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Depositional Environments of the Wakino Subgroup of the Lower Cretaceous Kanmon Group in the Kitakyushu Area, Japan

Sang-Geon SEO, Takashi SAKAI and Hakuyu OKADA

Abstract

The Lower Cretaceous Wakino Subgroup, the lower part of the Kanmon Group, is exposed extensively in North Kyushu and in the western area of Chugoku, Southwest Japan. This subgroup rests unconformably on Permian metamorphic rocks and Upper Jurassic brackish-water deposits. The sedimentary facies and depositional environments of the Wakino Subgroup were examined on the basis of lithofacies, fossil assemblages and primary sedimentary structures.

The Wakino Subgroup consists of seven sedimentary facies which can be organized into three facies suites: the disorganized conglomerate and purple siltstone facies suite, sandstone and black mudstone facies suite, and turbidite and rhythmite facies suite. The disorganized conglomerate and purple siltstone facies suite occurs in the lower part of the Sengoku Formation and is represented by disorganized conglomerate of debris flow origin and purple siltstone with frequent intercalations of channel-fill sandstone with cross-stratified bed. This facies suite is interpreted as the alluvio-fluvial deposits. The sandstone and black mudstone facies suite occurring in the upper part of the Sengoku Formation is composed of sandstone with parallel lamination and low angle cross-lamination, and black mudstone with parallel lamination. The facies suite is interpreted to show the marginal lacustrine environment. The turbidite and rhythmite facies suite is characterized by turbidite sandstone (mostly Ta and Tab), rhythmite and massive and parallel laminated mudstone with sporadic intercalations of conglomerate as channel-fill deposits. This facies suite is one of the most striking features of the Wakino Subgroup, which is interpreted as deposits of the offshore lacustrine environments.

I. Introduction

The Lower Cretaceous Kanmon Group is well exposed in northern Kyushu to western Honshu in the Inner Zone of Southwest Japan. The succession of the Kanmon Group is one of the representatives of the Cretaceous lacustrine sediments in Japan. The group was divided into the Wakino Subgroup below and the Shimonoseki Subgroup above by MATSUMOTO (1951). The Wakino Subgroup has been studied on the stratigraphy and paleontology by many authors, because this subgroup contains abundant fresh water fossils (SUZUKI, 1906, 1940, 1943;

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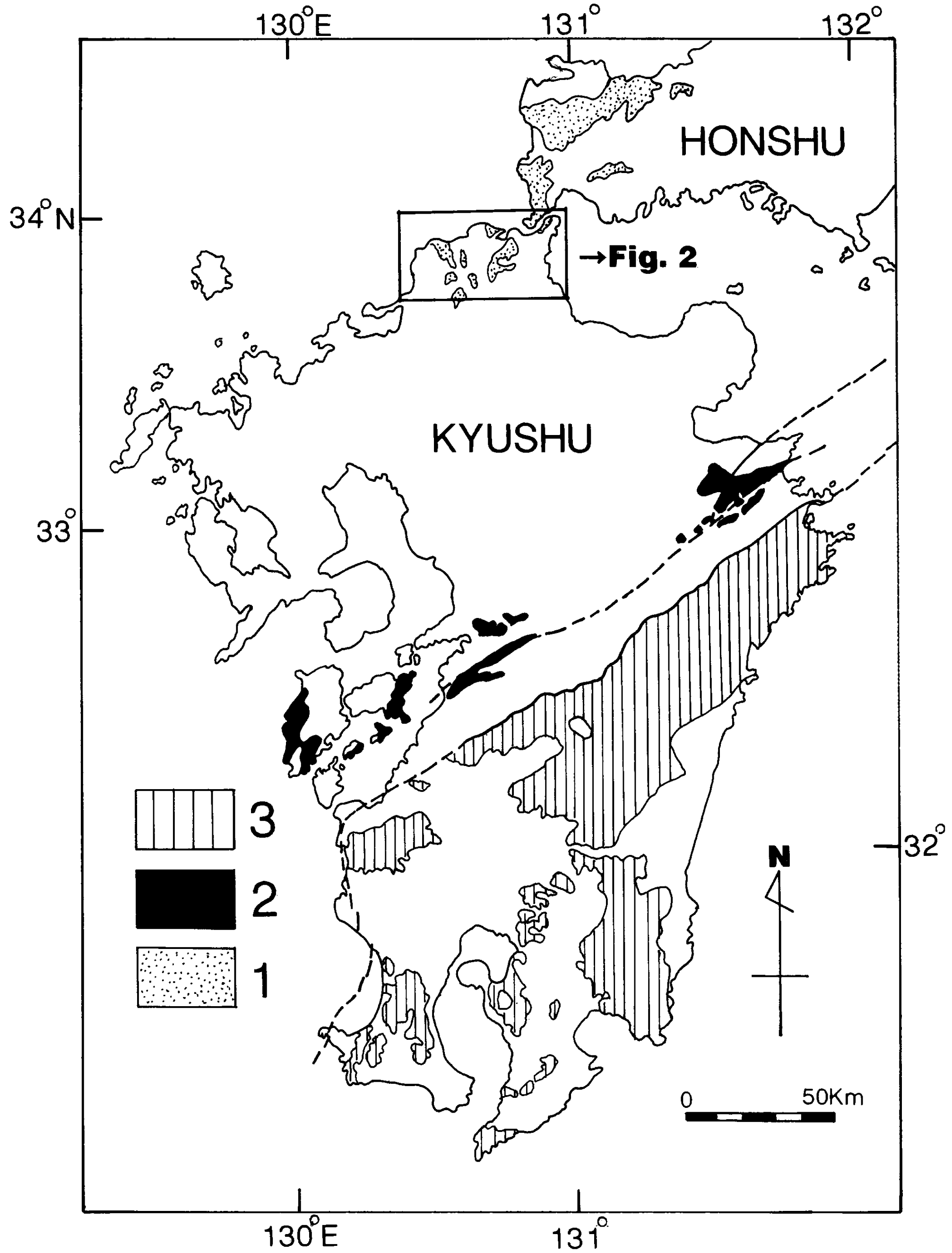


Fig. 1. Map showing the distribution of the Cretaceous strata in Kyushu and the location of the study area in the box. 1 : Early Cretaceous nonmarine strata (Kanmon Group), 2 : Early to Late Cretaceous strata in the Axial Zone, 3 : Late Cretaceous to Paleogene forearc-trench basins.

KOBAYASHI, 1931, 1941, 1949 ; TATEIWA, 1929, 1934 ; MATSUMOTO, 1951, 1954 ; HASE, 1958, 1960 ; OTA, 1955, 1960 ; OTA et al., 1979). However, sedimentary environments and depositional system of the Wakino Subgroup have been left unclear, because no detailed study of sedimentary facies and depositional processes has been undertaken for a long time.

