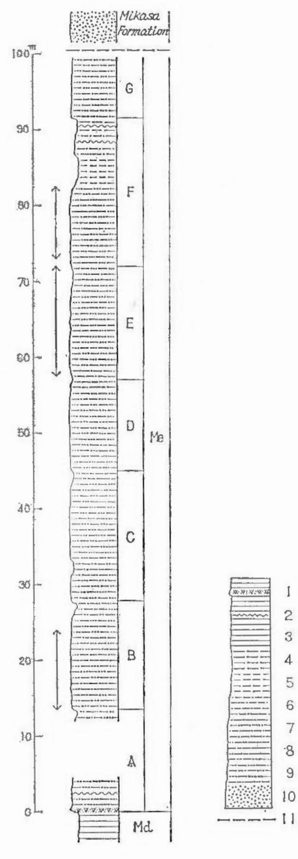


Fig. 31. Stratigraphic section of Member Me of facies δ along the Pombetsu Valley.

1: tuffaceous sandstone.
2: slump bed.
3: mudstone, laminated.
4: laminated sandy mudstone.
5: fine-sandy siltstone with occasional thin sandstones.
6: mudstone and sandstone in thin- to very thin-bedded alternation (mudstone being predominant).
7: mudstone and sandstone in very thin-bedded alternation (ditto).
8: sandstone and mudstone in very thin-bedded alternation (sandstone being predominant).
9: sandstone and mudstone in thin- to very thin-bedded alternation (ditto).
10: fine-grained sandstone.
11: fault relation.

Arrows indicate the sections selected for statistical investigation of graded units.

Division E, despite its some resemblance to division F in sedimentary

* Shale layer thicknesses are thinner on an average in the basal part of division F than in the uppermost part of division E.

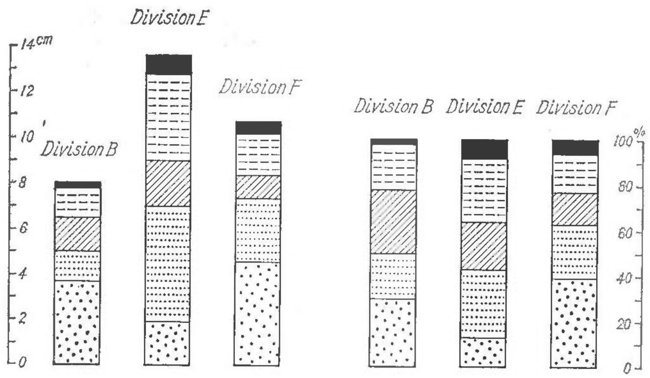


Fig. 33. Diagrams showing the vertical variation in average thickness and average division percentage of graded units in Member Me of facies δ along the Pombetsu Valley. For legends see Fig. 26.

features, is clearly distinct in many respects from divisions B and F which are similar to each other. The significant vertical changes from division B to division E are described in the lines to follow. Average thickness of graded sandstone division, average sandstone percentage and graded sandstone percentage all decrease; average thickness and percentage of shale layers increase. While graded units beginning with graded sandstone division become less common, the reverse is the case with those ending with massive mudstone division. Sandstone becomes less undulating at the sole and more poorly graded. On the contrary, the vertical change from division E to division F, roughly speaking, takes place in the reverse manner. Therefore, it must be conceded that Member Me of facies δ actually exhibits a single minor cycle. In this connection, WALKER's proximality index P_1 (WALKER, 1967) is 70.5 for division B, 64.3 for division E and 83.3 for division F. Furthermore, the flute casts in division E are smaller on the whole than those in divisions B and F.

Taken altogether, the vertical variation of sedimentary features from division B to division E displays the same tendency as the aforementioned idealized lateral variation from the medial to distal facies in a lenticular sedimentary body. There are some significant differences between them, however. For instance, both graded units and sandstone layers increase their average thicknesses from division B to division E. This tendency is similar to the lateral variation from the proximal to medial facies in a lenticular body, but not to that from the medial to distal facies. Such is the case with the vertical change from division F to division E. These contrasts are due largely to the essential differences in sedimentary attributes between Member Me of facies δ on the western wing of the Ikushumbetsu anticline and unit Mb_1 on the eastern wing as follows. As will be mentioned later, the current pattern of Member Me of facies δ is characterized by the predominance of transverse directions, whereas that of unit Mb_1 shows exclusively longitudinal directions in each facies. Thus, Me of facies δ is indicative of a relatively nearshore facies in comparison with Mb_1. Equally important is that the sediments of divisions B, E and F of Member Me were derived from different sources in contrast with the consistent derivation of the sediments of unit Mb_1. After all, it can be said that all the general tendencies of lateral variation of sedimentary features are not always reflected in any vertical variation in exactly the same manner. Furthermore, it is pointed out, as will be mentioned later, that divisions B and F exhibit a proximal facies characterized by transverse current directions and division E in which the shale is finer grained than that of the other two divisions shows a distal facies marked by longitudinal current directions.

There are, however, some exceptions to the cyclic variation of the sedimentary features in the member in question. One of the most significant phenomena is that the sandstones generally become finer grained in the order of divisions B, E and F. It will be inferred from this that the topographic relief in the source area for Member Me of facies δ became lower with time during the deposition of the member.

Vertical variation in thickness of the sandstone and shale layers

Whether or not the vertical variations of sedimentation in the Ikushumbetsu flysch sequence exhibit a general regularity on a relatively small-scale is examined here with special reference to the thickness of sandstone and shale layers in thin-bedded alternation.

The vertical variation of the sandstone thickness in thin-bedded alternations of sandstone and shale is classified into NEDERLOF's three types (NEDERLOF, 1959): oscillation, fluctuation and trend. The oscillations are small-scale variations in random sequence from layer to layer, hence not to be discussed here. The fluctuations and trends, on the other hand, are variations showing certain definite sequences, the former being of a much smaller scale than the latter.

The fluctuations recognized here are of at least two orders, major and minor, showing either a symmetrical or an asymmetrical pattern (Fig. 34). In the fluctuations of the asymmetrical type sandstone thickness decreases upwards, while in the fluctuations of the symmetrical type it shows an upward decrease which, in turn, is followed by an upward increase. The asymmetrical type is dominant over the symmetrical one. Any major fluctuation is composed of two to five minor fluctuations which, in turn, include ordinarily two or three sandstone layers for the asymmetrical type and three to five sandstone layers for the symmetrical type. The major fluctuations are of random variations in contrast with the minor ones. The former consists of five to, say, fifteen sandstone layers. The shale layer thickness, on the other hand, shows longer-term variability than does the sandstone layer thickness. The vertical variation of the shale layer thickness is not dealt with here, because the thicknesses measured do not represent the original thickness owing to erosion by the turbidity currents. As will be mentioned later, however, it may be possible to recognize cyclicity in the vertical change of mean level in the shale thickness. The major and minor fluctuations presented here correspond to SCHLEIGER's subcycle and unit (SCHLEIGER, 1964) respectively.

Trends or cycles, if present, should be detected by vertical variation of mean level, because they show much more random variations than do the fluctuations. For this purpose, taking the sequence of about 65 m within Member Me of facies δ along the Pombetsu Valley the vertical variation in thickness of the sandstone and shale layers, together with that of the sandstone percentages and sand-shale ratios, is expressed in terms of 25-layer moving average (Fig.

35*). It is clear from this figure that the sandstone layer thickness is variable in comparison with the shale layer thickness which is fairly constant in the sequence lower than layer 530 or so and on the other hand considerably variable in the sequence upper than that. However, going into detail, it may be seen that the cyclic variation of the shale thickness is nearly in harmony with that of the sandstone thickness throughout the greater part of the section under discussion. This suggests that the shale layers, or better expressed as the laminated sandy mudstone divisions, occupying the greater part of the shale layer concerned were similar in mode of deposition to the sandstone layers deposited by turbidity currents. An alternative, but less probable, explanation is that the thickness of the sandstone layers may have been controlled by the thickness of the shale layers or by the duration of deposition of the shale layers. At any rate, from the vertical change of the sandstone and shale thicknesses combined with that of the sandstone percentages and sand-shale ratios it can be pointed out that Member Me of facies δ, Pombetsu Valley shows various orders of cyclic sedimentation. For a more reasonable conclusion, as will be mentioned later, the variation with time of the current patterns or current directions also should be taken into consideration.

Thus, in the measured section that represents minor cycle III are recognized four major epicycles denoted by III1, III2, III3 and III4. Major epicycle III1 includes at least three minor epicycles (III1a, III1b and III1c). The sequences of the major epicycles are 20 to 35 m thick; those of the minor epicycles are 5 to 10 m thick, consisting of about 90 to about 120 graded units. As will be seen later, all the major epicycles and some minor ones are nearly correlative to and coincide with cycles recognized in the vertical change of the current patterns or current directions. Then minor epicycle III1a comprises two smaller-scale, less distinct cycles (III1aα and III1aβ), each consisting of some 60 graded units. In short, at least three different orders of epicycles are discriminated in the measured section. In reality, some discrepancy is found between the epicycle boundaries for the sandstone thicknesses and those for the sandstone percentages or sand-shale ratios. Furthermore, many fluctuations are recognizable in the vertical variation of mean level of the sandstone and shale thicknesses. They are composed of about ten graded units on the average (Fig. 34). Such fluctuations are to be correlated with the major fluctuations mentioned before.

Notes on the cyclic sedimentation of the flysch sequence

The Cretaceous flysch sequence of the Ikushumbetsu area is referred to the early stage of one major cycle and shows in itself three minor cycles which, in turn, consist of some epicycles. The stratigraphic range of the minor cyclic sequences which are 100 to 480 m thick or more is nearly one fourth to one third of that of one stage, a unit of time-stratigraphic classification.

The upward facies variation in the minor cyclic sequences is generalized in a symmetrical fashion as follows: fluxoturbidite facies → turbidite A facies → turbidite B facies → laminite facies → turbidite B facies → turbidite A facies → fluxoturbidite facies of the succeeding cycle. The generalized significant upward variations of the sedimentary aspects in the lower hemicyclic sequence are outlined in the following lines. Graded unit, sandstone layer and graded sandstone division decrease in thickness. Sandstone percentage and

* The blank in the curve for sand-shale ratio is due to the presence of a graded unit consisting of sandstone layer alone.

proportion of graded division to sandstone layer become lower. Sandstone becomes finer grained, less graded*, better laminated and composite graded bedding and multiple one therein become less common. Sole markings decrease in size. Interbedded shale layers increase in thickness and decrease in coarseness. Besides, slump deposits become fewer. With regard to the spatial distribution of the flysch deposits in the minor cyclic sequence, it is likely that the sedimentary body was wedge-shaped (tongue) at the earlier stage of the lower hemicycle, and lenticular (lentil) at the later stage. This change is supposed to have depended largely on decreasing sediment-supply due to progressive degradation of the source area and also on progressive sinking of the depositional area whereby the trough became deeper with increasing inclination of the lateral slope.

The major epicycles superposed on the minor cycles are represented by 20 to 130 m sequences and are composed of several minor epicycles. The general tendency of the vertical variation in the sedimentary features is essentially the same as that in the minor cyclic sequences mentioned above. The epicycles are mostly of asymmetrical type. Acid tuff beds are usually intercalated in the lower or upper part of epicyclic sequences, whether major or minor, and never in the middle.

It goes without saying that the deposition of the Cretaceous formations in the meridional zone of Hokkaido may have been fundamentally controlled by the geosynclinal sinking particular to the basin of sedimentation, i.e. the Yezo geosyncline in which the studied area is included, and by the epeirogenic movements of a much wider scope. Such is the case with the Ikushumbetsu flysch sequence. Judging from the time-space magnitudes and sedimentary aspects, however, it would be plausible to consider that the formation of each of the sedimentary cycles of various scales mentioned before cannot always be ascribed to the same cause.

In the first place, the major cycle comprising the flysch sequence under consideration began with the stage of transgression which, in turn, was followed by the stage of marine inundation combined with intense geosynclinal subsidence and ended with the stage of regression. The first stage, though unobserved in this field, is expected to be represented by the coarse sediments that unconformably covers the Lower Yezo Group in certain areas; the second stage is characterized by the flysch formation that is much thicker than the overlying neritic Mikasa Formation marking the third stage, in spite of the much shorter period of deposition. In short, it seems likely that the origin of the major cycle is ascribed largely to epeirogenic movements in comparison with that of the minor cycles involved.

In the second place, the individual minor cyclic sequences, judging from their general tendency of the vertical variation in the sedimentary features, are interpreted as largely indicating changes in the depositional environments, e.g. the depth of the depositional site and its distance from the source area. It is known that any cycle of this scale in the Yezo geosyncline is not always equal in chronologic position and time-length (TANAKA, 1963). Hence, it may be reasonable to ascribe the origin of the minor cycles largely to periodic changes of tectonic movement (uplift and subsidence) of a comparatively large scale in and around the whole basin which was closely related to the geosynclinal

* From the lowermost fluxoturbidite facies to the succeeding turbidite A facies graded bedding in sandstone becomes distinct.

sinking rather than to epeirogenic movements of a much wider scope. Such changes may have naturally affected the landward and basinward migration of the shoreline, the extension and general depth of the basin and the disposition of intensely subsiding parts of the basin, as well as the topographic relief of the source areas.

Tectonic movements in the depositional and source areas responsible for the epicycles were local and of a small scale in comparison with those responsible for the minor cycles. Therefore, it is most likely that epeirogenic movements of a much wider scope never played a role in the formation of the epicycles. At any rate, it is conceivable that the epicycles owe their origin largely to periodic changes of tectonic movement (magnitude of uplift) in the source areas, and the changes, at least in some cases, were closely related to periodic acid volcanism in the source areas and to periodic changes of tectonic movement (magnitude of subsidence) in the depositional areas. KSIAZKIEWICZ's idea (KSIAZKIEWICZ, 1960) that the megarhythms in the Carpathian flysch are regarded as having reflected cycles of erosion can be applied here to explain the origin of the epicycles. Thus, we are led to infer that in the lower hemicycle within the epicycle the magnitude of upheaval and resultant topographic relief and erosion of the source areas and the frequency and amount of sediment-supply into the basin all decreased with time. Moreover, it can be pointed out that such changes in the lower hemicycle, in an ideal case, were rapid at the earlier phase, but subsequently became gradual towards the later phase. This may suggest that rapid upheaval of the source areas took place intermittently.

Several orders of fluctuations of a smaller scale than the epicycles are recognized in the vertical variation of mean level of the thicknesses of thinly alternating sandstone and shale in Member Me of facies δ, Pombetsu Valley. These fluctuations are supposed to owe their origin largely to periodic changes in the local conditions of sedimentation at and around the point sources (mouth of submarine canyons) from which turbidity currents flowed into the trough, although their formation was possibly less influenced by tectonic movement responsible for the epicycles. By conditions of sedimentation are meant the amount of sediment-supply into the trough, the initial composition and intensity of the turbidity currents, the amount and distance of sediment-transport along the trough, the rate of accumulation, and so forth. At the same time, control of epeirogenic movements is completely negligible in the origin of such fluctuations. After all, the fluctuations described here may have been caused chiefly by successive, relatively short-term change of the properties of the turbidity currents from a common point source, because current directions were essentially constant throughout. On the other hand, relatively long-term migration of the point sources due largely to tectonic movements in the depositional and source areas is supposed to have played an important role in the formation of some of the epicycles in Member Me of facies δ that show, as will be mentioned later, a definite serial change of current directions or are characterized by a distinct current pattern.

Finally, the Ikushumbetsu Cretaceous flysch is compared with the Izumi Group of the Izumi mountain range which is dominated by turbidite sequence (TANAKA, 1965) in terms of cyclic sedimentation. The major cycles, minor cycles and major epicycles in the Ikushumbetsu area correspond respectively to the cycles of first, second (major cycle) and third (minor cycle) orders in the Izumi Group in time-space magnitude and mode of origin. The whole sequence of turbidite series occupying the main part of the Izumi Group is some 6,000 m thick, ranging from Upper Campanian to Lower Maastrichtian in age, and the major and minor cyclic sequences therein are nearly 2,000 m and 400 m in respective maximum thickness. Therefore, the general rate of sedimentation of the Ikushumbetsu flysch may be roughly estimated at one fourth to one third of that of the turbidite formation in the Izumi Group. This striking contrast is closely related to the lithological difference between the two sequences since coarse sediments such as conglomerate and sandstone are much more predominant in the Izumi Group than in the Ikushumbetsu flysch.

VIII. Palaeocurrents

VIII. 1 Current Directions

Notes on the palaeocurrent measurements

Among various types of inorganic sedimentary structures to be examined for the palaeocurrent data on the Ikushumbetsu Cretaceous flysch, representatives are flute casts and groove casts of sole markings and parting lineation and carbonaceous flake lineation, whose down-current sense is undeterminable, of internal structures (Table 22). Flute casts, bounce casts and prod casts, when as minute as several milimetres in length, are not dealt with here, because they occur together in groups constituting striation casts. Cross-laminations are of minor importance in the palaeocurrent measurements because of the difficulty in obtaining accurate reading in the field, although they are quite ubiquitous throughout the flysch deposits. Thus about 590 azimuthal measurements were made of the directional-current structures of the flysch sequence.

The general orientation of each type of directional sedimentary structures in a single sandstone layer was usually represented by only one reading. On rare occasions where two or more considerably different orientations are discriminated in one layer, two or more readings were taken. For presentation of the palaeocurrent data, any member (e.g. Ma) along a given route (e.g. Ikushumbetsu Valley) is designated here as a single station which will be called a station-member for convenience' sake (Fig. 36). A single station comprises several small areas or observation points for azimuthal measurements. For directional readings of the current indicators, post-depositional tilting of the strata concerned is removed by rotating the strata about a horizontal axis. Since the plunge of the axis of the Ikushumbetsu anticline is generally gentle, its influence on the current directions measured is almost negligible throughout the area, except the southernmost part of the anticlinal area. Furthermore, apparent horizontal flexures of the strata having current structures, due to faults or local structural behaviour must be modified to meet the general trend of the strata.

In principle the current directions of each type of sedimentary structures at any station-member are represented by a mean direction that is referred to as a station-member direction, i.e. a mean of mean directions at individual observation points within a given member or unit. In some cases, however, they are indicated by two or more widely separated modal directions or a principal modal direction accompanied by subordinate directions. In this manner, the palaeocurrent data obtained from the sole markings and from the internal

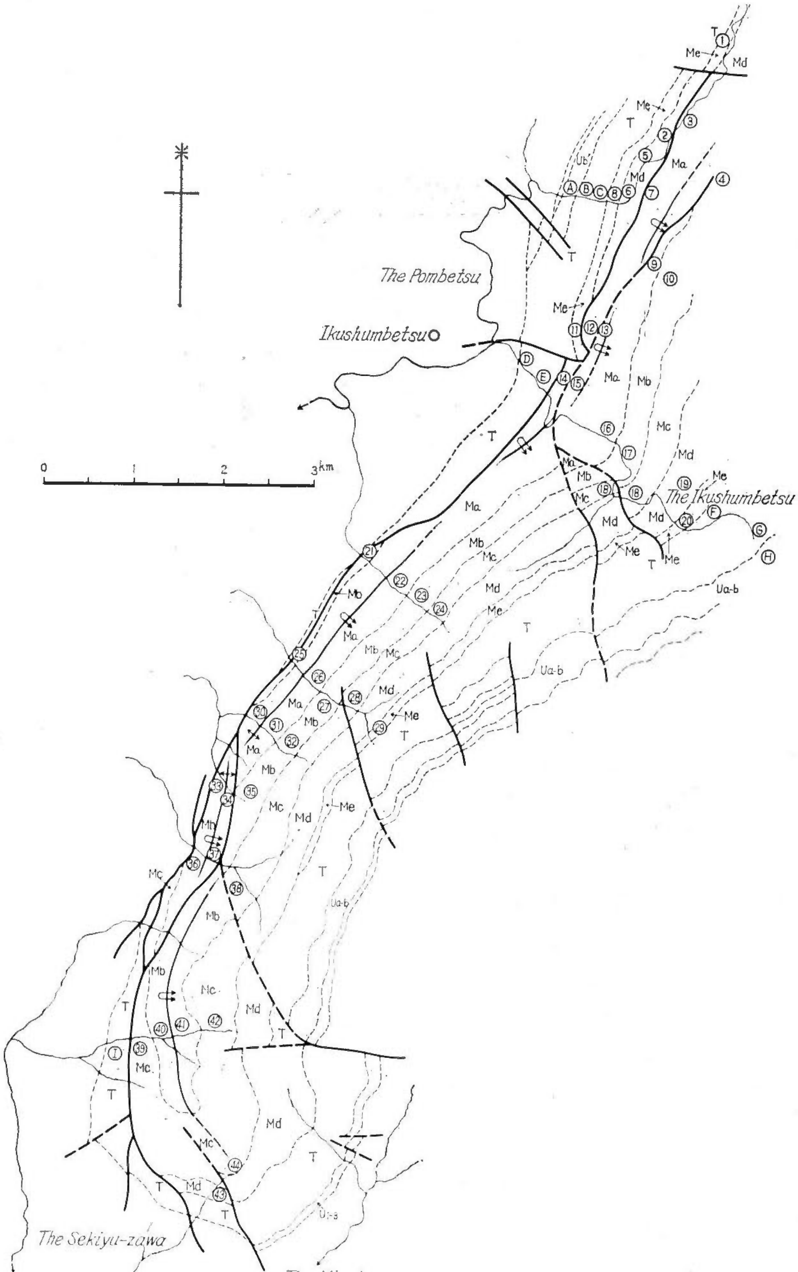


Fig. 36. Map showing the locations of station-members for palaeocurrent measurements of the Cretaceous deposits in the Ikushumbetsu area.

Figures: station-members in the main part of the Middle Yezo Group. Romans: station-members in the Mikasa Formation and Upper Yezo Group. Ma, Mb, Mc, Md and Me: main part of the Middle Yezo Group, T: Mikasa Formation, Ua-b, Ub' and U_{1-3}: Upper Yezo Group.

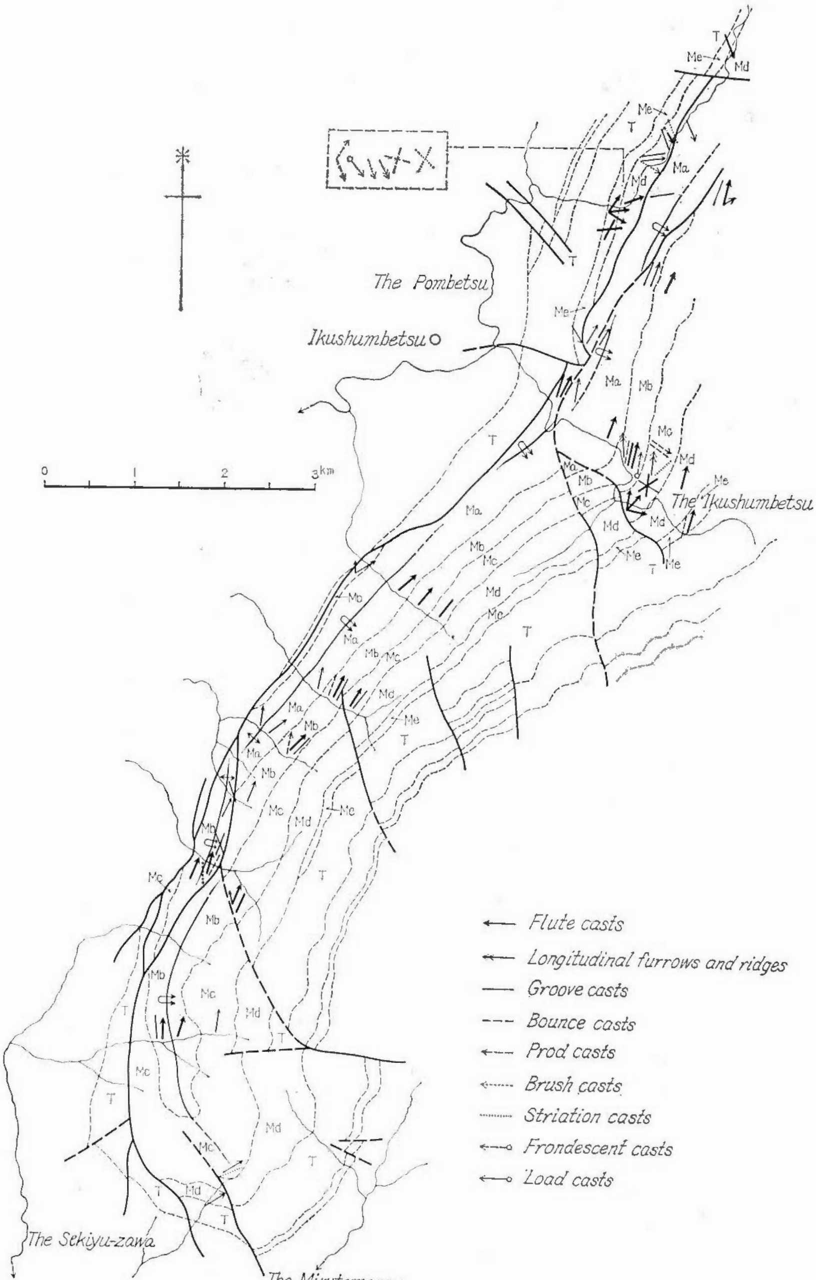


Fig. 37. Current directions deduced from the sole markings in the main part of the Middle Yezo Group in the Ikushumbetsu area.

Heavy symbols indicate three or more readings. Short arrows indicate subordinate direction or subordinate mean direction. Ma, Mb, Mc, Md and Me: main part of the Middle Yezo Group.

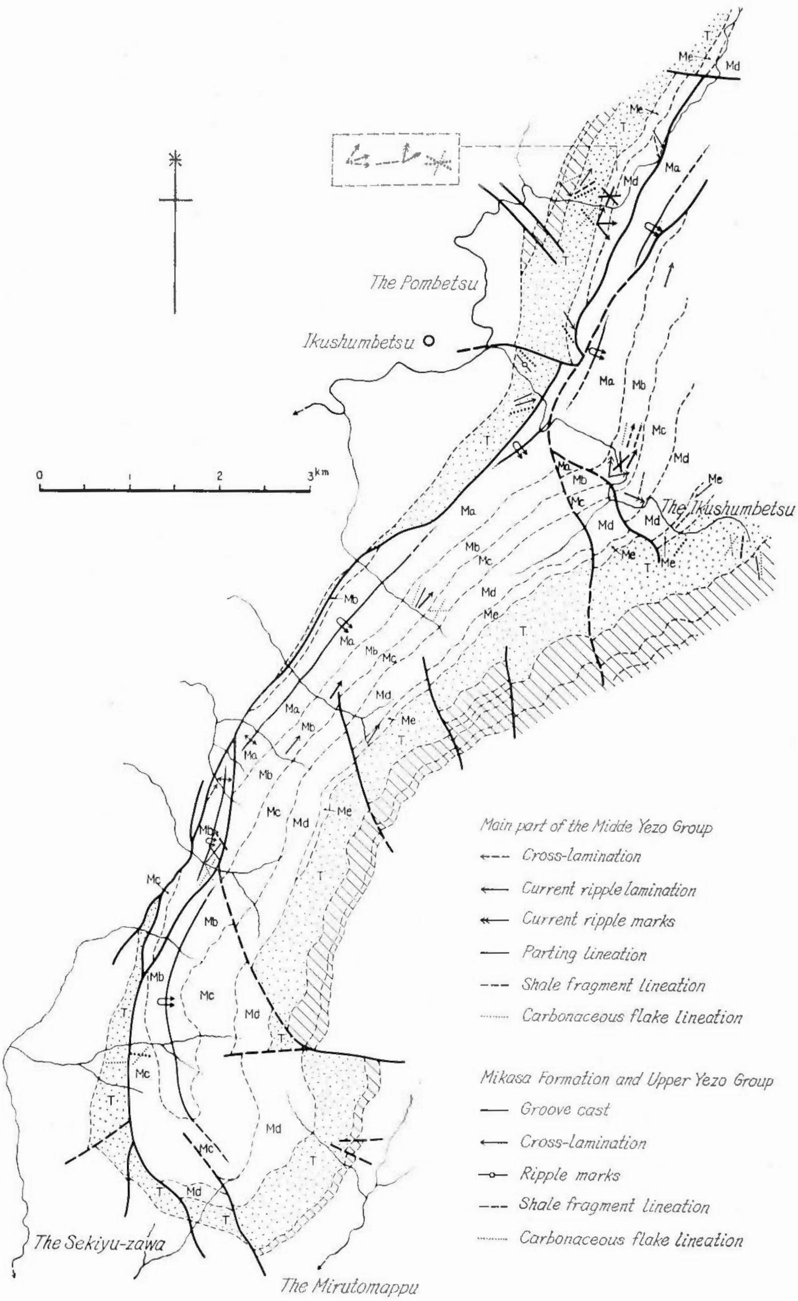


Fig. 38. Current directions deduced from the internal structures and top surface structures of sandstone layers in the Cretaceous deposits of the Ikushumbetsu area.

Heavy symbols indicate three or more readings. A groove cast of the Mikasa Formation is exceptionally dealt with here. Ma, Mb, Mc, Md and Me: main part of the Middle Yezo Group. Dotted areas: Mikasa Formation, hatched areas: Upper Yezo Group.

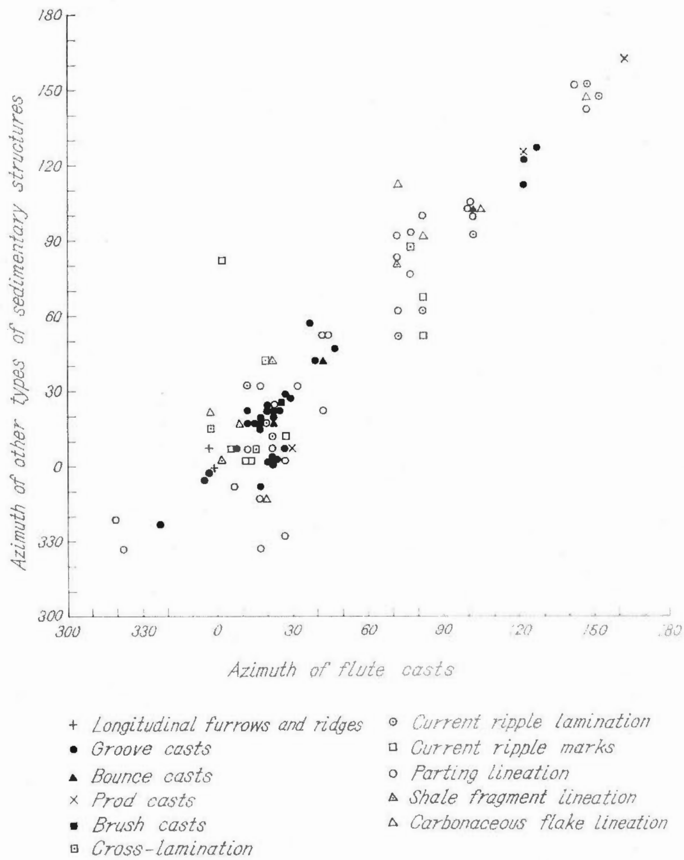


Fig. 39. Relation between orientation of flute casts and that of other types of sedimentary structures in a single sandstone layer.

structures and top surface structures are shown in Figs. 37 and 38 respectively.

General remarks on the current directions

The directions of various kinds of sole markings on the same bottom surface are usually, though not always, nearly consistent with one another (Fig. 39). No significant difference in orientation is found between the flute casts and the internal structures or top surface structures in the same sandstone layer, although there are a few exceptions (Fig. 39; Table 23). In other words, the current directions deduced from various types of current indicators measured tend to remain nearly constant during the deposition of materials from the base to the top of any sandstone layer. This point may strongly demonstrate that both the eroding current responsible for the formation of the sole markings and the depositing current forming the internal structures and top surface structures generally belonged to a single turbidity current. A similar conclusion was drawn also from the Prealpine flysch in Switzerland (CROWELL, 1955).

Table 23. Relation between orientation of flute casts and that of two or more types of sedimentary structures other than sole markings in a single sandstone layer

The data are given in azimuthal deviation from the orientation of flute casts. Plus signs: clockwise deviation, minus signs: counterclockwise deviation.

Station-member	Member or unit	Type of facies	Parting lineation	Carbonaceous flake lineation	Cross-lamination	Current ripple lamination	Current ripple marks
8	Division B of Me	δ	+20°			−20°	
			+35°	+30°		−30°	
				0°		−10°	
			0°		+5°		
	Division E of Me	δ	0°				−10°
11	Upper part of Me	δ		0°		+5°	
17	Mb_1	α	0°	0°			
			−25°	−25°			

Entering into further details, however, it can be pointed out that deviation from the direction of the flute casts in the same sandstone layer has a tendency to become greater in the order of the other sole markings (e.g. groove casts), internal structures and current ripple marks (Fig. 39). A probable explanation for this is that during the deposition of materials from the base to the top of the sandstone layer the turbidity current slowed down progressively and thus its course became more sensitively influenced either by submarine topographic relief or by indigenous currents. In this context, it is noteworthy that a very marked azimuthal discrepancy up to about 90 degrees is detected between the flute casts and the current ripple marks on a certain sandstone layer (Fig. 39). Such divergence implies that the reworking current forming the current ripple marks flowed nearly at a right angle to the course of the turbidity current that produced the flute casts. A nearly perpendicular relation between directions of sole markings and those of current ripple marks has been noticed in other turbidite sequences (WALTON, 1963; KELLING, 1964; NAGAHAMA, 1967).