Therefore, this study aims to describe the detailed sedimentary facies and to discuss depositional environments of the Wakino Subgroup.

II. Geologic setting and stratigraphy

A. General geology

The Cretaceous strata in the Kyushu area are mainly exposed in three zones ; the Early Cretaceous nonmarine successions in the Inner Zone, the Early to Late Cretaceous nonmarine to marine strata in the Axial Zone, and the Late Cretaceous deep marine deposits in the Outer Zone (OKADA and SAKAI, 1993) (Fig. 1). The Kanmon Group occupies roughly the northernmost part of the Inner Zone.

The Kanmon Group approximately attains the thickness of about 3000m and is stratigraphically subdivided into the lower Wakino Subgroup and the upper Shimonoseki Subgroup (MATSUMOTO, 1951) (Fig. 2). This group intruded by Late Cretaceous granitic rocks was locally subjected to contact metamorphism (SAKAI et al., 1992).

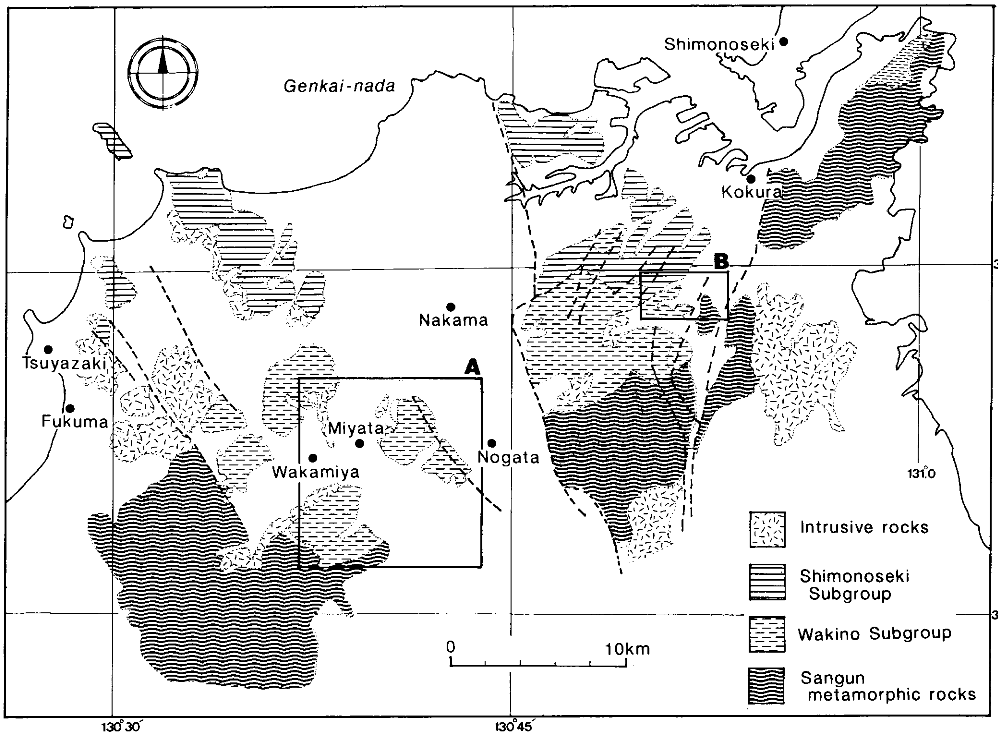


Fig. 2. Geologic map showing the distribution of the Kanmon Group in the study area (after Seo et al., 1992a). A : Wakamiya area, B : Kokura area.

The Wakino Subgroup, about 1000m thick, is composed mainly of black shale, conglomerate, sandstone, purple siltstone and acid tuff, containing abundant fresh water mollusks (OTA, 1960). It unconformably rests on the Sangun metamorphic rocks and Upper Jurassic brackish-water deposits (Toyonishi Group) (OKADA, 1981).

The Shimonoseki Subgroup, more than 2000m thick, disconformably overlies the Wakino Subgroup in places and unconformably covers pre-Cretaceous rocks in other places. This subgroup consists largely of andesitic lavas and volcaniclastic sediments, accompanied by clastic sediments (SAKAI et al., 1992).

The Wakino Subgroup has been biostratigraphically correlated with the Late Neocomian (OTA, 1960). The Shimonoseki Subgroup was assigned to the Aptian to Albian (MURAKAMI, 1974), though no age-determinable fossils have been obtained. From a paleomagnetic viewpoint, samples from the lower part of the Shimonoseki Subgroup show the normal polarity (SASAJIMA and SHIMADA, 1966). On the basis of this paleomagnetic data, SHIBATA et al. (1978) inferred that the Shimonoseki Subgroup is of the Albian age. IMAOKA et al. (1993) also reported that the Shimonoseki Subgroup is assigned to the Albian by means of the K-Ar dating of hornblende in volcanic rocks.

B. Stratigraphy of the Wakino Subgroup

The Wakino Subgroup is subdivided into the following three formations, on the basis of the lithofacies, sedimentary cycle and geological map of the Wakamiya and Kokura areas (Figs. 3 and 4): Sengoku, Nyoraida and Wakamiya Formations in ascending order (Fig. 5). The detailed lithofacies of each formation is as follows.

1. Sengoku Formation

The basal conglomerate of this formation nonconformably covers the Sangun metamorphic rocks. The basal conglomerate consists of pebbles to huge boulders of limestone, chert, sandstone, metamorphic rocks in sandy or silty matrix. Pebbles to cobbles of orthoquartzite and granitic rocks are found in a small amount.

The lower part of this formation consists mainly of conglomerate, pebbly mudstone, red to purple siltstone and black mudstone with

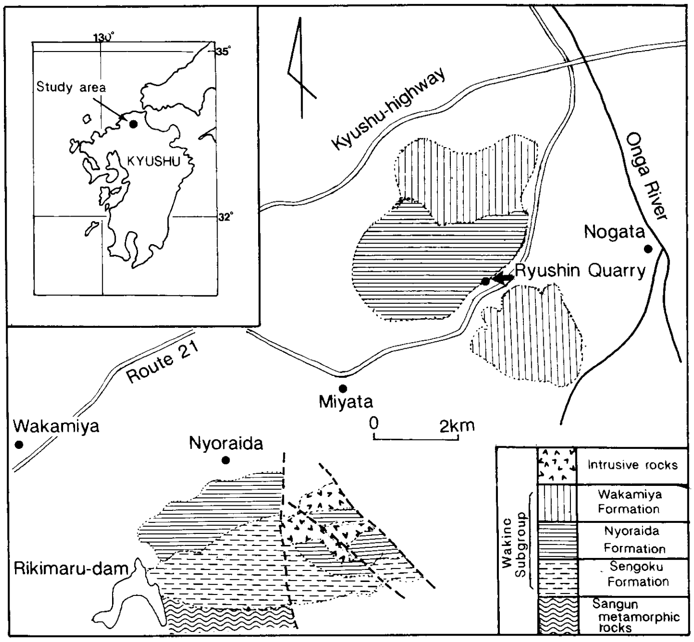


Fig. 3. Geological map of the Wakamiya area showing the distribution of the Wakino Subgroup (after Seo et al., 1992b).