Mention, furthermore, is made of the discrepancy in direction among different kinds of sedimentary structures other than sole markings in the same sandstone. The direction of current ripple marks on the top surface of sandstone layers and current ripple laminations in the relatively upper part of sandstone layers tends to deviate from the direction of parting lineation more greatly than does the direction of carbonaceous flake lineation which is developed in the relatively lower part of sandstone layers (Fig. 40). A very extreme case is the azimuthal discrepancy up to some 150 degrees between the current ripple marks and the parting lineation in a certain sandstone layer (Fig. 40*). It is added here that the directions of internal structures and top surface structures show no marked systematic deflexion, whether clockwise or counterclockwise, from the directions of sole markings throughout the area,

* The direction of the parting lineation whose down-current sense is undeterminable can be inferred from the current directions of the flute casts on adjacent sandstone layers.

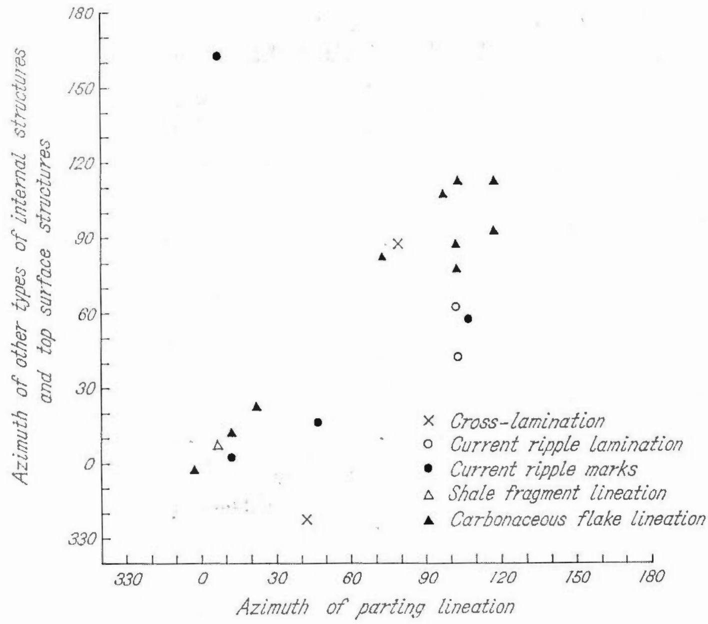


Fig. 40. Relation between orientation of parting lineation and that of other types of internal structures and top surface structures in a single sandstone layer.

although there are a few exceptions as mentioned below (Fig. 39). No progressive divergence from the direction of sole markings is found within a single sandstone layer (Table 23).

Various types of directional-current structures measured have a strong tendency to have nearly the same mean or modal direction in most of the station-members (Figs. 37, 38). Going into details, however, in the case, for example, of station-member 17, Member Mb of facies α along the Ikushumbetsu Valley, the mean direction varies more or less with the type of structure, and the mean directions of the internal structures and top surface structures show a greater diversity than do those of the sole markings, as a whole deviating clockwise from the latter (Fig. 41A). In reality, any type of the sedimentary structures at a given station-member often exhibits a fairly directional spread. For instance, at station-member 17 the orientations of the groove casts are variable in comparison with those of the flute casts (Fig. 41B). The azimuthal distribution of the flute casts measured displays a stronger mode or a narrower spread in unit Mb_2 of facies α than in unit Mb_1 of the same facies (Fig. 41C). This may suggest that the turbidity currents producing the flute casts had a higher velocity during the Mb_2 time than during the Mb_1 time. Counter-clockwise deflexion of the direction of cross-laminations from that of sole markings is recognized at station-member 37, unit Mb_1 of facies γ, Honsawa. Here the cross-laminations are consistently directed towards the north-northwest throughout the greater part of the sequence, whereas the flute casts indicate a general north-northeasterly direction. Furthermore, two or more strong principal modes of the current directions at a given station-member

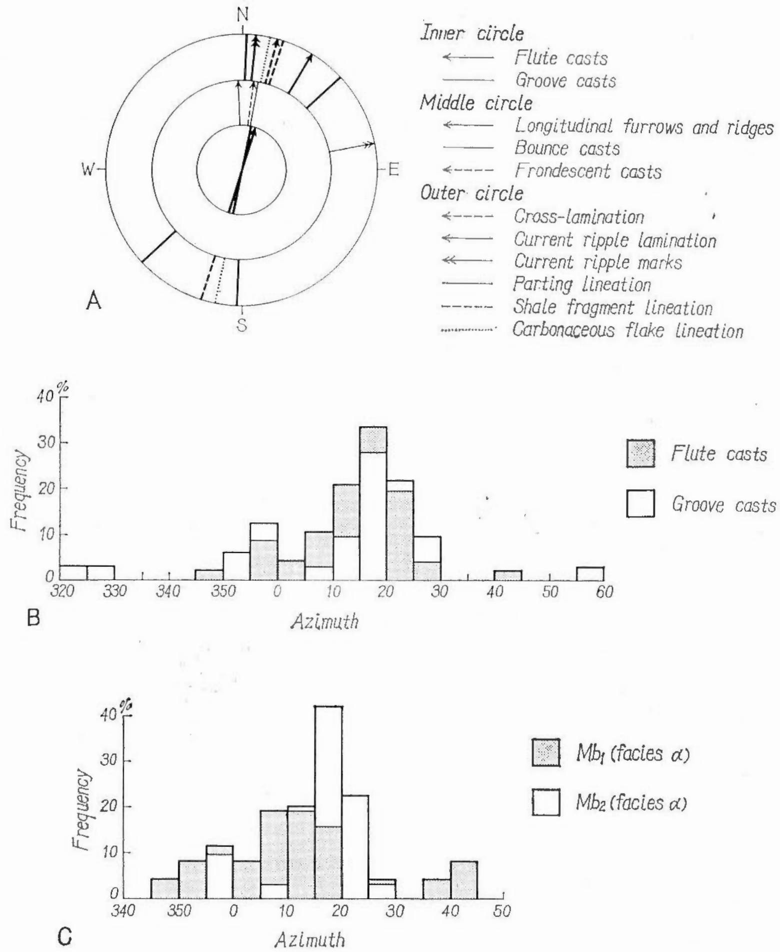


Fig. 41. Current data for Member Mb.

A. Average orientation of each type of the current-directional structures in Member Mb of facies α along the Ikushumbetsu Valley. Heavy symbols indicate three or more readings.

B. Histogram showing the azimuthal distribution of flute casts and groove casts in Member Mb of facies α along the Ikushumbetsu Valley.

C. Histogram showing the azimuthal distribution of flute casts in Member Mb of facies α in the whole Ikushumbetsu area.

For number of readings see Table 22.

depend on distinct differences in current direction between two or more stratigraphical units within the member concerned, as exemplified by the cases of station-member 8, Member Me of facies δ, Pombetsu Valley and station-member 18, Member Mc of facies α, Ikushumbetsu Valley (see Figs. 43, 44).

Regional current pattern

Apart from the current directions in the northern part of the western

Table 24. Discrepancy between orientation of flute casts and strike of sandstone layers with flute casts

The data are given in percentages.

Discrepancy	Northern part Ikushumbetsu Valley	Central part Takambetsu -Honsawa	Southern part Sekiyu-zawa
0°–15°	51.4	47.5	45.5
15°–30°	41.3	47.5	45.5
30°–45°	7.3	5.0	9.1
Total number	109	40	11

wing of the Ikushumbetsu anticline, the dominant current directions are towards the north-northeast in the northern part of the studied area, the northeast in the central part and again the north-northeast in the southern part. In order to find out whether the above-mentioned difference in the general direction of currents is due to pre-tectonic cause or to post-tectonic cause, the three parts of the studied area, each differing in the general trend of the strata, were compared in view of the relation of discrepancy between the direction of flute casts and the strike of sandstone layers on which these casts occur to the general trend of the flysch deposits. In consequence of this, it can be said that the relation is essentially similar throughout the area (Table 24). This clearly demonstrates that the local difference of the leading current directions depends fundamentally on the horizontal flexure of the general trend of the strata caused by tectonic deformation.

The sole markings, internal structures and top surface structures of the Ikushumbetsu flysch succession are found to be oriented consistently in most of the station-members (Figs. 37, 38). It is evident that north-northeasterly and

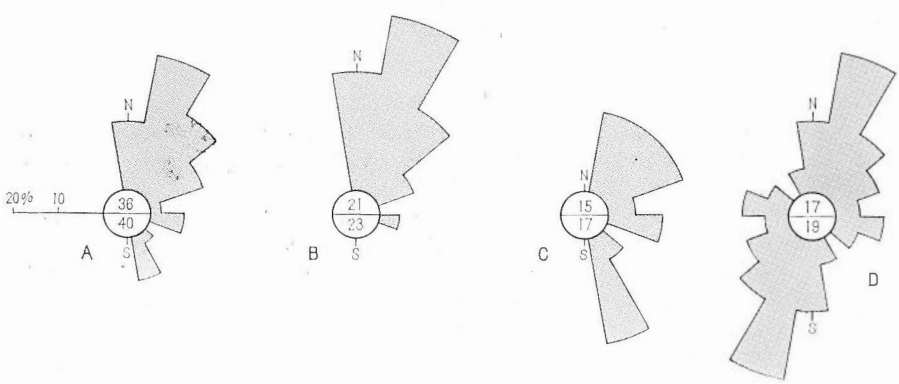


Fig. 42. Rose diagrams showing the current directions of the main part of the Middle Yezo Group.
A-C: flute casts, A: whole area, B: eastern wing of the Ikushumbetsu anticline, C: western wing of the Ikushumbetsu anticline, D: groove casts, whole area.

Upper figures: number of station-members, lower figures: number of data. The data from station-members 43 and 44 are omitted from the diagrams.

northeasterly flowing, longitudinal turbidity currents which run nearly parallel with the regional tectonic trend or the axis of the Cretaceous flysch basin played the leading part in the studied area. On the other hand, in the northern part of the western wing of the Ikushumbetsu anticline, much predominant over longitudinal turbidity currents are transverse ones flowing to the east, southeast and south-southeast, intersecting the axis of the flysch basin at large angles. The regional current pattern just described is well confirmed by the rose diagrams showing the current directions of the flute casts which have the largest number of measurements (Fig. 42B, C). It is added here that the southernmost part of the Ikushumbetsu anticlinal area is characterized by transverse currents flowing towards the east-northeast. The general orientation of the groove casts nearly coincides with that of the flute casts (Fig. 42A, D).

From the overall current pattern of sediment-transport in conjunction with the lateral variation in the gross sedimentary facies mentioned before, it would be concluded that the source area for the Ikushumbetsu flysch sequence and associated sediments, though its exact location is uncertain, was probably situated to the west of the studied area and that the offshore facies of the eastern wing of the anticline passes into distal facies northwards. Thus, the major longitudinal currents in the east may be regarded as representing the axial turbidity currents, in the sense that they flowed along the presumed axial part of the trough or in the relatively offshore part of the basin. On the other hand, subordinate are longitudinal currents in the northern part of the western wing of the anticline which was nearer the presumed western margin of the basin than the eastern wing.

It should be noticed that the general direction of the axial currents is reverse to the direction of the plunge of the Ikushumbetsu anticline. A similar relation is found in the Izumi Group where the west-flowing, axial turbidity currents indicate a direction opposite to that of the plunge of the synclinal structure (TANAKA, 1965). The situation of the Izumi Group presents a strong contrast with the examples given by KNILL (1959) and DEWEY (1962) in which the direction of the flute casts is consistent with that of the plunge of the syncline. Another matter to be noted is that the locus of maximum accumulation shifted northwards, i.e. in the same direction as the axial currents, from the Mb_1 time to the Mb_2 time. In the lower subgroup of the Izumi Group, on the contrary, the locus of maximum accumulation is found to be shifted successively in a direction opposite to that of the axial sediment-transport (TANAKA, 1965).

VIII. 2 Variation of the Current Patterns

Stratigraphical and areal variations of the current patterns

The current flows in Member Ma show consistently longitudinal directions throughout the studied area, except in the northernmost part of the western wing of the Ikushumbetsu anticline where they are characterized by transverse directions. Member Mb which is not exposed in the northern part of the west wing is represented almost exclusively by longitudinal currents all over the area. For Member Mc dominated by longitudinal currents transverse ones play an important role in the northeastern and southernmost parts of the studied area. Members Md and Me exhibit consistently longitudinal current directions on the eastern wing of the anticline, whereas in the northern part of the western wing the current directions are dominantly transverse (Figs. 37, 38).

The current pattern of Members Mc and Md in the southernmost part of the area is characterized by transverse directions.

To sum up, for the deposition of the coarse sediments of the Cretaceous flysch sequences transverse (or lateral) currents flowing eastwards to south-southeastwards are the rule in the northern part of the western wing of the Ikushumbetsu anticline. The sediments deposited consequently, i.e. those of facies

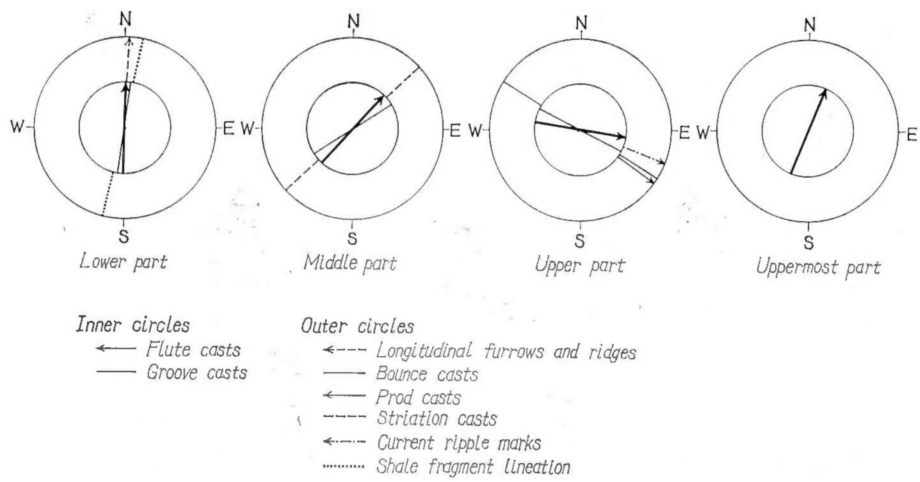


Fig. 43. Current data for Member Mc of facies α along the Ikushumbetsu Valley. Heavy symbols indicate three or more readings.

δ, can be easily discriminated lithologically from the sediments of facies α, β and γ deposited by the north-northeastward flowing, major longitudinal (or axial) currents. Furthermore, the fan-like spread of the current directions in Member Mc of facies α, Ikushumbetsu Valley is ascribed to the fact that the directions vary with stratigraphical unit (Fig. 43). In this case transverse directions are restricted to the upper part of the member in which the sandstone layers are generally thicker and coarser grained than in other parts.

Vertical variation of the current pattern in Member Me along the Pombetsu Valley

The current pattern is characterized exclusively by transverse directions in division B, the lower part of the member, and in divisions F and G, the upper part; it is dominated by longitudinal directions in division E, the middle part. Therefore, it can be said that division E shows an offshore facies in comparison with divisions B, F and G. The current pattern of division A, the lowermost part of the member, exhibits both longitudinal and transverse directions (Fig. 44). The vertical variation of the current pattern, together with that of the sedimentary features described in the preceding chapter, strongly demonstrates that the member in question shows a single cycle of sedimentation (minor cycle) preceded by at least one smaller cycle (epicycle) represented by division A. Judging from the facies distribution in Member Me, it may well be said that the longitudinal currents of the member of facies δ in the west were

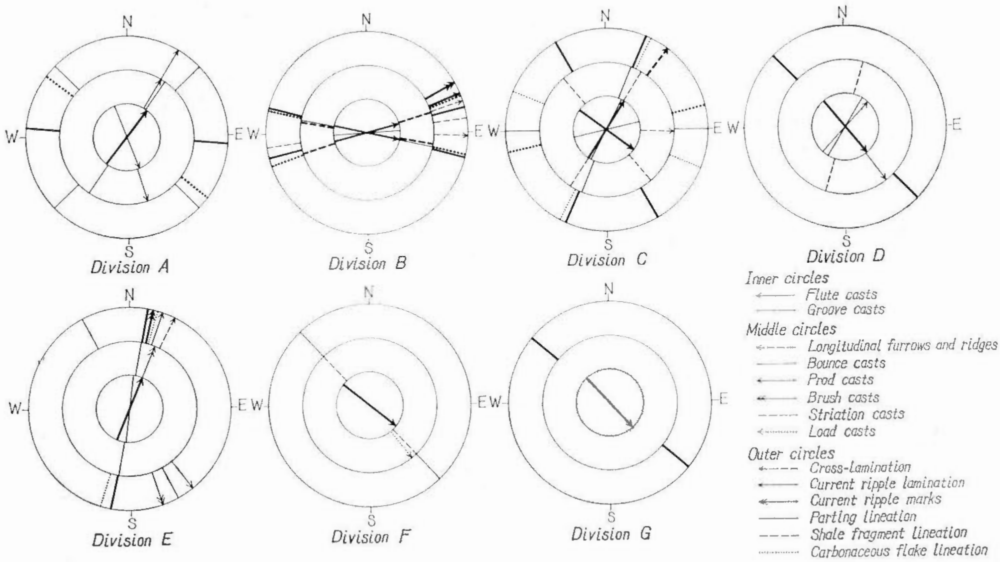


Fig. 44. Current data for Member Me of facies δ along the Pombetsu Valley. Heavy symbols indicate three or more readings.

independent of the major, longitudinal currents in the east, i.e. the axial currents depositing the member of facies α.