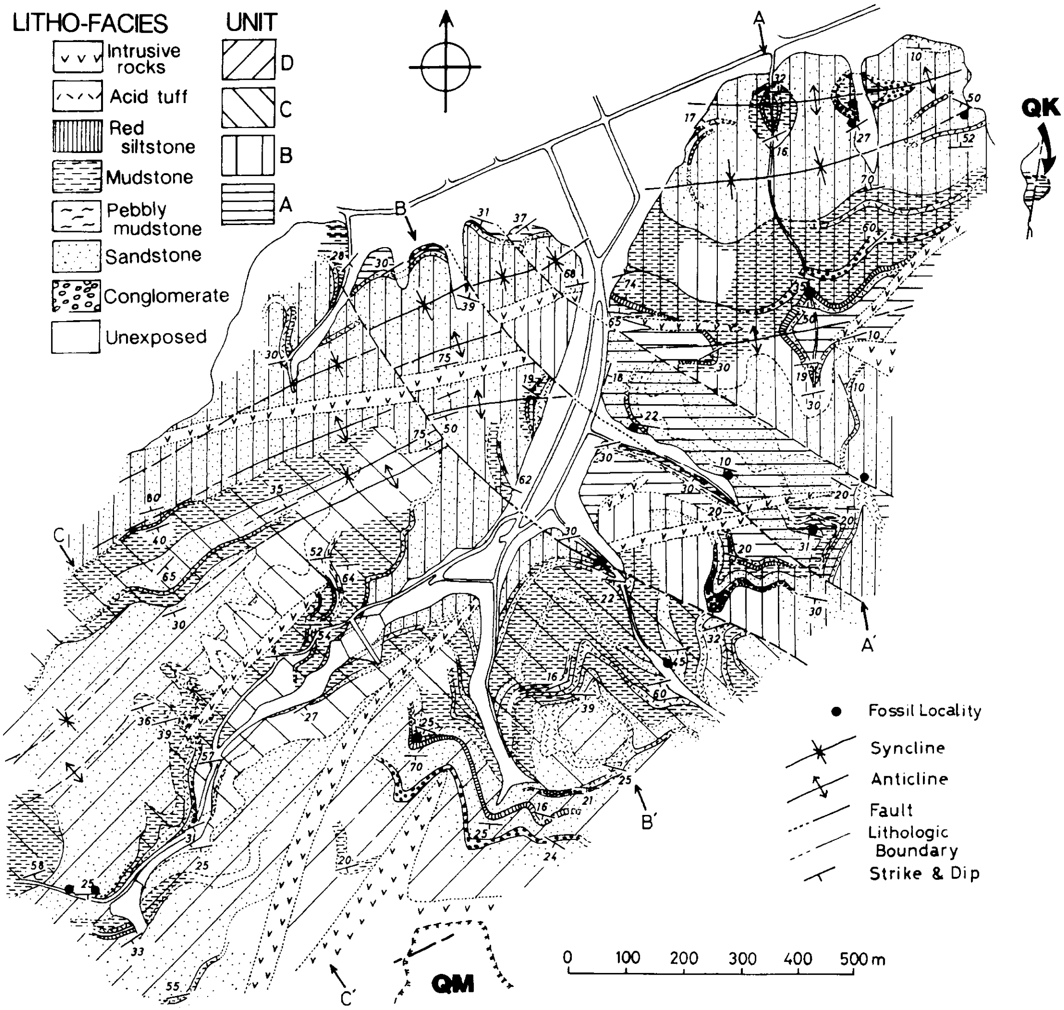


Fig. 4. Geological map of the Kokura area. Units A-D are the upper part of the Sengoku Formation (after Sakai et al., 1992). QM : Quarry of Moriyama Ind. Co., QK : Quarry of Kinoshita Mineral Product Co., Ltd.

some intercalations of slump bed and acid tuff (Fig. 5). The upper part is composed of massive to cross-bedded sandstone and massive to laminated black mudstone with intercalations of acid tuff (Fig. 5). This formation approximately attains the thickness of about 400m.

OTA (1960) reported fresh water molluscan fossils from the black mudstone of the formation. Representative species of them are *Brotiopsis wakinoensis* Kobayashi and Suzuki, "*Nipponaia*" *wakinoensis* Ota, and "*N.*" *sengokuensis* Ota.

2. Nyoraida Formation

This formation disconformably overlies the Sengoku Formation (OTA, 1955). The conglomerate of the lower part consists mainly of pebbles of quartz, limestone, chert, sandstone and siltstone in sandy matrix. The formation is mainly

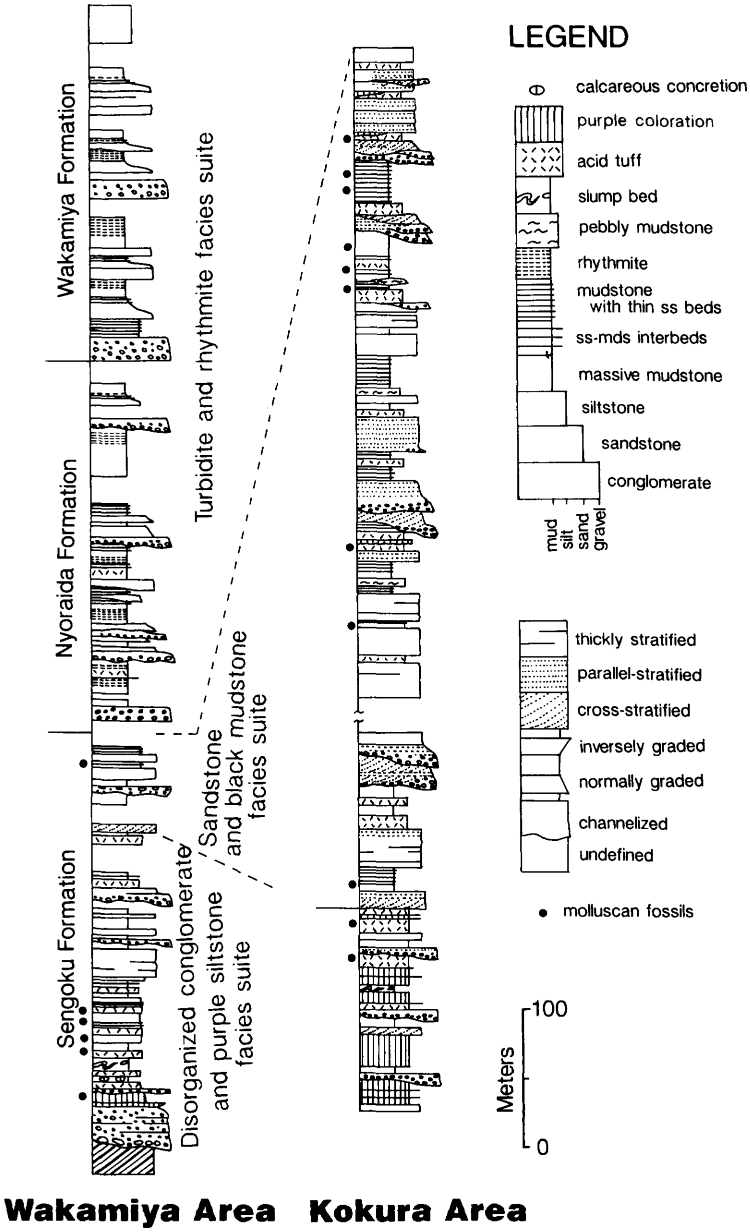


Fig. 5. Summarized columnar sections of the Wakino Subgroup in the Wakamiya and Kokura areas showing the facies characteristics (after Sakai et al., 1992).

composed of turbidite sandstone, massive to laminated black mudstone and very tightly bedded mudstone with intercalations of acid tuff (Fig. 5). Thickness of this formation is about 300m. The sequence of the Nyoraida Formation is commonly characterized by fining - and thinning-upward cycles.

The turbidite sandstone is characterized by Ta and Tab of the Bouma sequence. Mudstone is generally siliceous due to contact metamorphism, and contains authigenic pyrite grains concentrated in parallel to bedding.

The formation is very rare in fossils, but such molluscs as *Brotiopsis wakinoensis* Kobayashi and Suzuki, and *Viviparus onogaensis* Kobayashi and Suzuki are detected in mudstone in the Kokura area (OTA, 1960). Stromatolites rarely occur in parallel to bedding of black mudstone (Fig. 6).

3. Wakamiya Formation

The Wakamiya Formation disconformably overlies the Nyoraida Formation (OTA, 1955). The conglomerate of the lower part contains angular pebbles of quartz, limestone, sandstone and mudstone. This formation consists of conglomerate, turbidite sandstone, massive to laminated black mudstone and very tightly bedded mudstone (Fig. 5). The formation is characterized by fining-upward cycles of about 300m thick, which begin with conglomerate, pass into thick bedded sandstone and end with mudstone.

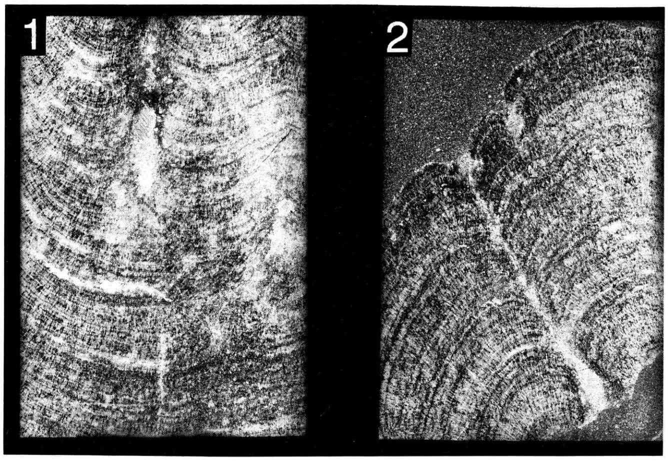


Fig. 6. Photomicrographs of stromatolite collected from the black mudstone of the Nyoraida Formation at the Ryushin Quarry. All the photomicrographs show the microstructure of the same specimen. 1 and 2 : polars crossed. The entire width of the photo is 0.8 cm.

Conglomerate and sandstone present graded-bedding and suggest the gravity-flow origin. Turbidite sandstones are characterized by Ta, Tab and Tabc of the Bouma sequence. This formation is also barren of fossils, except for *Viviparus* sp. from only limited places (OTA, 1960).

III. Sedimentary facies analysis

A. Facies analysis

Facies analysis was carried out on the basis of 1: 100scale columnar sections and observations of lithofacies, fossil assemblages and primary sedimentary structures.

The term "facies suite" is used here in order to express facies sequence with an environmental sense (TEICHERT, 1958). Of course, each facies suite is made up of several facies associations. The concept of the facies suite is useful to