In an about 65 m sequence within the member under discussion in which consecutive azimuthal measurements were made of various kinds of current indicators wherever possible, four cycles are recognized which are represented by periodic changes from, say, transverse to longitudinal current directions (Fig. 35*). Such a cyclic variation of the current pattern indicates that the site of deposition changed periodically from a relatively near-shore to relatively off-shore environment. These cycles are correlative with and correspond nearly to the four major epicycles (III1, III2, III3 and III4) which are detected in terms of cyclic change of mean level of the sandstone and shale layer thicknesses, sandstone percentages and sand-shale ratios. Roughly speaking, the transverse currents are towards the east for the first cycle, while they are towards the southeast for all the succeeding cycles. Thus, the point sources for the coarse sediments of the member may have migrated laterally, say, northwards. Any minor epicycle is represented either by a transverse current series succeeded by a longitudinal one or by a transverse current series alone. The transverse current series in minor epicycle III1a barely displays cyclic variation of current directions in the manner in which the azimuths at the later stage deviate slightly northwards from those at the earlier stage, that is, they somewhat approach longitudinal current directions. Roughly speaking, the two current series thus separated mark much smaller cycles III1aα and III1aβ respectively. Apart from the aforementioned several different orders of cyclic variation in current pattern, longitudinal current directions are accidentally found

* The azimuths of the directional structures whose sense of current movement is undeterminable can be inferred with a high degree of reliability from the current directions especially of the flute casts on the same or adjacent sandstone layers.

within the transverse current series, while transverse current directions occur rarely within the longitudinal current series. Furthermore, the short-term variations of the azimuth appear to be random.

In short, cyclic variation of various scales are recognized not only in the thickness of sandstone and shale layers, the sandstone percentage and the sand-shale ratio but also in the current directions. In fact, the long-term cyclicity of sedimentation in the member under discussion would be better expressed as a cyclic variation in current direction. It is worthy of mention that the sequences represented by the longitudinal current series have smaller moving average values of sandstone percentage or sand-shale ratio than do the subjacent and superjacent sequences represented by the transverse current series. A further point which requires emphasis is that the transition from the transverse current series to the longitudinal one or that from the latter to the former is rapid as a rule. This point may suggest that the individual current series, each having its characteristic general direction, were derived from different point sources that were relatively far apart. However, the transition from the eastward, transverse current series to the succeeding longitudinal one is rather slow. Eventually it is concluded that the major epicycles in Member Me of facies δ fundamentally reflect periodic changes in position of the depositional site within the basin and migration with time of the point sources which were caused by tectonic movements in the depositional and source areas. On the other hand, the cyclic azimuthal variation of a small scale within the transverse current series with a roughly eastward direction in minor epicycle III1a (i.e. the case of III1aα and III1aβ) may have taken place in response to a slight change with time of the slope (or submarine topography) as caused by differential accumulation of sediments from a common point source and other conditions rather than in response to migration of the point sources.

VIII. 3 Current Systems and Palaeogeography

Supplementary data concerning the regional current pattern

In order to supplement the current pattern of the Ikushumbetsu flysch, described here are the current patterns of the contemporary flysch deposits in the adjacent areas and of the overlying Mikasa Formation and Upper Yezo Group in and around the Ikushumbetsu area. Concerning the flysch sequence along the upper valley of the Pombetsu, northeastward, longitudinal turbidity current directions seem to be dominant on the eastern wing of the Ikushumbetsu anticline and eastward, transverse ones on the western wing in harmony with the current pattern of the Ikushumbetsu area (Fig. 45). Another example of current pattern of the contemporary flysch deposits is given of the Yubari area south of the Ikushumbetsu area. Here, the palaeocurrent measurements were made of sole markings in Member M_2, some 100 m thick and Member M_3, about 150 m thick, which are nearly comparable with Member Mb-Mc and Member Md of the Ikushumbetsu area respectively. As a result, it is found that the general sediment-transport was controlled exclusively by easterly to southeasterly flowing, lateral turbidity currents (Fig. 46). The conclusion presented here, therefore, is that the resemblance between the Yubari area and the southernmost part of the Ikushumbetsu anticlinal area is found not only in lithofacies and thickness but also in current pattern.

The palaeocurrent data on the Mikasa Formation and Upper Yezo Group of

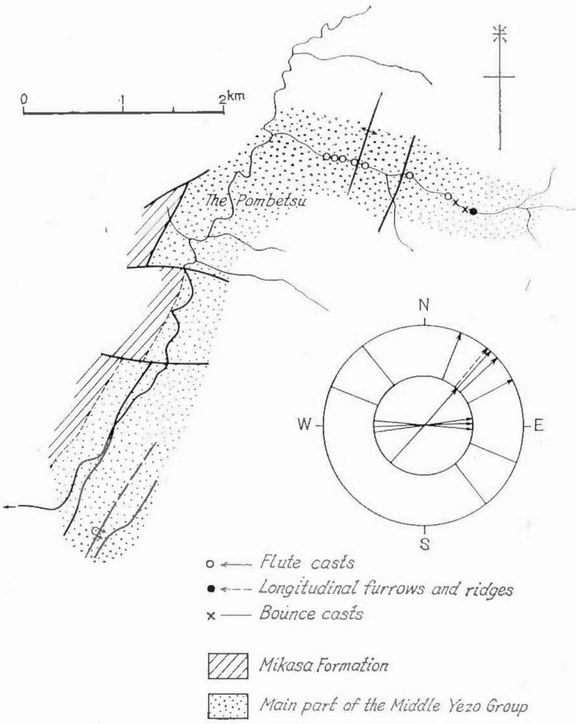


Fig. 45. Current data for the main part of the Middle Yezo Group along the upper course of the Pombetsu Valley.

Inner circle: western wing of the Ikushumbetsu anticline, outer circle: eastern wing of the same anticline. The southern part of the map corresponds to the northernmost part of the area shown in Fig. 37.

the Ikushumbetsu area were obtained from current-oriented structures, including carbonaceous flake lineation and cross-lamination, in sandstones or sandy siltstones at a limited number of station-members (see Fig. 36; Table 25). A large-sized groove cast found in the Mikasa Formation of shallow-sea deposition draws one's attention. The Mikasa Formation and the lower part of the Upper Yezo Group are characterized by northward to northeastward, longitudinal (or axial) currents (traction currents) on the east wing of the Ikushumbetsu anticline and by east-northeastward or southeastward, transverse (or lateral) currents (traction currents) on the west wing in harmony with the regional current pattern of the flysch formation (see Fig. 38). In addition, the lateral currents of the Mikasa Formation in the northern part of the western wing vary in direction from place to place and from horizon to horizon. This phenomenon may be ascribed largely to shifting deltaic distributary patterns.

As regards the Upper Yezo Group along the mid-valley of the Ashibetsu, the eastern wing of the Sorachi anticline where turbidite sediments are common in several parts, the turbidity currents were longitudinally directed towards the north and northeast as in the case of the group on the eastern wing of the Ikushumbetsu anticline (Fig. 47). This current pattern supports the

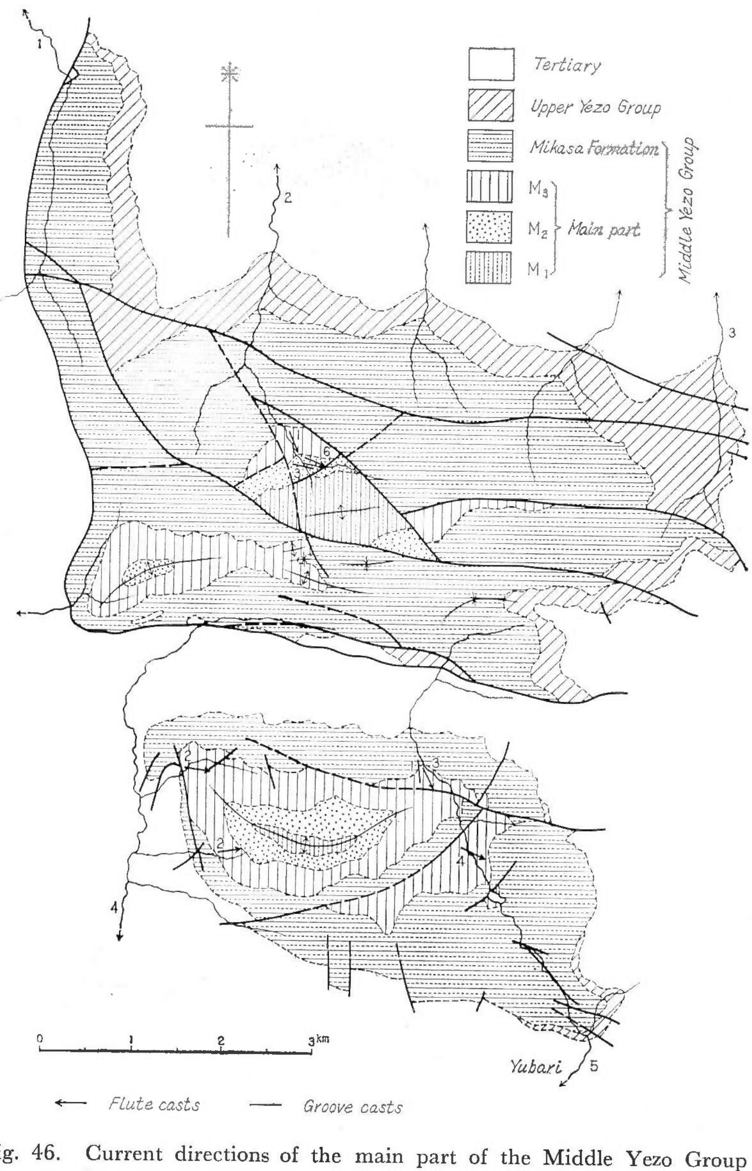


Fig. 46. Current directions of the main part of the Middle Yezo Group in the Yubari area.

The data are given in average directions. Numerals attached to symbols indicate number of readings.

1: Ichi-no-sawa.
2: Shikoro-zawa.
3: Futami-zawa.
4: Anoro-gawa.
5: Pomporokabetsu.

interpretation that the Upper Yezo Group on the eastern wing of the Sorachi anticline approaches a proximal facies southwards as discussed in my previous paper (TANAKA, 1959).

Table 25. Number of palaeocurrent measurements for the Mikasa Formation and the Upper Yezo Group in the Ikushumbetsu area

The data are given in numbers of sandstone layers dealt with for measurements.

Area	Station-member	Member		Facies	Groove cast	Cross-lamination	Current ripple marks	Shale fragment lineation	Carbonaceous flake lineation
Pombetsu Valley	A	Lower part of the Upper Yezo Group	Ub′			2			2
	B	Upper part of the Mikasa Formation	Twd	β				1	2
			Twc	β		1		2	2
	C	Lower part of the Mikasa Formation	Twb	β					2
			Twa	β					3
Ikushumbetsu Valley	D	Upper part of the Mikasa Formation	Twd	β			1		7
			Twc	β					4
	E	Lower part of the Mikasa Formation	Twb	β					4
			Twa	β	1	1			2
Katsurazawa	F	Lower part of the Mikasa Formation	Tb	α					8
	G	Upper part of the Mikasa Formation	Td	α				4	4
	H	Lower part of the Upper Yezo Group	Ua					1	1
Sekiyu-zawa	I	Mikasa Formation	Middle part	δ					1
			Lower part	δ					1
		Total			1	4	1	8	43

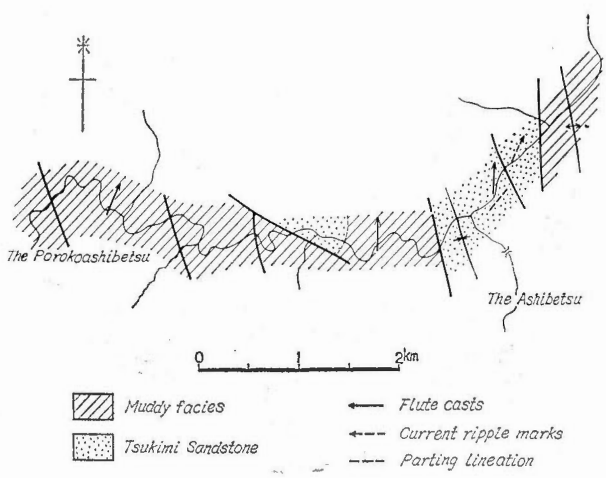


Fig. 47. Current data for the Upper Yezo Group along the Ashibetsu and Porokoashibetsu valleys on the eastern wing of the Sorachi anticlinal area.

Palaeogeographic control of the sedimentation

As can be seen from what has been mentioned so far the coarse sediments of the Cretaceous flysch sequence in and around the Ikushumbetsu area were transported, on the one hand, by lateral turbidity currents coming from the west and on the other by northward, axial turbidity currents in the relatively offshore part of the basin or along the axial part of the trough in the east (Fig. 48). This general pattern of sediment-transport is well confirmed by the lateral facies variation of the flysch sequence. It suggests that a part of the main land mass was situated to the west of the Cretaceous outcrop area during the deposition of the Cretaceous flysch formation. From the prevalence of lateral turbidity currents in the western part of the area under discussion, we are led to an inference that the trough where the flysch sequence was deposited may have been in a relatively deep-sea environment not very far from the western land mass.

It is well established that longitudinal currents played an important role in sediment-transport in many elongated flysch basins. Such is the case with the flysch succession in and around the Ikushumbetsu area. Judging from the areal distribution of longitudinal, transverse and intermediate (oblique) current directions in the flysch sequence, it may be suggested that the lateral turbidity currents turned to the axial ones flowing down on the basin floor or along the axial part of the trough as discussed on some other flysch or turbidite deposits by KUENEN (1958), DZULYNSKI *et al.* (1959) and KNILL (1959). Longitudinal filling from one end of flysch basins as postulated by KUENEN (1957b) does not apply to the Cretaceous flysch in and around the Ikushumbetsu area. Also, DEWEY's idea of the independence of lateral currents on axial currents for a certain turbidite sequence (DEWEY, 1962) is not applicable to the flysch formation. Thus, it is concluded that the east-flowing, gravity-controlled, lateral turbidity currents from point sources flowed down the lateral slopes into the trough and then changed their courses according to the northerly, longitudinal slope (or axial plunge) of the trough floor to turn into the axial currents.

Judging from the current patterns and facies distribution of the flysch series, it can be pointed out that at least two major point sources for the turbidite sediments existed somewhere to the west of the Cretaceous field studied (Fig. 48). These two major point sources thus inferred were spaced at an interval of some 20 km. Similar distances are noted also in the Izumi Group (TANAKA, 1965). In view of the lateral variation of the sedimentary facies, especially the areal distribution of coarse sediments, it may be said that the southern major point source, as compared with the northern one, was more contributory to sediment-supply into the basin owing mainly to the higher relief of the source area in some periods (e.g. the Mb, Mc and Me times), but was less contributory in other periods (e.g. part of the Mc time and the Md time) owing mainly to the lower relief of the source area. It follows that a large delta or sub-sea fan facing the northeast was situated on or beyond the shelf near the southern major point source during certain periods. In addition to the above two major point sources, the western marginal part or edge of the trough is naturally supposed to have been fringed with minor point sources discharging a small amount of sediments. A similar palaeogeographic situation and sediment-transport pattern are displayed also in the overlying Mikasa Formation and Upper Yezo Group.