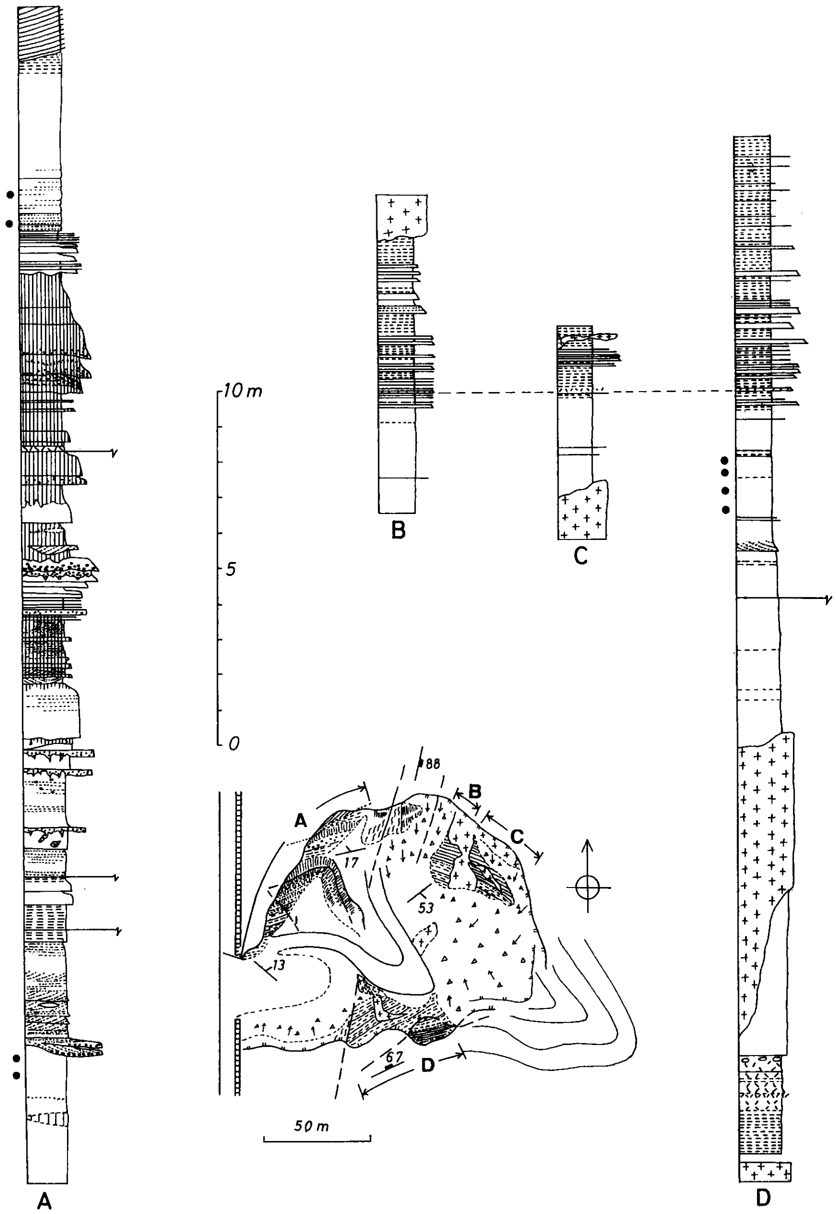


Fig. 7. Sketch and columnar sections at the quarry of Kinoshita Mineral Product Co. (after Sakai et al., 1992). A : sandstone and black mudstone facies suite, B : turbidite and rhythmite facies suite.

concisely understand the depositional system of the Wakino Subgroup.

The sedimentary sequence of the Wakino Subgroup can be classified into the following three major facies suites :

1. Disorganized conglomerate and purple siltstone facies suite
2. Sandstone and black mudstone facies suite
3. Turbidite and rhythmite facies suite

These facies suites are in fault contact with each other. These relations are well shown in a quarry outcrop of the Kinoshita Mining Co., Ltd., south of Kokura (Figs. 4 and 7). Each boundary fault strikes NNE-SSW and dips nearly vertically, accompanying shear zones, up to 20m wide with thin granitic dykes along shear planes.

B. Description of facies suite

1. Disorganized conglomerate and purple siltstone facies suite

This suite is applicable to the lower part of the Sengoku Formation, and exhibits marked lateral changes in lithofacies and thickness, which ranges from 10m to about 80m. The suite is exposed extensively around the Rikimaru Dam (Fig. 3) and at the quarry of Moriyama Industry Co., Ltd. (Fig. 4) in the Kokura area, which is composed mainly of massive conglomerate of the debris flow origin, massive to weakly stratified sandstone, purple shale, acid tuff and tuffaceous shale, massive or laminated black mudstone and slump beds (Fig. 5). This facies suite is subdivided into the disorganized conglomerate facies and purple siltstone facies.

a. Disorganized conglomerate facies

This facies characterizes the basal part of the Wakino Subgroup in the Wakamiya and Kokura areas. The conglomerate consists of subangular to rounded gravels, locally breccia, ranging in size from granule to boulder, of which pebble is predominant. It has ill-sorted and massive mud matrix, showing a disoraganized stratification. Thickness of this facies ranges from 2 to 5m.

b. Purple siltstone facies

This facies is a major constituent and occupies up to 25% of the total succession in the columnar section in the Sengoku Formation. The purple siltstone facies is subdivided further into two subfacies ; massive ill-sorted purple siltstone subfacies and thinly interbedded purple siltstone and sandstone subfacies.

The former contains granules and pebbles, and shows a disorganized stratification. The purple siltstone is also associated with ill-sorted pebble to cobble beds of debris-flow origin. The latter consists of interlayers of purple siltstone and graded sandstone. This sandstone is fine-to coarse-grained, light gray in color, and bears granules. It is accompanied by channel-lag conglomerate and large to medium scale cross-stratified and/or parallel laminated, well-sorted sandstone beds. Purple siltstone interbedded with sandstone beds shows rain prints and mud cracks (Fig. 8), though rarely.

According to OTA (1960), this facies contains many molluscan fossils such as *Broptiopsis wakinoensis* Kobayashi and Suzuki, "*Nippononaia*" *wakinoensis* Ota, "*N*"*sengokuensis* Ota, and so on.

2. Sandstone and black mudstone facies suite

This facies suite characterizes the upper part of the Sengoku Formation in the Wakamiya and Kokura areas. The facies suite is subdivided into the sandstone facies and black mudstone facies.

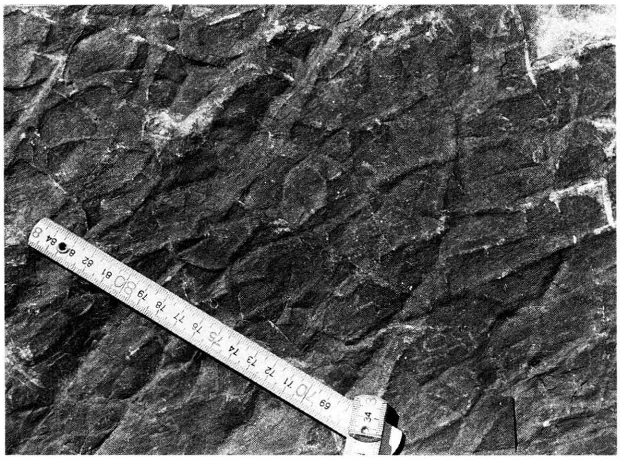


Fig. 8. Mudcrack developed on the purple siltstone from the lower part of the Sengoku Formation, Kokura area. At the quarry of Moriyama Ind. Co.

a. Sandstone facies

This facies is characterized by thickly stratified sandstone, parallel lamination and low angle cross-lamination, being frequently mottled by bioturbation. In addition, the facies is characterized by the prevalence of fining-upward cycles and rarely shows hummocky cross-bedding of storm origin. Sandstone is fine-to medium-grained and rarely well-sorted. Conglomerate in the sandstone facies occurs as sediments of density currents, channel-fill (Fig. 9) and channel lag. It commonly shows an erosive base, and its lateral extension is very poor.

Fig. 9. Channel-fill conglomerate in the sandstone facies of the Sengoku Formation which consists mainly of chart, limestone, quartz and other sedimentary clasts. At the quarry of Moriyama Ind. Co.

b. Black mudstone facies

This facies is represented by black mudstone and tuff or tuffaceous siltstone interbeds with frequent intercalations of purple siltstone. Black mudstone shows tight parallel lamination, rarely includes ripple marks, and is partly calcareous. Tuff and tuffaceous siltstone show parallel lamination and cross-lamination on a small scale. Purple siltstone in this facies shows irregular and rugged surfaces with angular mud clasts. Conglomerate contains small pebbles at the base, accompanied by poorly preserved cross-laminations.

Fresh water fish fossils were found from tightly banded mudstones in this facies (YABUMOTO, 1994). Massive black mudstone rarely contains gastropods and stromatolites (Fig. 6) as ill-preserved moulds at some horizons. In addition, OTA et al. (1979) reported lacustrine fauna such as Clupeidae, Lycopteridae, estherid and algal stromatolites from the equivalent succession in the Kokura area.

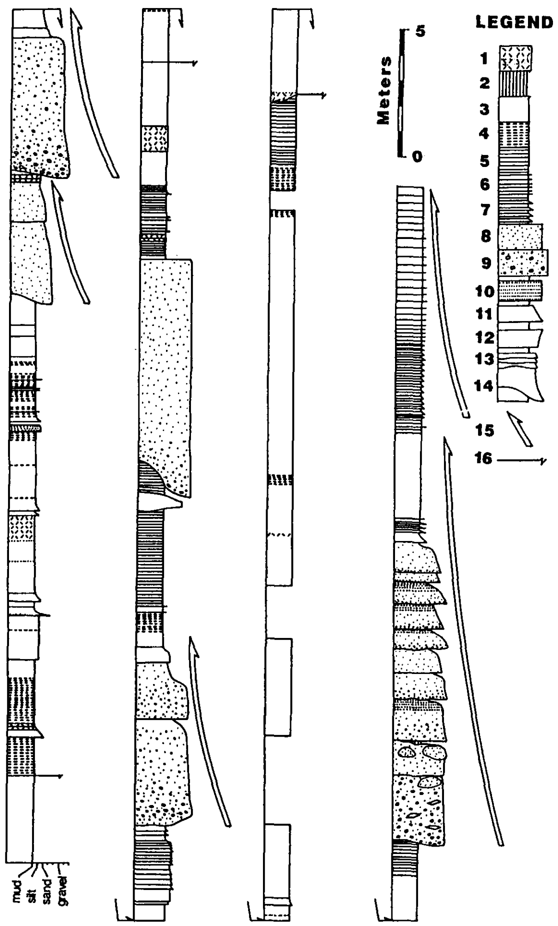


Fig. 10. Columnar sections obtained at the quarry of Ryushin Mining Co., Ltd (after Seo et al., 1992b). 1, tuff and tuffite ; 2, coaly shale ; 3, massive mudstone ; 4, rhythmite ; 5, very thin interbeds of sandstone (1 to 5cm thick) and mudstone ; 6, thin interbeds of sandstone (5 to 10cm thick) and mudstone ; 7, medium interbeds of sandstone (10 to 20cm thick) and mudstone ; massive sandstone ; 9, massive pebbly sandstone ; 10, parallel lamination ; 11, normally graded ; 12, inversely graded ; 13, amalgamated ; 14, channeled ; 15, fining-upward cycle ; 16, fault.

3. Turbidite and rhythmite facies suite

This facies suite mainly occurs in the Nyoraida and Wakamiya Formations and is excellently exposed in the Ryushin Quarry, east of Wakamiya (Figs. 3 and 10). The facies suite consists of turbidite sandstone, rhythmite, massive to laminated black mudstone and conglomerate, being further subdivided into the fine siltstone facies, rhythmite facies and turbidite facies. This facies suite is not restricted in this area, but can be traced to West Honshu at least over the distance of 60 km.

a. Fine siltstone facies

This facies exposed on the northeastern side of the Ryushin Quarry shows a very homogeneous lithology with dominant mudstone. This sequence is made up of interbeds of laminated mudstone and thin tuffaceous siltstone in the lower part, massive coarse-to fine-grained sandstone and mudstone in the middle, and alternating beds of laminated mudstone and thin turbidite sandstone in the upper.

The vertical facies change from the middle to the upper is gradational with increasing sandy laminae and beds towards the top. The laminated mudstone is characterized by the interlayers of ripple- (Fig. 11) and/or parallel-laminated coarse silt or very fine sand laminae and black to deep green mud.

Simultaneously, this facies is intercalated by channelized sandstones (Fig. 12) with large-scaled cross-stratification. The presence of cross-laminated silt and the abundance in much thicker and coarser graded-beds than those in the rhythmite facies are characteristic of the facies.

The thinly bedded sandstones are fine-grained and show graded bedding. Some graded sandstone beds contain pebble clasts at the basal part. The bedding is very flat and even without any erosion and lateral change in bed thickness. Internally, graded bedding is rarely accompanied by parallel and ripple-cross laminations.

Fig. 11. Straight-ripple mark on the surface of a mudstone bed in the fine siltstone facies at the quarry of Ryushin Mining Co.,Ltd. in the Wakamiya area.

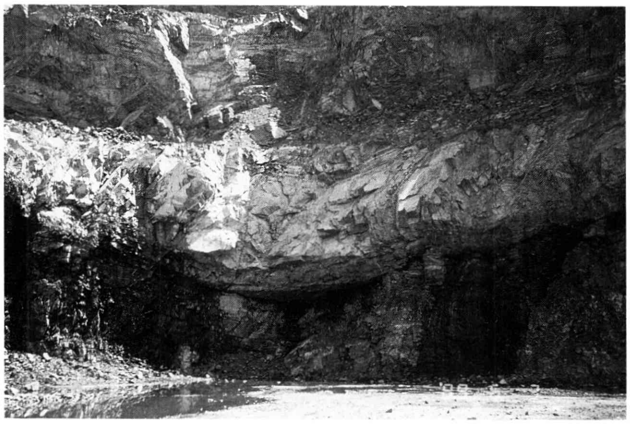


Fig. 12. A channelized sandstone bed in the fine siltstone facies. The entire width of the photo is about 20m. At the quarry of Ryushin Mining Co., Ltd. in the Wakamiya area.

b. Turbidite facies

About 30% of the succession in the Ryushin Quarry is occupied by coarse-grained sediments consisting of medium-to thick-bedded pebbly conglomerate, pebbly sandstone and coarse-to fine-grained sandstone (Fig. 10). All of these coarse-grained sediments show diagnostic sedimentological features as described below.

Most of conglomerate beds show a sharp erosive base. Gravels contained are generally well-rounded, except for angular clasts of black shale. Clasts of sandstone and black shale range up to tens of centimeters in size. Conglomerate shows in general a matrix-supported fabric and a coarse-tail normal grading, and rarely inverse grading at the base of beds. Medium-to thick bedded sandstone shows Ta or Tab of the Bouma sequence (Fig. 13), but Tabc is not so common.

These coarse-grained beds occur intermittently in the argillite facies and are little amalgamated. As for the occurrence of these coarse-grained sediments, the following two modes are recognizable: one is that they occur solely and show a sharp contact with the underlying and overlying rhythmites. The other constitutes sequences which begin with conglomerate at the base, grades into thick-to medium-bedded sandstone and thinly interbedded sandstone/shale, and ends with massive mudstone. Thus, the latter represents a fining-upward cycle (Fig. 10).