It is important characters of the flysch deposits that conglomeratic rocks of

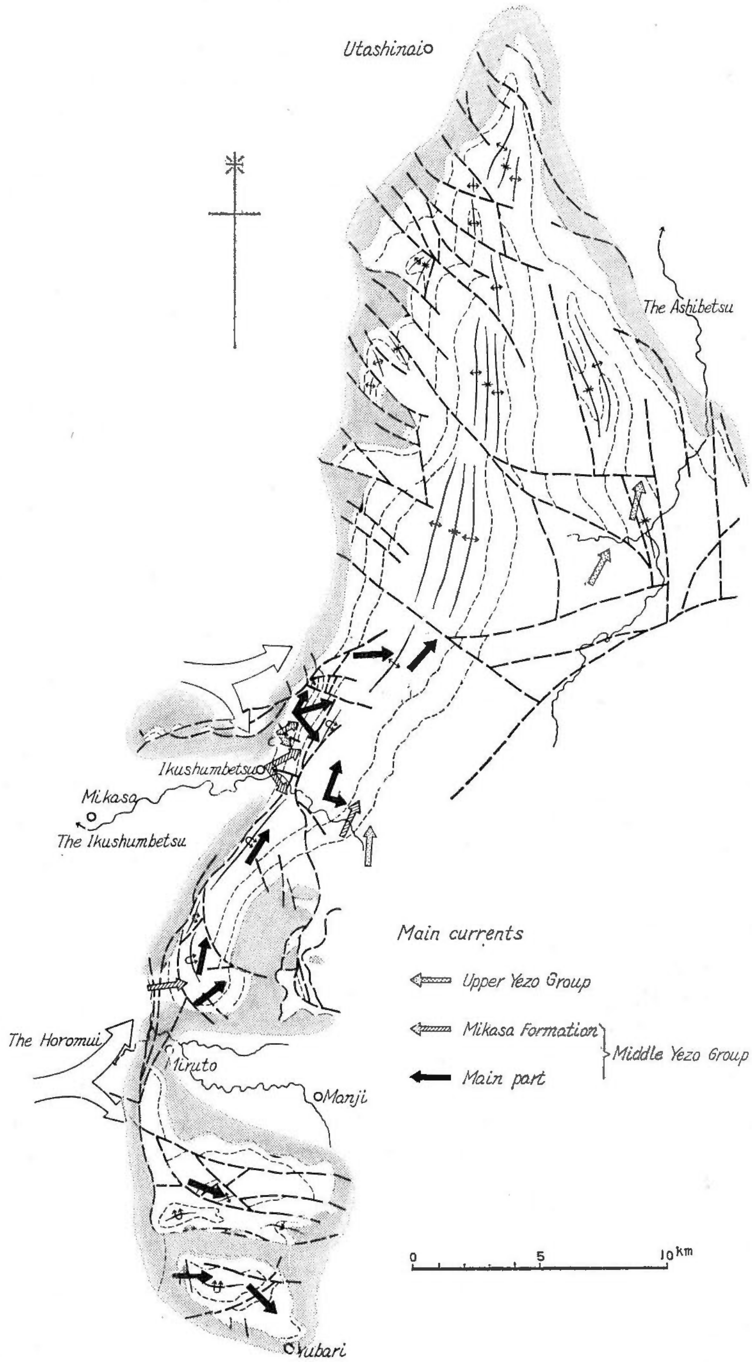


Fig. 48. Map showing the current pattern of the Cretaceous deposits in the Ishikari coal-field.

The open arrows indicate presumed major point sources for the coarse sediments of the main part of the Middle Yezo Group.

insignificant thickness or dispersed pebbles are found only at several levels (see Fig. 4) and that structures indicating downslope slumping or sliding of sediments are very rare even in the laterally derived sediments (Figs. 24, 25). Hence, it will be inferred that during the accumulation of the flysch sequence the western source area was a low land on the whole and the trough was flanked with rather gentle slopes on the west side. It is also possible that the basin was considerably wide. On the contrary, the Izumi Group is rich in conglomerate and slump deposits (TANAKA, 1965), thus showing different tectonic setting. That is to say, the group was deposited probably in a relatively narrow, steep-walled basin which was bordered by very intensely rising source areas on the north side. Another significant difference is that the general rate of subsidence of the basin was much greater in the Izumi Group than in the Cretaceous flysch sequence. Members Md and Me in the northern part of the western wing of the Ikushumbetsu anticline are characterized by the predominant occurrence of laterally derived sediments. Their lateral current directions vary markedly with horizon (Figs. 36, 37, 38, 44; Table 22). This implies that the conditions of the lateral slopes flanking the trough changed with time owing largely to tectonic movements of both the depositional and the source areas. Therefore, it seems probable, as would be expected, that the marginal part of the trough usually had irregular depositional surface or submarine configuration. On the other hand, as regards the axially derived sediments on the eastern wing of the Ikushumbetsu anticline, the current directions exhibit a unimodal but somewhat widely spread distribution as exemplified by Member Mb (see Fig. 41). This may suggest that the axial part of the basin floor has a gentle inclination and the turbidity currents flowing along it were of low velocity.

Slump deposits are found in divisions A and F in Member Me of facies δ in the northern part of the western wing of the Ikushumbetsu anticline (Figs. 24, 31). Therefore, they occur in the relatively marginal part of the trough where the coarse sediments resulted mainly from lateral supply. In this connection it should be noticed that the lateral supply on occasion invaded the offshore part of the basin where axial sediment-transport played solely the leading part. A good example is presented in the current pattern of the upper part of Member Mc of facies α, Ikushumbetsu Valley (see Fig. 43). Additional indirect evidence is that pebbly mudstone beds of probably western derivation are met with in the middle of Member Mc of facies α and in unit Ma_2 of facies β (see Figs. 24, 25). The laterally deposited turbidite sequences as represented by Member Me of facies δ on the west wing of the Ikushumbetsu anticline are regarded as deposits of sub-sea fans with a roughly eastward downslope axis. On the other hand, axially deposited Member Me on the east wing of the anticline may be referred to a distal extension of the deposits of northeast-facing delta fronts in the south. The overall sedimentary facies combined with the current pattern of Member Me succeeded by the neritic Mikasa Formation records the beginning of shallowing conditions for a part of the flysch basin. Unstable tectonic environments concurrent with such shallowing of the basin are reflected in the discrepancy in epicycles of sedimentation in Member Me between the eastern wing and the western wing of the Ikushumbetsu anticline (see p. 68 of this paper). Furthermore, it may be remarked here that the northerly gradient of the longitudinal slope of the trough floor roughly coincided with the northward trend of thickening of the formation (e.g. unit Mb_2, Member Md and

Member Me), hence it may have been closely related to the differential subsidence of the trough keeping pace with the differential accumulation of the flysch sediments.

Taking into consideration the current pattern and facies distribution of the Upper Yezo Group in and around the Ikushumbetsu area, it is very likely that the axial slope of the basin floor was directed towards the north and the aforementioned two major point sources responsible for the coarse sediment of the flysch sequence still existed without remarkable shifting during the deposition of at least some parts of the group. Unit Ub′, the lower part of the group, in the northern part of the western wing of the Ikushumbetsu anticline is much thicker and intercalated with much more thin sandstone beds than the equivalents (the upper part of unit Ub and the lower part of unit U_1) in certain places within the Ikushumbetsu anticlinal area and the equivalent (the lower part of unit U_1) in the Yubari area. These facts demonstrate that the northern major point source supplied more sediments into the trough than did the southern one during the deposition of the lower part of the Upper Yezo Group. Another indirect evidence for such a palaeogeographic situation is given in the following lines. The Tsukimi Sandstone Member, the middle part of the Upper Yezo Group, is developed only on the eastern wing of the Sorachi anticline where sandstone beds of turbidity current origin occur commonly in some other parts within the group. The member is characterized by the abundant occurrence of pebbly mudstone in its western facies. The member of the eastern facies, on the other hand, is dominated by turbidite sandstone especially in its lower part. It is plausible that the coarse materials constituting the pebbly mudstones and sandstones may have been derived mainly from the southwest, i.e. somewhere near the northern major point source mentioned above. In this connection, it is interesting to note that the southern part of the eastern wing of the Sorachi anticlinal area subsided deeper than the adjoining areas, especially the northern part of the eastern wing of the Ikushumbetsu anticlinal area, during the deposition of the lower half of the Upper Yezo Group (TANAKA, 1959).

IX. Summary and Conclusions

The Cretaceous deposits in the Ikushumbetsu area, central Hokkaido form an anticlinal structure plunging southwards and is divided into the Middle Yezo and overlying Upper Yezo Groups. The main part of the Middle Yezo Group is about 1,000 m thick and composed chiefly of bedded sandstone, alternating sandstone and shale, and shale frequently interlaminated with sandstone, being extremely poor in conglomeratic rocks. It is stratigraphically divisible into five members, provisionally named Ma to Me, and ranges from Middle Albian (?) to Upper Albian in age. Apart from the ammonoids, inocerami and other marine molluscan fossils which occur sporadically, trace fossils such as *Helminthoida* and *Paleodictyon* are commonly found on the underside of thin sandstone layers. The sediments constituting the main part of the Middle Yezo Group are referred to as flysch on the basis of the tectonic, sedimentological and biological characters.

The sandstone rhythmically alternating with shale and the bedded sandstone with or without shale interbeds are often poorly sorted and provided with various kinds of sedimentary structures typical of turbidites, particularly graded bedding and directional sole markings such as flute casts and groove casts. From all available information, it is natural and reasonable to regard most, if not all, of these sandstones as turbidites including their proximal variety, fluxoturbidites. Slump beds, however, are very rare in the whole sequence of the flysch deposits. The sandstones are referred to the subgreywacke and the greywacke clans of PETTIJOHN's scheme of classification. The provenance of the sandstones was older sedimentary rocks such as sandstone, slate and chert and subordinate igneous rocks (e.g. andesite).

A single sedimentation unit composed of sandstone below and shale above is called here a graded unit. An ideal unit is divisible into five divisions in ascending order as follows: graded sandstone with occasional reworked shale fragments, laminated sandstone characterized by parallel lamination, cross-laminated sandstone with common current ripple laminations and convolute laminations, laminated sandy mudstone and massive mudstone. As regards the sandstone layers, some definite relationships are recognized between the thickness and the sedimentary features such as sequence of internal structures, undulation of lower contact, grain size at the base, type of graded bedding and proportion of graded sandstone division to sandstone layer. The abundance or size of several types of sole markings, whether inorganic or biogenic, are closely related to thickness and coarseness of sandstone layers. The thickness distribution of the sandstone and shale layers and that of the individual divisions within the graded units tend to show different distributional patterns according to sedimentary facies or depositional environment. They, however, generally approximate a log-normal distribution.

In the flysch sequence the following different facies are discriminated according to the mode of deposition of sandstones: fluxoturbidite, turbidite A (the proportion of graded division to sandstone layer being generally high), turbidite B (the same proportion being generally low) and laminite (laminated sandy mudstone) facies. Accompanying the flysch deposits, neritic sandstone or massive siltstone occurs in a relatively near-shore facies and shale (laminated mudstone) occurs in a relatively offshore facies. The flysch and associated sediments come to show a distal facies northwards on the eastern wing of the Ikushumbetsu anticline, and partly come to show an offshore, deep facies eastwards in the southernmost part of the anticlinal area.

The lateral variation of the sedimentary facies in the flysch sequence comprises two principal types. One type is displayed in the wedge-shaped sedimentary body (tongue) which is represented by sandstone facies (e.g. Member Me on the eastern wing of the Ikushumbetsu anticline). The sandy flysch facies involved passes shorewards into the neritic sandstone facies. Noticeable proximal, massive siltstone facies to be mentioned below does not intervene between these two facies. The other type is exhibited in the lenticular sedimentary body (lentil) which consists principally of sandstone and shale in alternation (e.g. unit Mb_1 on the eastern wing of the anticline). The normal flysch facies involved becomes thinner and finer grained proximally as well as distally, passing towards the source into the massive siltstone facies which, in turn, comes to be replaced by the neritic coarse-grained facies in the same direction.

The flysch sequence marks the early stage of a single major cycle of sedimentation that is represented by almost the whole sequence of the Middle Yezo Group. It shows in itself three minor cycles represented by 100 to 500 m sequence which, in turn, consists of epicycles of various scales. In a certain section made up of sandstone and shale in thin-bedded alternation, major and minor epicycles can be detected by means of vertical variation of the sandstone and shale layer thicknesses in combination with that of the current directions. Acid tuff usually occurs in the lower and upper parts of the epicyclic sequences, especially of the major ones, but never in the middle. The larger the scales of the cycles, the more important is the part played by epeirogenic movements of a much wider scope in the formation of the cycles; the smaller the scales of the cycles, the greater becomes the influence of tectonic movements of a much narrower scope on the formation of the cycles.

From the palaeocurrent measurements of the directional-current structures, it can be said that for the coarse sediments of the flysch sequence in and around the Ikushumbetsu area northward, axial transport by turbidity currents took the leading part in the east, while in the west lateral transport by turbidity currents from the west was predominant and the resultant deposits are accompanied by some, if not remarkable, slump beds. This general sediment-transport pattern, together with the lateral facies variation, strongly indicates that a part of the main land mass, the exact position of which is uncertain, may have been situated to the west of the Cretaceous outcrop area during the deposition of the flysch succession. Moreover, it is suggested that there existed to the west of the Cretaceous field two major point sources from which sediments were supplied eastwards into the trough by turbidity currents. A quite similar regional sediment-transport pattern is recognized in the overlying Mikasa Formation dominated by neritic sandstone and the Upper Yezo Group consisting mostly of argillaceous sediments with local turbidite sediments in and around the Ikushumbetsu area.

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(Written in September 1968)

Alphabetical List of Place Names, with Japanese Letter

Anoro-gawa	阿野呂川	Nunobiki-no-sawa	布引の沢
Ashibetsu	芦別	Pombetsu	奔別
Ban-no-sawa	盤の沢	Pomporokabetsu	ポンポロカベツ
Futami-zawa	二見沢	Pomporonai	ポンポロナイ
Hakobuchi	函渕	Porokoashibetsu	幌子芦別
Hatonosu	鳩の巣	Sekiyu-zawa	石油沢
Honsawa	本沢	Shikoro-zawa	シコロ沢
Horomui	幌向	Shimanto	四万十
Ichi-no-sawa	一の沢	Sorachi	空知
Ikushumbetsu	幾春別	Takambetsu	多寒別
Ishikari	石狩	Tsukimi	月見
Izumi	和泉	Utashinai	歌志内
Katsurazawa	桂沢	Yamamoto-no-sawa	山本の沢
Kii	紀伊	Yezo	蝦夷
Manji	万字	Yubari	夕張
Mikasa	三笠	Yunosawa	湯の沢
Miruto	美流渡	Washi-no-sawa	ワシの沢
Mirutomappu	ミルトマップ		

北海道幾春別地域白亜紀フリッシュの堆積

田中 啓策

要 旨

北海道石狩炭田幾春別地域は北海道における白亜系の古典的な標準地域の1つである。幾春別地域の白亜系は古第三系石狩層群に不整合に覆われ，南へ向かって沈下する幾春別背斜を形成する。この白亜系は中部蝦夷層群と上位の上部蝦夷層群からなり，中部蝦夷層群はさらに主部と三笠層に区分される。

幾春別地域の白亜系については，これまでに層序学的にも古生物学的にも多くの研究がなされてきたが，堆積学的には砂岩の岩石学的研究が2，3あるにすぎない。筆者はフリッシュ相が卓越する中部蝦夷層群主部について，とくに砂岩頁岩互層の堆積学的特徴，層相変化や古流系などの解明に重点をおいて研究を行なった。その結果は次のように要約される。

(1) 中部蝦夷層群主部は，下限が不明であるが，約1,000 m の厚さを有し，下位から Ma・Mb・Mc・Md および Me の5部層に区分される。さらに各部層は水平的に α・β・γ および δ の4相に識別される。Ma と Md は主として頁岩（ここでは泥質岩の総称）から，Mb はおもに砂岩頁岩互層からなる。Mc は砂岩に富み，Me は砂岩および砂岩頁岩互層から構成される。中部蝦夷層群主部は宮古統上部階（同統最上部亜階に及ぶ可能性がある），すなわちアルビアン階中部（?）—上部に対比される。なお，上位の三笠層では三角貝を多産する浅海成砂岩が代表的である。

(2) 中部蝦夷層群主部は砂岩頁岩互層が優勢なことで特徴づけられる。このような地層は，日高造山運動における構造発達史的位置および後述するような堆積学的諸性質や生物相（とくに生痕化石相）の特徴からみて，フリッシュ相を示すものとみなされる。さらに，砂岩はしばしば turbidite の特徴を示している。中部蝦夷層群主部には，凝灰岩がいくつかの層準に挟在するが，礫質岩はきわめてまれにしか見いだされない。

(3) 中部蝦夷層群主部を構成する砂岩では，無層理砂岩・成層砂岩および頁岩と有律互層をなす砂岩が代表的である。

無層理砂岩は比較的粗粒で，あまり泥質でなく，淘汰が比較的よい。さらに，この種の砂岩には級化層理や水流の方向性を示す sole marking が発達せず，また大規模の斜交層理はまったくなく，斜交葉理もほとんどみられない。無層理砂岩の多くは fluxoturbidite とみなされるであろう。

成層砂岩はしばしば頁岩の薄層を挟むが，構成する砂岩単層は比較的厚い（0.3～2 m）。この種の砂岩には級化層理がしばしばよく発達し，級化層理の繰返しもときにはみられるが，葉理はむしろ貧弱にしか発達していない。水流の方向性を示す sole marking は普通に存在するが，あまり顕著でない。自生の浅海生動物の化石は砂岩中にも，挟みの頁岩中にもまったくみいだされない。成層砂岩は比較的沖合の深い環境に堆積したものと推察され，多くは turbidite，一部は fluxoturbidite とみなされる。

頁岩と有律互層をなす砂岩は，厚さが 3～100 cm で，概して比較的泥質であり，かつ淘汰があまりよくない。この種の砂岩では級化層理や flute cast, groove cast のような水流の方向性を示す sole marking が特徴的に発達している。また，平行葉理のほかに，小規模の斜交葉理，current ripple

lamination, convolute lamination もよく発達し，水流漣痕もときどき存在するが，振動漣痕や大規模の斜交層理はまったく認められない。底棲生物の自生性遺骸は砂岩中にはまったく含有されていないが，比較的薄い細粒の砂岩の下底面には生痕化石がしばしばみられる。この種の砂岩は比較的沖合の深い環境に堆積したものと推察され，turbidite とみなされる。

以上に述べた砂岩は PETTIJOHN の分類による亜グレイワッケおよびグレイワッケに属する。その供給源岩には古期堆積岩（チャート・砂岩・スレート）のほかに，従属的なものとして火成岩（たとえば安山岩）がある。

(4) 中部蝦夷層群を構成する頁岩では，シルト岩・葉理砂質泥岩および葉理泥岩が代表的である。頁岩はアンモナイト，イノセラムスなどの二枚貝や有孔虫の化石を含む。アンモナイトは殻が薄く，装飾が細かい正常巻のもの (Desmoceratids, Gaudryceratinids) に富むが，装飾の強い正常巻のもの (Mortoniceratids) もみられる。有孔虫では砂質有孔虫の方が石灰質有孔虫より優勢である。頁岩中の石灰質団塊や化石は上部蝦夷層群の場合に較べてはるかに乏しい。

(5) 礫岩には砂質物を基質とし古期岩類の円礫からなる通常の礫岩，頁岩の偽礫からなる層内礫岩 (intraformational conglomerate)，海底泥流または slumping に由来すると考えられる含礫泥岩 (pebbly mudstone) がある。凝灰岩は一般に数 cm ～ 数10 cmの厚さをもち，一部石英安山岩質，他は安山岩質とみなされる。

(6) 中部蝦夷層群主部を特徴づけるフリッシュ相の砂岩頁岩互層や成層砂岩を構成する基本単位の地層は，砂岩（ときには著しく砂質の粗いシルト岩）層と上位の頁岩層からなる１組の地層で代表され，このような単位層をここでは級化層 (graded unit) と呼ぶ。

級化層についてはとくに次のような諸要素の観察，または測定を行なった。級化層・砂岩部・頁岩部それぞれの厚さ，砂岩部と下位の頁岩部・上位の頁岩部それぞれとの接触状態，砂岩部基底の粒度，砂岩部における級化層理の発達程度・堆積構造（非生物源）の発達状況や性状・生痕化石の産状・頁岩偽礫の量・炭質物の量，砂岩部・頁岩部それぞれにおける細分単位（下記のようにそれぞれ特定の堆積構造で特徴づけられる）の発達状態と厚さ。

級化層を厚さと砂岩百分率にもとづいていくつかのタイプに区分し，さらにこのような級化層のタイプによってフリッシュ相の地層を岩相的に細かく区別した。級化層は，堆積構造の出現順序からみると，標式的には下から上へ向かって級化砂岩（ときどき頁岩偽礫を含む）・平行葉理砂岩・斜交葉理砂岩（しばしば current ripple lamination, convolute lamination を伴う）・葉理砂質泥岩・塊状（均質）泥岩の５単位に区分される。砂岩層の頂上面にはときどき水流漣痕が存在し，葉理砂質泥岩部には平行葉理のほかに，斜交葉理や ripple cross-lamination も普通にみられる。級化層における砂岩部は turbidity current によって堆積したとみなされる。頁岩部については，とくに砂岩部から漸移する場合，頁岩部の少なくとも比較的下部の部分は微弱な（または希薄な）turbidity current によって堆積したと考えられ，上部は沖合の定常的な normal current によって堆積したであろう。

(7) 級化層における砂岩部については，層厚と堆積現象（たとえば堆積構造の出現順序，下底面の起伏・基底部の粒度・級化層理のタイプ・級化砂岩部の占める比率）との間に密接な関係が認められる。また，頁岩部についても，塊状泥岩部の有無と直上砂岩部の厚さ・基底粒度との間に密接な関連がある。

(8) 級化層における砂岩部の層厚分布は一般に頁岩部のそれよりも大きく分散する。砂岩部の層厚分布は，厚さが概して小さい場合ではむしろ正規分布に近いが，厚さが比較的大きいときは多峰型分布を示す。頁岩部の層厚分布は，頁岩部の頂上部に塊状泥岩が存在することが多ければ多いほど正規分布に近づく傾向がある。砂岩部・頁岩部と同じく，級化層内の堆積構造にもとづく細分単位についても，厚さの累積頻度分布は原則として対数正規分布を示す。なお，砂岩部の厚さと直下および直上

の頁岩部の厚さとの相関についても検討した。

(9) フリッシュ相の地層を構成する砂岩層には，turbidite に特徴的な種々の非生物源堆積構造が発達している。まず，下底面に発達する sole marking には flute cast, longitudinal furrows and ridges, groove cast, bounce cast, prod cast, brush cast, striation cast, frondescent cast, load cast が識別され，さらに pit and mound structures と推定されるものもみいだされる。なかでも flute cast, groove cast, load cast が最も代表的である。若干種の sole marking については，分布（または発達状態)•大きさと砂岩部の厚さ・基底部の粒度との間に密接な関係がある。内部構造としては，級化層理，平行葉理，斜交葉理，current ripple lamination, wavy lamination, convolute lamination, parting lineation, clast lineation （炭質物ないし植物片や頁岩偽礫の平面的配列状態で示される），スランプ(slump)構造が認められ，はじめの３者が普遍的である。級化層理にかんしては，単一の場合では５タイプが，繰り返されている場合では２タイプ（composite graded bedding および multiple graded bedding) が区別される。スランプ構造はまれにしか発達せず，それはシルト岩中に砂粒が雑然と混合したきわめて淘汰の悪い無層理の地層（たとえば含礫泥岩）や堆積時に褶曲した地層として表現されている。頂上面に発達する構造には水流漣痕がある。

(10) 生物源の堆積構造は，種々の底棲動物（おそらく環形動物ならびに腹足類）のくいあるきあと（Pascichnia) やすみくいあと (Fodinichnia) として，多くは砂岩層の下底面に，一部は砂岩層の頂上面や内部にも発達している。生物源の堆積構造は，それらがみいだされる砂岩層の堆積前に形成されたものと，堆積後に形成されたものとに区別される。砂岩層の下底面にみられる堆積前の生物源構造は，砂岩層の厚さや基底部の粒度と密接に関連して発達し，とくに薄くて粒度の細かい砂岩に多い。砂岩層の頂上面にみられる堆積後の生物源構造は，全体としては堆積前の生物源構造に較べて薄い砂岩層によく発達している。

以上のような生物源の堆積構造，すなわち生痕化石には少なくとも９属10種が識別される。堆積前のものでは ***Helminthoida, Paleodictyon*** がとくに優勢であり，さらに ***Spirorhaphe*** (？) も目立っており，堆積後のものでは ***Neonereites*** が代表的である。このような生痕化石群集は地向斜地域またはフリッシュ相を特徴づける ***Nereites*** 相を示す。

(11) フリッシュ相の地層では，砂岩の堆積様式によって fluxoturbidite, turbidite A（砂岩層において級化部の占める比率が一般に高い），turbidite B （同比率が一般に低い）および laminite（葉理砂質泥岩を構成する砂岩葉層）の相が識別される。さらに，フリッシュ相の地層に伴って，浅海成砂岩または無層理のシルト岩が比較的沿岸に近い相として，他方頁岩（葉理が発達した泥岩）が比較的沖合の相として発達する。

以上のフリッシュおよびそれに伴う地層は，幾春別背斜東翼では全体として北へ向かって供給地点（turbidity current の trough への流入口）から遠ざかっていく相に変化する。また，少なくとも一部の地層(Md) は，背斜南端部において東から西へ向かって粗粒化すると同時に層厚を減ずる。この点は少なくともMdの堆積期間中に供給源地が西方に存在したことを示唆する。フリッシュおよびそれに伴う地層は，理想化すると供給源地または供給地点から離れるにつれて次のような相の側方変化を示す。砂岩を主とする地層では浅海成砂岩相→fluxoturbidite 相→turbidite A 相→turbidite B 相，砂岩頁岩互層からなる地層では laminite 相→turbidite B 相→turbidite A 相→turbidite B 相→laminite 相，泥質堆積物を主とする地層では無層理シルト岩相→葉理シルト岩（または葉理泥岩）相→laminite 相→葉理泥岩相。

(12) フリッシュにおける堆積相の側方変化には２つの基本的なタイプが認められる。１つのタイプはおもに砂岩からなる tongue 状の堆積岩体にみられる（例： 幾春別背斜東翼の Me)。標式的には，供給源地（または供給地点）から遠ざかるにつれて浅海成砂岩相はフリッシュ相（前者に近い方

では砂岩が優勢）に移化し，両者の間には後述するような顕著な無層理シルト岩相が発達しない。

他の1つのタイプは砂岩頁岩互層からなる lentil 状の堆積岩体に特徴的である（例： 幾春別背斜東翼の Mb_1）。標式的には，フリッシュ相の地層は lentil 状の岩体の中部（供給地点に近い方に偏在する）において最も厚く，かつ粗くなるが， 中部から前部 （供給地点から遠い方） および後部（供給地点に近い方）に向かって全体として厚さを減じ，同時に細粒化する。lentil 状の岩体の前部・後部に較べて，中部では平均して頁岩と互層する砂岩層の厚さ・基底部の粒度・下底面の起伏はいずれも大きく，また砂岩層においては級化部が厚く，その占める比率も高く，かつ級化層理がよく発達し，さらに級化層は級化砂岩部に始まることが多く，塊状泥岩に終ることが少ない。lentil 状の岩体に発達するフリッシュ相は供給源地（または供給地点）に向かって無層理シルト岩相に移化し，さらに後者は浅海成粗粒岩相ないし縁辺粗粒相に移化する。

⒀ フリッシュ相の地層はほぼ中部蝦夷層群で代表される1つの堆積大輪廻 (major cycle) における前期の段階を代表している。 この輪廻の初期の段階は 下部蝦夷層群を覆う 粗粒相 （幾春別地域には露出しない）によって，後期の段階は浅海相の三笠層によって代表される。この堆積大輪廻は下位から Ma—Mb, Mc—Md, Me（ある場所では三笠層最下部に及ぶ） それぞれで示される3つの堆積小輪廻 (minor cycle) からなる。

堆積小輪廻を示す地層は 100～500 m の厚さを有し，年代層序区分単位としての階の1/4～1/3にあたる層序的範囲を占めるであろう。このような堆積小輪廻層は理想的には下から上へ向かって次のような相の垂直的変化を示す。fluxoturbidite 相→turbidite A 相→turbidite B 相→laminite 相→turbidite B 相→turbidite A 相→次期輪廻初期の fluxoturbidite 相。堆積小輪廻の下部半輪廻(lower hemicycle) では標式的に下から上へ向かって次のような堆積相の垂直的変化がみられる。 級化層・砂岩層・級化砂岩部それぞれの厚さ・砂岩部の級化層に対する比率・級化砂岩部の砂岩層に対する比率はいずれも減少し，粒度が細かくなり，淘汰がよくなり，級化層理の発達が悪くなるのに対して葉理はよく発達するようになる。sole marking は大きさを減ずる。さらに，砂岩層と互層する頁岩層は厚さを増す。

堆積小輪廻は規模のより小さい epicycle からなる。 epicycle には規模を異にする少なくとも2つの段階のものが認められ，そのうち大きい方の major epicycle は厚さ 20～130m の地層で示される。酸性凝灰岩層は epicycle をなす地層の下部，または上部に限られて存在し，中部からはみいだされていない。 砂岩・頁岩の細かい互層からなり， 1堆積小輪廻 (minor cycle) をなすある層序断面（例： 幾春別背斜西翼の Me） では，古流向の垂直的変化とともに砂岩・ 頁岩の層厚ならびに砂岩百分率 （級化層において砂岩部の占める比率）や砂岩—頁岩比の移動平均値の垂直的変化に major epicycle, minor epicycle それぞれに相当する周期性をみいだすことができる。

堆積輪廻の成因にかんしては，堆積小輪廻 (minor cycle) の成生は北海道白亜系堆積盆地 （蝦夷地向斜）全体の内部および周辺にわたる比較的大きい規模の構造運動（地向斜的沈降と密接に関係があった)に大きく由来したと推察される。堆積大輪廻 (major cycle) は，上記の構造運動のほかに広域の造陸運動にもある程度支配されたであろう。これに対して，堆積小輪廻より規模の小さい epicycle の形成は根本的に供給域における構造運動 （隆起量）・堆積域における構造運動（沈降量）の周期的変化に帰せられ，さらに前者の構造運動は後背地における周期的な酸性火山活動と密接な関連があったと考えられる。

⒁ フリッシュにおける古流向の測定は，おもに sole marking では flute cast, groove cast, 内部構造では parting lineation, 炭質物微片の平面的配列について行なわれ，全測定数は約 590 に及んだ。sole marking, 内部構造，頂面構造（水流漣痕） は一般に同一砂岩層においてほぼ一致した方向を示す。しかし，詳しくみると，同一砂岩層において flute cast の方向からの偏倚は groove cast

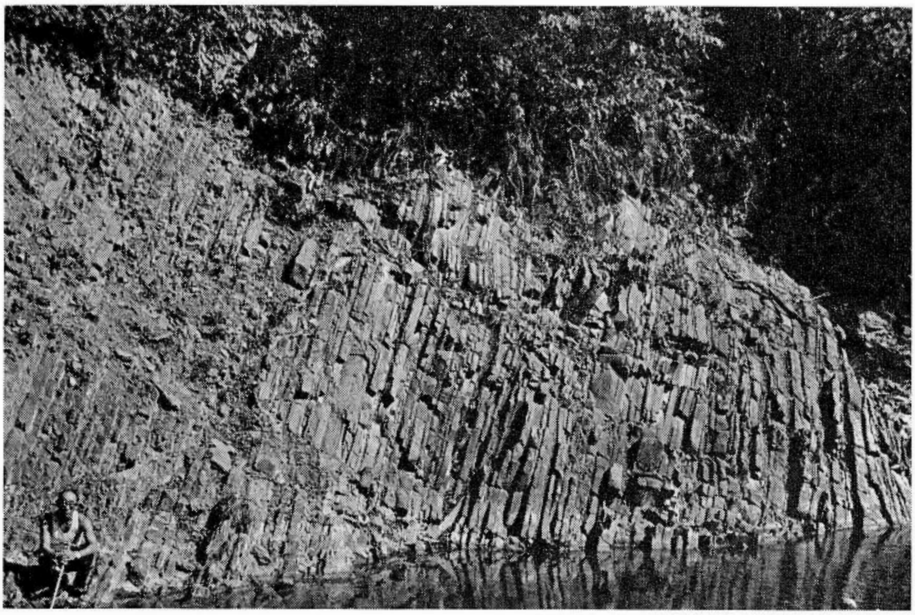
のような他の sole marking，内部構造，水流漣痕の順に，すなわち上位の構造ほど大きくなる傾向を示し，水流漣痕では直角に近い食い違いを示すこともある。また，同一砂岩層内の sole marking 以外の構造についてみると，砂岩層頂上面に発達する水流漣痕や砂岩層内のかなり上部の方に現われるcurrent ripple lamination の方向は，炭質物微片の方向に較べて parting lineation の方向から大きくずれる傾向がある。

⒂ 幾春別地域周辺（南方の夕張地域などを含む）の中部蝦夷層群主部を構成するフリッシュの粗粒堆積物の運搬には，東部（おもに幾春別背斜東翼）では北北東向きの axial turbidity current（堆積盆地の伸びの方向にほぼ平行）が支配的であり，他方西部（幾春別背斜西翼の北部・夕張地域）では西方から発した東～南東向きの lateral turbidity current （堆積盆地の伸びの方向に著しく斜交）が大きく関与し，後者の流れに由来した堆積物にはわずかながらもスランプ層が伴われる。このような堆積物の運搬経路は堆積相の側方変化とともにフリッシュの堆積期間に陸地が白亜系分布地域の西側に存在したことを示唆する。さらに主要な供給地点が約20km隔てて２カ所推定される。