Fig. 13. The turbidite sandstones in the turbidite facies are characterized by the Ta and Tab divisions of the Bouma sequence. At the quarry of Kinoshita Mineral Product Co., Ltd.

c. Rhythmite facies

The term "rhythmite" was first introduced and defined by BRAMLETTE (1946) as a bedding that is a repetitious sequence of generally thin and alternating types of sediment particles. The rhythmite is here introduced to describe very tightly bedded argillites, which exhibit alternating thin layers of slightly different composition, texture and color. The bedding is indicated by varve-like color-banded patterns. Thickness of individual laminae is usually less than 1 cm. The light-colored layer consists generally of coarse to fine silt, while the dark-colored one of very fine silt or clay. Microscopic observation reveals that all of the coarse layers show normal grading. The color change from light to dark is gradational, whereas that from dark to light is sharp. Individual layers retain constant thickness, and microcycles shown by changes of layering density are repeated at 1 to 1.5cm intervals.

Fig. 14. Alternating beds of rhythmite and black mudstone in the rhythmite facies. At the quarry of Ryushin Mining Co., Ltd.

The rhythmite facies (Fig. 14) forms units 2 to 15m thick, which are interbedded with massive to laminated black mudstone or much coarser siltstone and turbidite sandstone, and appear over 10 times repeatedly in the Nyoraida Formation (Fig. 10). The facies shows sometimes de-gassing passage structures, pillar structures, and hydro-fracturing structures.

The rhythmite facies is classified into three types (type A, B and C), according to internal structure and thickness of lamina (Fig. 15) (SEO et al., 1992b). The type A is characterized by alternating dark and light gray laminae, showing varve-like couplets. The thickness of a couplet is less than 1mm, though thicker ones than 1mm are rarely met with (Fig. 15). Individual laminae commonly show grading from fine-silt to clay under microscope.

Type B consists generally of lamina of 1-5mm thick. The base of laminae shows very weak erosional surface and contacts between individual lamina is sometimes amalgamated (Fig. 15). This type is characterized by grading, convolution and parallel lamina.

Type C is composed of dark and light gray laminae of more than 5mm in thickness (Fig. 15). Contacts between individual lamina is sharp, but other types of rhythmites are sometimes irregular. This type consists of fine to coarse silt and shows no internal structure.

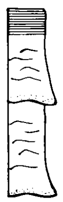
Type	Facies	Structure & thickness	Interpretation
TYPE A		•thickness: less than 1mm •graded to massive •couple of two laminae	• suspension cloud
TYPE B		•thickness: 1-5mm •erosive base •graded •convolute •parallel to massive	• low-density turbidity current • suspension cloud
TYPE C		•thickness: thicker than 5mm •massive to irregular	• overflow • mudflow

Fig. 15. Classification of rhythmites in the Wakino Subgroup (after Seo et al., 1992b).

IV. Discussion

As described above, the Wakino Subgroup is subdivided into seven major facies regarding lithofacies and fossil assemblages; the disorganized conglomerate, purple siltstone, sandstone, black mudstone, fine siltstone, turbidite, and rhythmite facies. According to TEICHERT (1958), these facies are grouped into three facies suites: the disorganized conglomerate and purple siltstone facies suite, the sandstone and black mudstone facies suite, and the turbidite and rhythmite facies suite. On the basis of Miall's classification of facies (1978), depositional environments of these three facies suites in the Wakino Subgroup are discussed in this chapter. Facies classification of MIALL (1978) is shown in Table 1.

Table 1. Classification of sedimentary facies by Miall (1978).

Facies code	Facies	Sedimentary Structures	Interpretation
Gms	massive, matrix supported gravel	grading	debris flow deposits
Gm	massive or crudely bedded gravel	horizontal bedding, imbrication	longitudinal bars, lag deposits, sieve deposits
Gt	gravel, stratisfied	trough cross beds	minor channel fills
Gp	gravel, stratisfied	planer cross beds	longitudinal bars, deltaic growths from older bar remnants
St	sand, medium to very coarse, may be pebbly	solitary or grouped trough cross beds	dunes (lower flow regime)
Sp	sand, medium to very coarse, may be pebbly	solitary or grouped planer cross beds	linguoid, transverse bars, sand waves (lower flow regime)
Sr	sand, very fine to coarse	ripple cross lamination	ripples (lower flow regime)
Sh	sand, very fine to very coarse may be pebbly	horizontal lamination parting or streaming lineation	planer bed flow (upper flow regime)
Sl	sand, very fine to very coarse may be pebbly	low angle (<10°) cross beds	scour fills, washed-out dunes, antidunes
Se	erosional scours with intraclasts	crude cross bedding	scour fills
Ss	sand, fine to very coarse, may be pebbly	broad, shallow scours	scour fills
Fl	sand, silt, mud deposits	fine lamination, vey small ripples	overbank or waning flood
Fsc	silt, mud	laminated to massive	backswamp deposit
Fcf	mud	massive, with freshwater molluscs	backswamp pond deposits
Fm	mud, silt	massive, desiccation cracks	overbank or drape deposits
C	coal, carbonaceous mud	plant, mud films	swamp deposits
P	carbonate	pedogenic features	paleosol

A. Disorganized conglomerate and purple siltstone facies suite

The disorganized conglomerate and purple siltstone facies suite occurring in the lower part of the Sengoku Formation and is characterized by disorganized conglomerate and purple siltstone with frequent intercalations of channel-fill sandstone with cross-stratified bed. This facies suite consists of the disorganized conglomerate facies and purple siltstone facies.

The disorganized conglomerate facies is mainly developed at the basal part of the Wakino Subgroup and is represented by disorganized conglomerate. It has ill-sorted and massive mud matrix, showing disorganized stratification. These features indicate that this conglomerate is of debris flow origin (MIALL, 1978). It corresponds to Miall's facies code Gms, which is interpreted to be the alluvial fan deposits (Fig. 16).

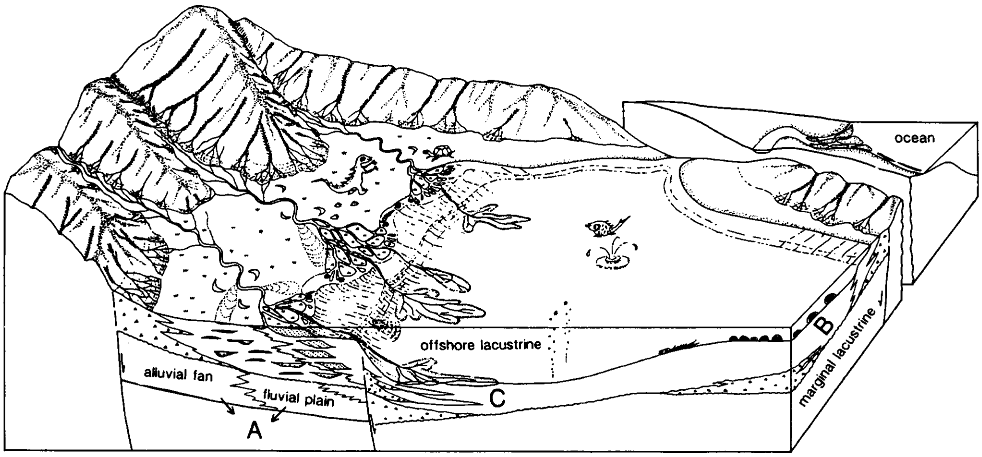


Fig. 16. Model showing depositional environments for the Wakino Subgroup in the Kitakyushu area. A : Disorganized conglomerate and purple siltstone facies suite, B : Sandstone and black mudstone facies suite, C : Turbidite and rhythmite facies suite.