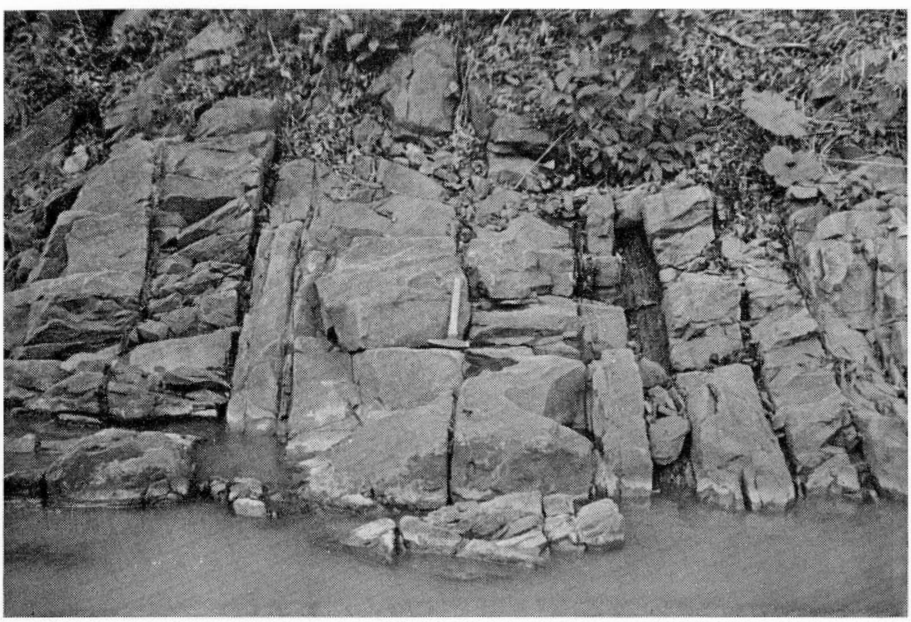
ここに述べたような幾春別地域周辺の古地理的状況および堆積物の運搬経路は，引続き上位の三笠層や上部蝦夷層群の堆積期間中にも本質的に同じであった。とくに，幾春別背斜の北方延長にあたる空知背斜の東翼に分布する上部蝦夷層群中部の月見層では，西部相に含礫泥岩が卓越し，この含礫泥岩は前記の２主要供給地点のうち北の地点近くから由来した可能性が大きい。これに関連して，空知背斜東翼南部の上部蝦夷層群，とくに下半部（月見層を含む）は，周囲の地域の相当層と違って turbidity current から堆積したとみなされる砂岩層をしばしば挟み，かつ全体としてかなり厚いことは注目すべきである。

PLATES
AND
EXPLANATIONS

(With 12 Plates)



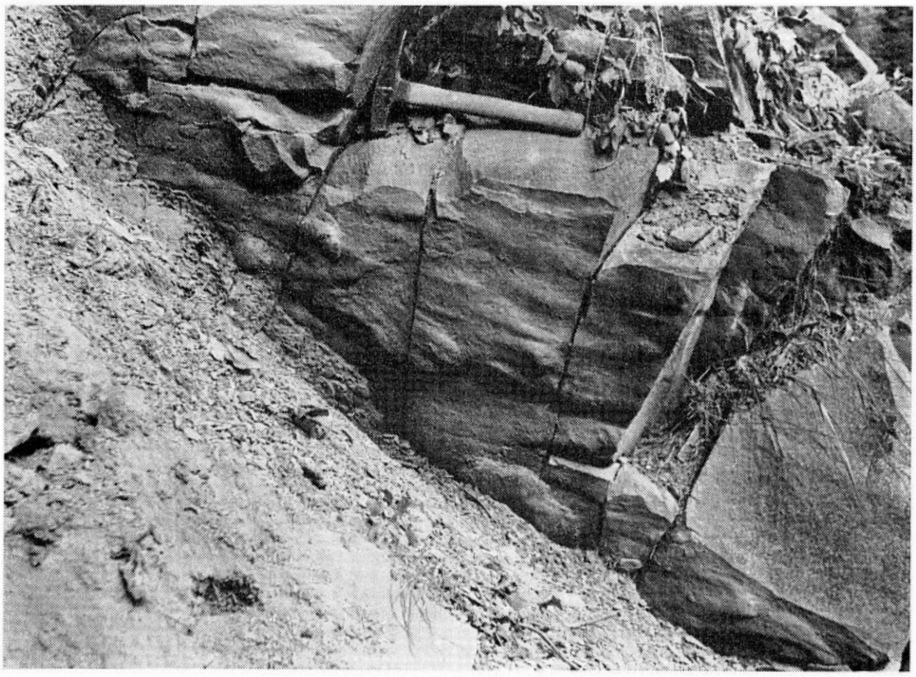
1. Outcrop of normal flysch, sandstone and shale in thin-bedded alternation (sandstone being predominant over shale). Stratigraphic top is to the left. Division B, Member Me of facies δ, Middle Yezo Group, right bank of the Pombetsu.



2. Outcrop of sandy flysch, thick-bedded sandstone interbedded with thin shale. Stratigraphic top is to the left. Lower part of Member Mc of facies α, Middle Yezo Group, left bank of the Ikushumbetsu.

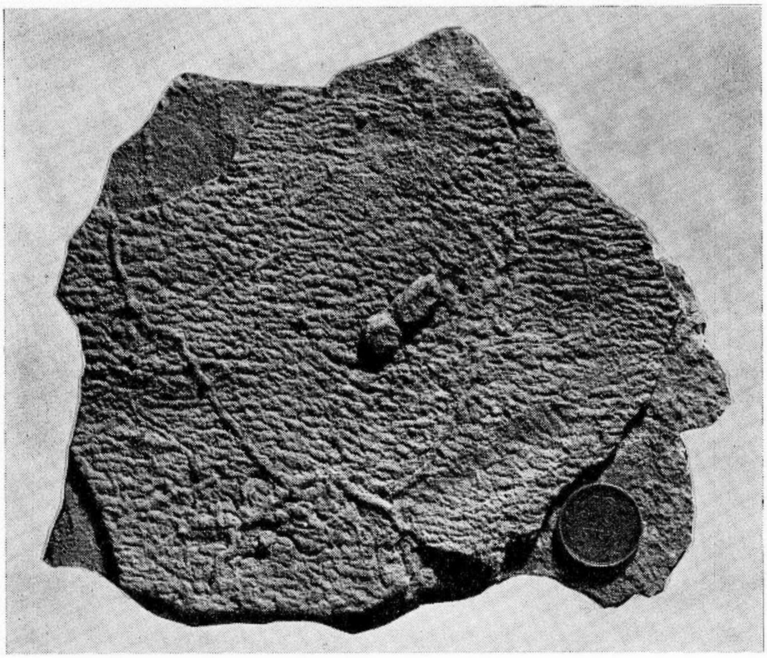
1. Pebbly mudstone with some twisted lumps of laminated sandy mudstone. Member Mc of facies α, Middle Yezo Group, right bank of the Ikushumbetsu.

2. Outcrop of soles of successive sandstone layers. Note the orientation of sole markings (e.g. groove casts and flute casts) nearly parallel with the strike of sandstone layers. Unit Mb_2 of facies α, Middle Yezo Group, right bank of the Ikushumbetsu.



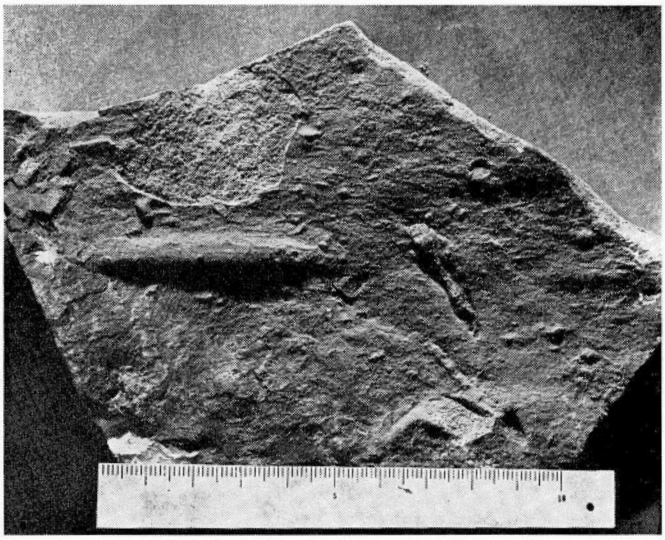
1. Flute casts on sole of sandstone. Current from right to left. Unit Mb_2 of facies α, Middle Yezo Group, right bank of the Ikushumbetsu.

2. Longitudinal furrows and ridges (ridge casts showing a dendritic pattern) on sole of sandstone. Current from right to left. Main part of the Middle Yezo Group, upper course of the Pombetsu.

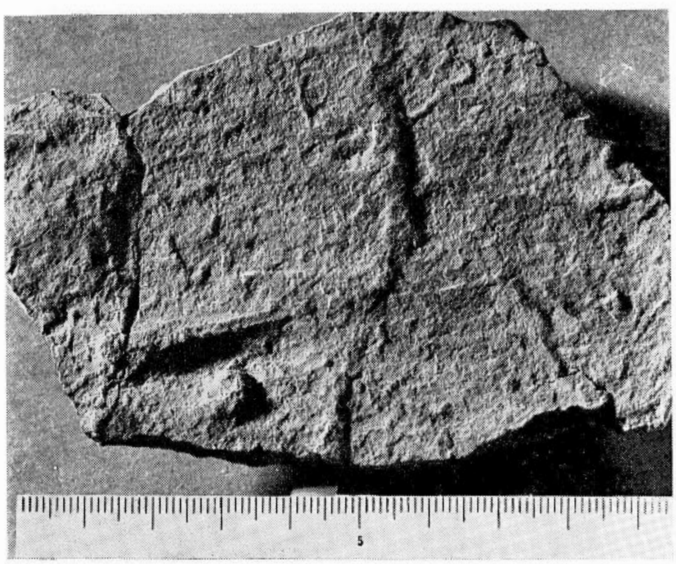


1. Longitudinal furrows and ridges (furrow casts and furrow-flute casts) on sole of sandstone. Current from right to left. Member Me of facies δ, Middle Yezo Group, right bank of the Pombetsu.

2. Groove casts on sole of sandstone. Current from right to left. Unit Mb_2 of facies α, Middle Yezo Group, right bank of the Ikushumbetsu.

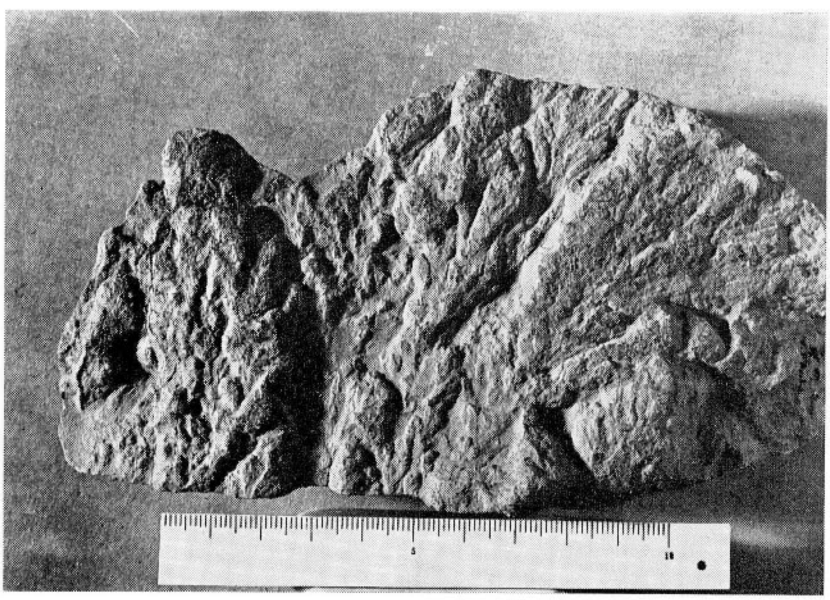


1. Bounce cast on sole of sandstone. Member Me of facies δ, Middle Yezo Group, right bank of the Pombetsu. Scale in centimetres.

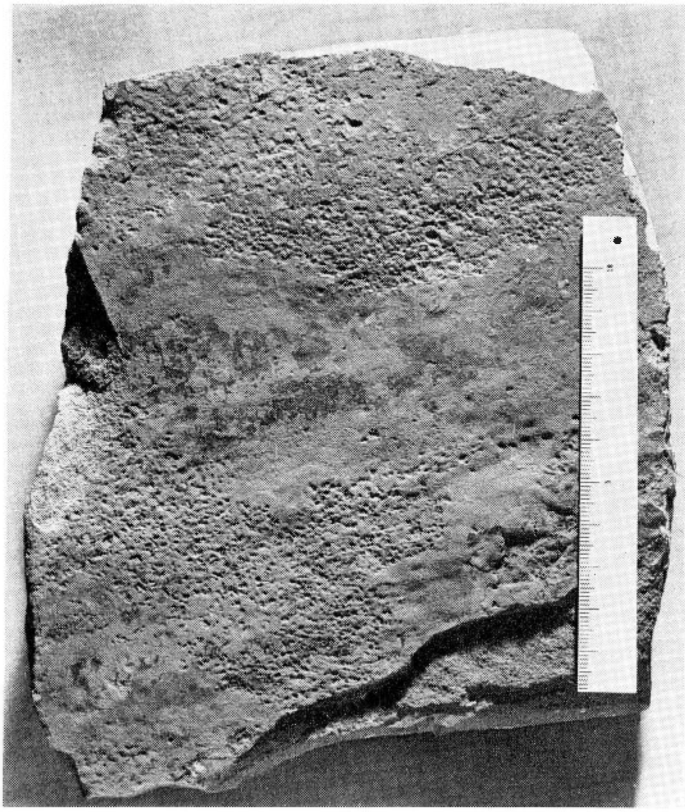


2. Prod cast on sole of sandstone. Current from right to left. Member Me of facies δ, Middle Yezo Group, right bank of the Pombetsu. Scale in centimetres.

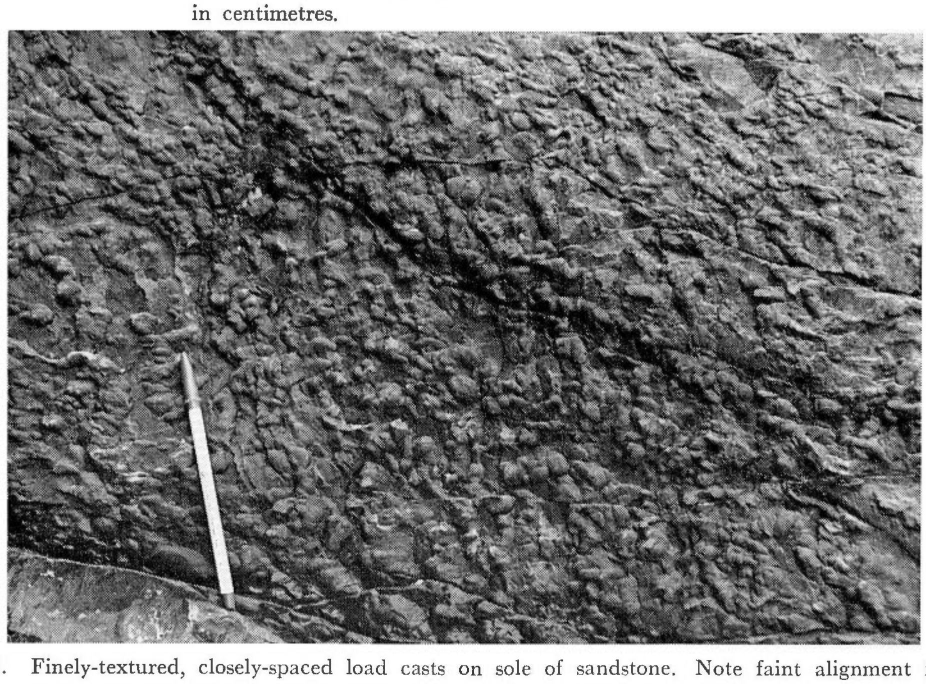
1. Brush cast on sole of sandstone. Current from lower left to upper right. Unit Md_2 of facies δ, Middle Yezo Group, right bank of the Ikushumbetsu. Scale in centimetres.



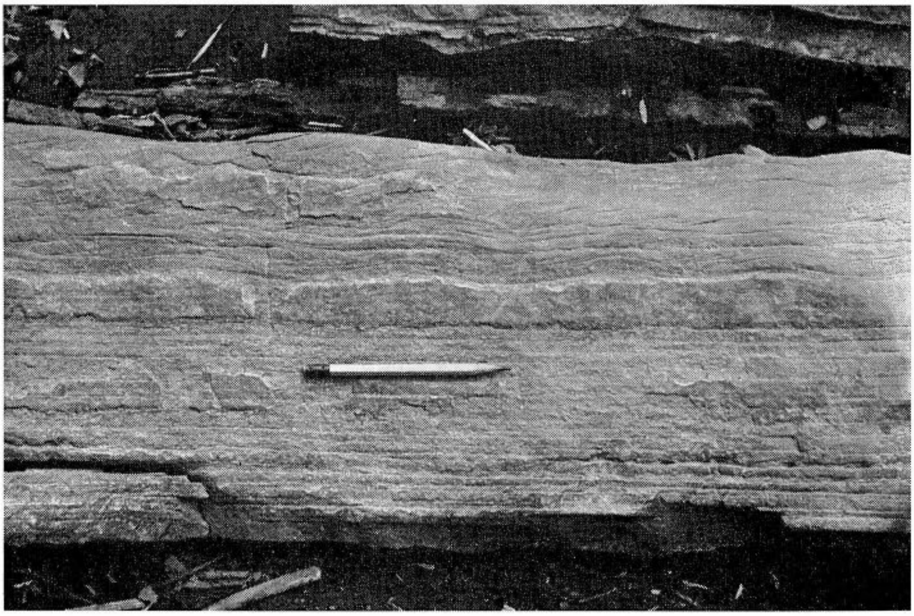
2. Frondescent casts on sole of sandstone. Current from lower left to upper right. Unit Mb_2 of facies α, Middle Yezo Group, right bank of the Ikushumbetsu. Scale in centimetres.



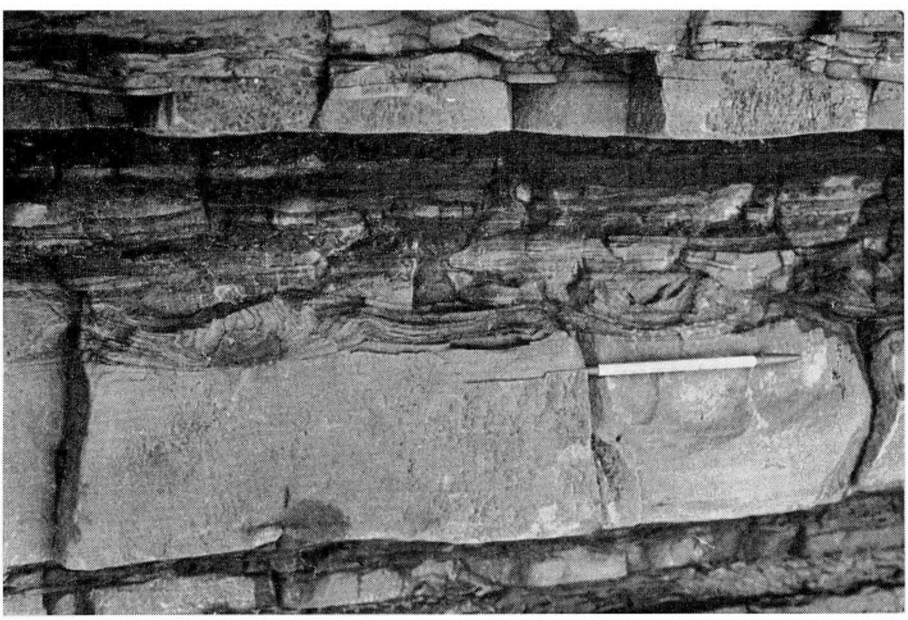
1. Sole markings of unknown origin (probably pit and mound structure) on sole of sandstone. Member Me of facies δ, Middle Yezo Group, right bank of the Pombetsu. Scale in centimetres.



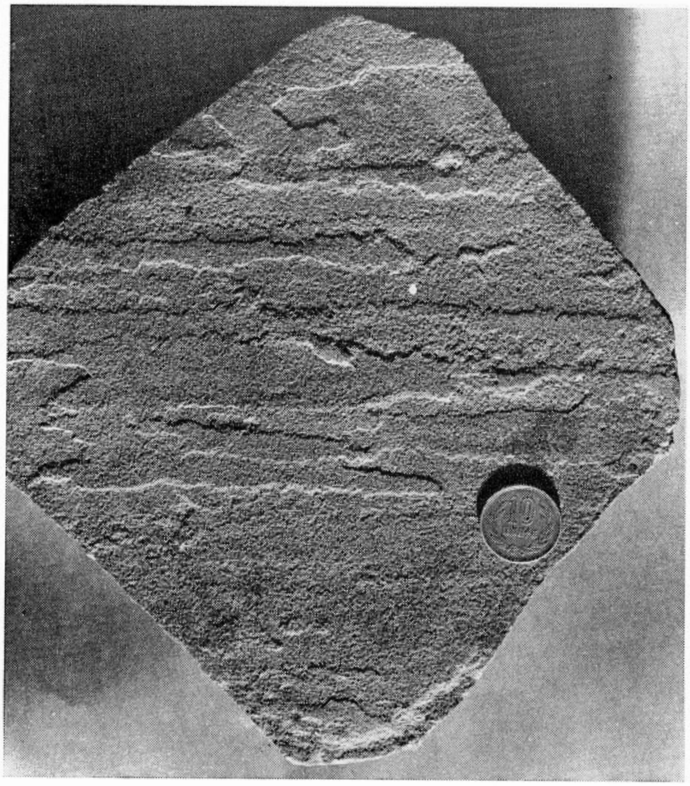
2. Finely-textured, closely-spaced load casts on sole of sandstone. Note faint alignment in the direction from upper left to lower right. Member Me of facies δ, Middle Yezo Group, left bank of the Pombetsu.



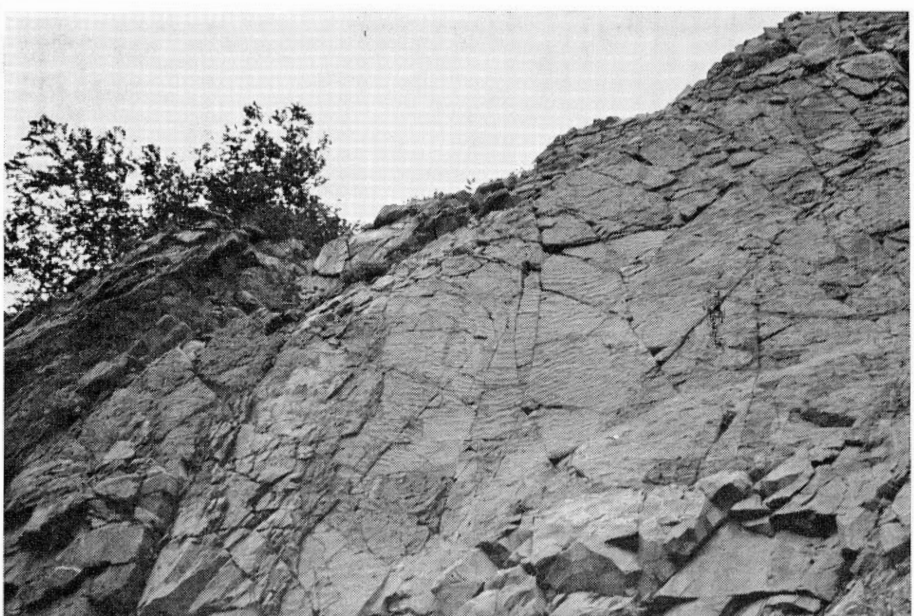
1. Parallel lamination, current ripple lamination and current ripple marks in ascending order in sandstone layer. Current from right to left. Unit Mb_1 of facies α, Middle Yezo Group, right bank of the Ikushumbetsu.



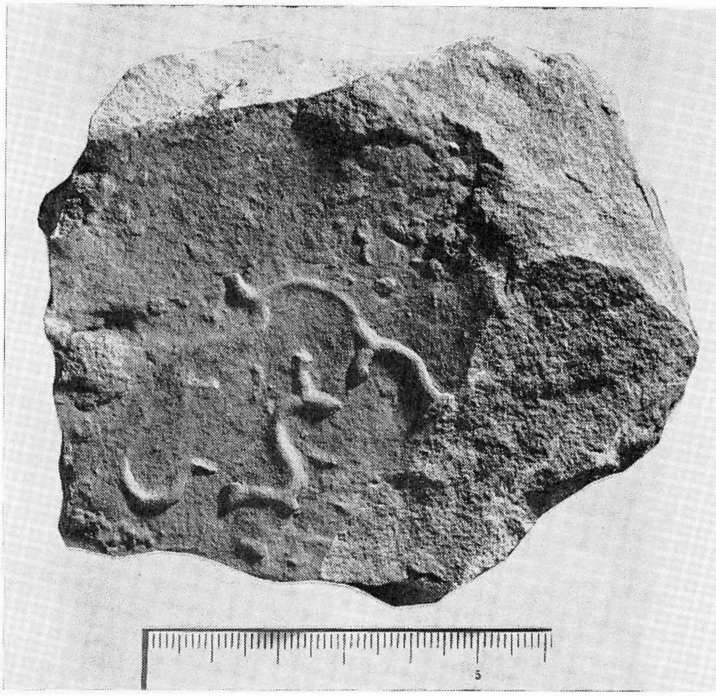
2. Convolute lamination in sandstone layer. Member Me of facies δ, Middle Yezo Group, left bank of the Pombetsu.



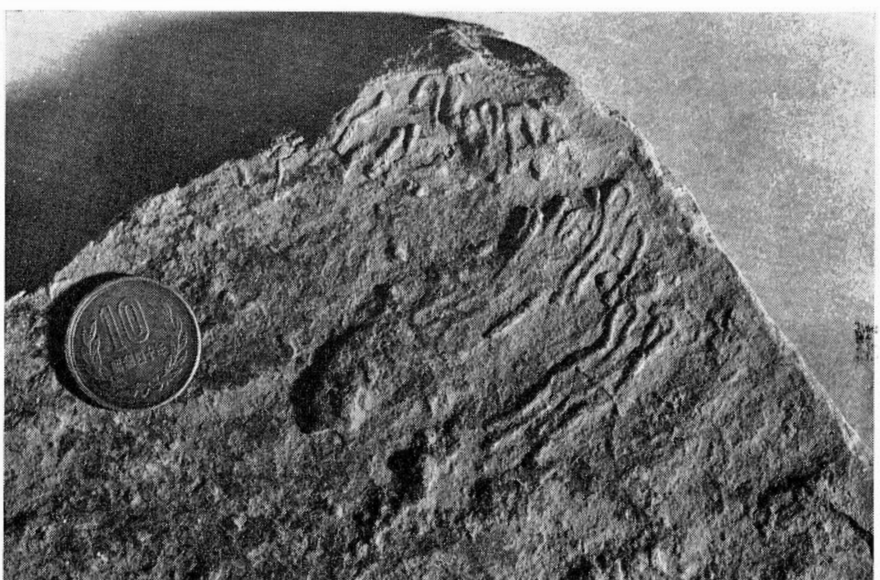
1. Parting lineation in sandstone slab. Member Me of facies δ, Middle Yezo Group, right bank of the Pombetsu.



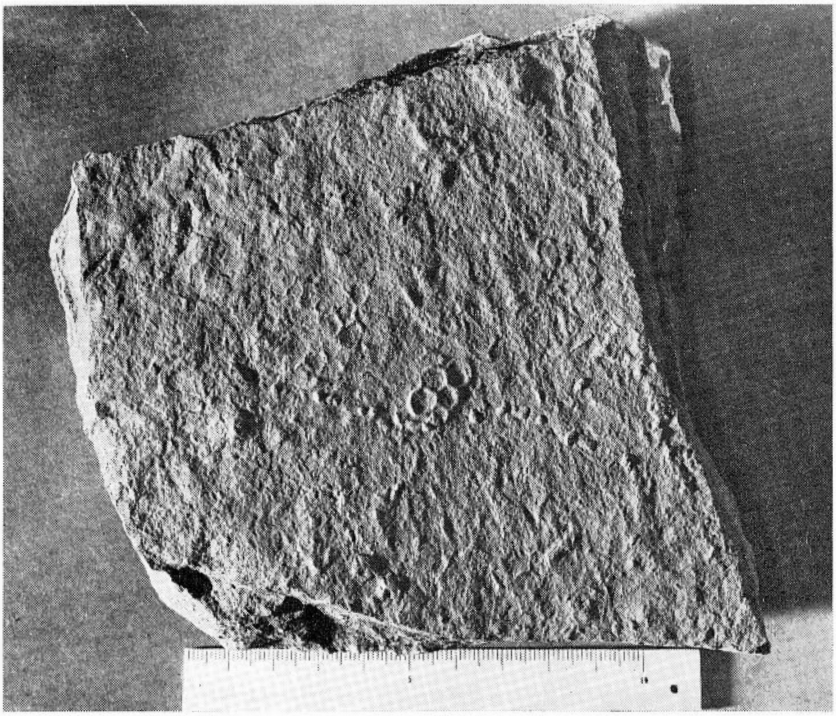
2. Outcrop of current ripple marked sandstone. Current from upper to lower. Member Mc of facies α, Middle Yezo Group, right bank of the Ikushumbetsu.



1. *Anapaleodictyon irregulare* TANAKA (MS.) on sole of sandstone. Member Me of facies δ, Middle Yezo Group, right bank of the Pombetsu. Scale in centimetres.

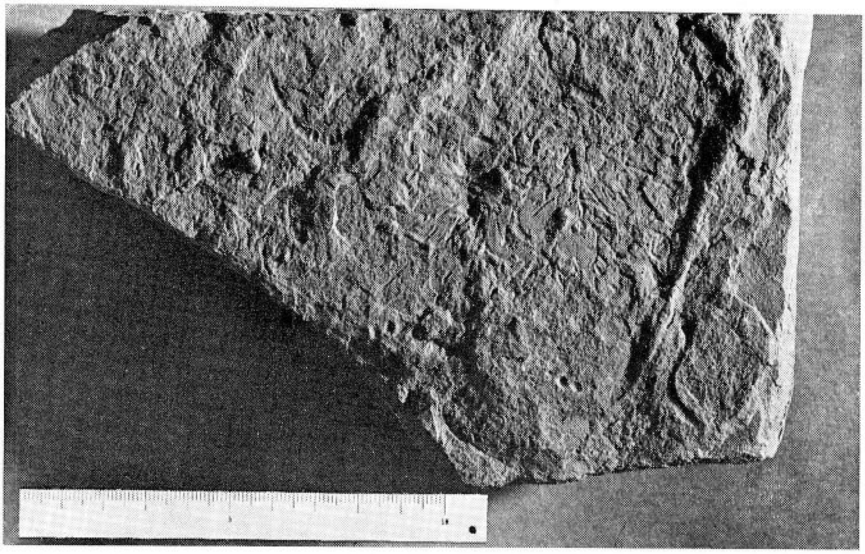


2. *Helminthoida japonica* TANAKA (MS.) on sole of sandstone. Member Me of facies δ, Middle Yezo Group, right bank of the Pombetsu.



1. *Paleodictyon* sp. α (regular type) on sole of sandstone. Member Me of facies δ, Middle Yezo Group, right bank of the Pombetsu. Scale in centimetres.

2. *Neonereites* aff. *uniserialis* SEILACHER on upper bedding surface of sandstone layer. Member Me of facies δ, Middle Yezo Group, left bank of the Pombetsu. Scale in centimetres.



1. *Chondrites* sp. on upper bedding surface of sandstone layer. Unit Mb_1 of facies α, Middle Yezo Group, left bank of the Ikushumbetsu. Scale in centimetres.

2. *Helminthopsis akkeshiensis* (MINATO and SUYAMA) (lower middle) and *Paleodictyon* sp. α (regular type) (upper left) on sole of sandstone. Member Me of facies δ, Middle Yezo Group, left bank of the Pombetsu.

地質調査所報告は１報文について報告１冊を原則とし，その分類の便宜のために，次のようにアルファベットによる略号をつける。

A．地質およびその基礎科学に関するもの
- a．地　質
- b．岩石・鉱物
- c．古生物
- d．火山・温泉
- e．地球物理
- f．地球化学

B．応用地質に関するもの
- a．鉱　床
- b．石　炭
- c．石油・天然ガス
- d．地下水
- e．農林地質・土木地質
- f．物理探鉱・化学探鉱および試錐

C．そ の 他

D．事業報告

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- b. Petrology and Mineralogy
- c. Paleontology
- d. Volcanology and Hot spring
- e. Geophysics
- f. Geochemistry

B. Applied geology
- a. Ore deposits
- b. Coal
- c. Petroleum and Natural gas
- d. Underground water
- e. Agricultural geology and Engineering geology
- f. Physical prospecting, Chemical prospecting and Boring

C. Miscellaneous

D. Annual Report of Progress

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TANAKA, K.

Sedimentation of the Cretaceous Flysch Sequence in the Ikushumbetsu Area, Hokkaido, Japan

Keisaku TANAKA

Report, Geological Survey of Japan, no. 236, p. 1 ~107, 1970
48 illus., 12 pl., 25 tab.

The Cretaceous flysch sequence in the Ikushumbetsu area, central Hokkaido is described with reference to its sedimentary attributes. The lithological features and thickness distribution of the sedimentation units (graded units) and the inorganic and biogenic sedimentary structures are described. Two types of lateral facies variation and cyclic sedimentation of various scales are discussed. Palaeocurrent analysis also is one of the main subjects of this paper.

551.763 : 551.3(524.32)

昭 和 45 年 1 月 26 日 印刷
昭 和 45 年 1 月 31 日 発行

工業技術院地質調査所

印刷者 小 林 銀 二
印刷所 泰成印刷株式会社
東京都墨田区東両国3—1—12

地 質 調 報
Rept. Geol. Surv. J.
No. 236, 1970