The purple siltstone facies characterizing the lower part of the Sengoku Formation consists mainly of pebbly mudstone and interlayers of purple siltstone and graded sandstone which are correlated with Miall's code Fl and Fsc. In addition, purple siltstone shows rain prints and mud cracks. It corresponds to Miall's code Fm. These features indicate a fluvial plain environment (Fig. 16).

The disorganized conglomerate and purple siltstone facies suite is interpreted to be alluvio-fluvial deposits. This is warrantably supported by molluscan fossils, as reported by OTA (1960).

B. Sandstone and black mudstone facies suite

This facies suite occurring in the upper part of the Sengoku Formation is composed of sandstone with parallel lamination and low angle cross-lamination, and black mudstone with parallel lamination. The facies suite is subdivided into the sandstone facies and black mudstone facies.

The sandstone facies is characterized by thick sandstone with parallel lamination and low angle cross-lamination, which are frequently mottled by bioturbation. This sandstone corresponds to Miall's code Sh and Sl. Moreover, this facies is also characterized by prevalence of fining-upward cycles and well-sorted sandstone with hummocky cross-bedding of storm origin. This facies is very similar to the nearshore lacustrine facies of the Ridge Basin in California, as described by LINK and OSBORNE (1978). Judging from the facies association of MIALL (1978) and LINK and OSBORNE (1978), this facies may indicate the nearshore lacustrine environments.

The black mudstone facies consists of massive to stratified black mudstone (Miall's Fcf) and siltstone with parallel lamination and cross-lamination (Miall's Fsc), and of alternating beds of purple siltstone. Black mudstone is partly calcareous and rarely shows ripple lamination. This feature shows that of Miall's code C and Fl. Purple siltstone intervened in the black mudstone facies shows irregular and rugged surfaces and includes angular mud clasts. The coarse-grained beds with normal grading in the purple siltstone correspond to Miall's code Gt and Gp. Conglomerate contains small pebbles at the base, accompanied by poorly preserved cross-lamination (Miall's code Gm or Gt). This conglomerate may be a channel-lag gravel.

The deposits of this facies suite yield a fresh water fauna such as Clupeidae, Lycopteridae, estherid and algal stromatolite (OTA et al., 1979). As discussed above, this facies suite is interpreted to show the marginal lacustrine environment (Fig. 16).

C. Turbidite and rhythmite facies suite

This facies suite is one of the most striking facies suites of the Wakino Subgroup, which has not been reported as yet in any other nonmarine strata of the Cretaceous in Japan. It is characterized by turbidite sandstone (mostly Ta and Tab), rhythmite, black mudstone with parallel lamination and massive black mudstone with intercalations of conglomerate as channel-fill deposits. The facies suite shows fining-and thinning-upward cycles. The facies suite is subdivided into the fine siltstone facies, rhythmite facies and turbidite facies.

According to STURM and MATTER (1978), the characteristics of the fine siltstone facies indicate evidently that it was deposited under the stagnant-water condition, where the fine materials were transported as suspension clouds. This facies is interpreted to have been accumulated probably on the offshore slope apron rather than on the offshore basin floor.

The turbidite facies is characterized by fining-upward cycles and coarse-grained sediments consisting of medium-to thick-bedded pebbly conglomerate, pebbly sandstone and coarse-to fine grained sandstone. According to WALKER (1978), all of these coarse-grained sediments may have been deposited mainly by density currents. The turbidite facies was originated as non-channelized lobes in the offshore lacustrine fan system.

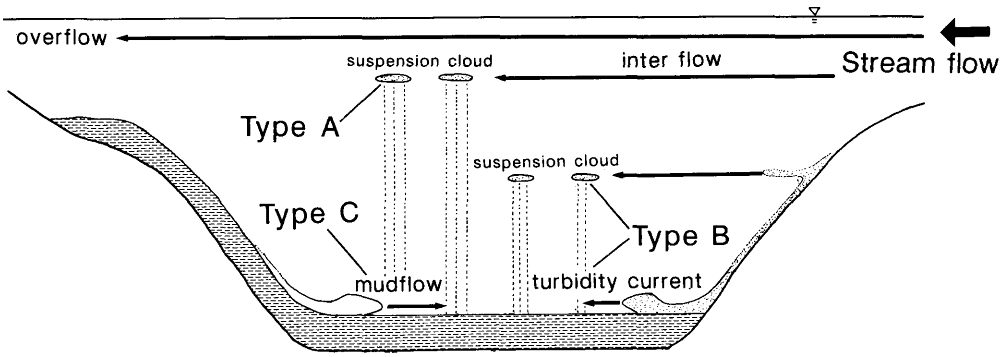


Fig. 17. Model showing the origin of three types of rhythmite in the Wakino Subgroup (after Seo et al., 1992b).

The rhythmite facies in the Wakino Subgroup is classified into three types (type A, B and C), mainly based on the internal structure and thickness of laminae (Fig. 15), as mentioned above. According to SEO et al. (1992b), these rhythmites may have been originated from interflows, low-density turbidity currents, overflows and mudflows. Fig. 17 presents a model showing origins of three types of rhythmites in the Wakino Subgroup. This facies is interpreted to have been deposited probably on the offshore basin floor, according to STURM and MATTER (1978).

STURM and MATTER (1978) suggest that the characteristics of the turbidite and rhythmite facies suite was mainly deposited under the stagnant-water condition, where the fine materials were transported as suspension clouds. This facies suite from the three facies associations is interpreted to have been accumulated in the offshore lacustrine (Fig. 16).

V. Conclusion

(1) The Wakino Subgroup is subdivided into seven major facies regarding lithofacies, fossil assemblages and sedimentary structures : the disorganized conglomerate, purple siltstone, sandstone, black mudstone, fine siltstone, turbidite, and rhythmite facies. Among these facies, the turbidite and rhythmite facies is one of the most striking facies of the Wakino Subgroup.

(2) Three major facies suites in the Wakino Subgroup are distinguished ; the disorganized conglomerate and purple siltstone facies suite, the sandstone and black mudstone facies suite, and the turbidite and rhythmite facies suite. These facies suites are interpreted as the deposits of alluvio-fluvial, marginal and offshore lacustrine environments, respectively.

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