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Sedimentary Cyclicities and their Implications of the Junicho Formation (late Pliocene-early Pleistocene), Central Honshu, Japan

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Abstract : The Junicho Formation in Central Honshu, represents the Plio-Pleistocene shallow marine non-tropical (temperate) carbonate and mixed-sediments. This formation with a wide variety of sedimentary facies is stratigraphically divided into three parts, the lower, middle and upper, and reveals distinct cyclic changes of litho- and bio-facies in its middle and upper parts.

Sedimentary facies distribution (particularly, the onlap pattern) and molluscan assemblages, indicate that the Junicho Formation was initially deposited under a rapid transgression due to relative sea-level rise. After the transgression was terminated, it turned to a regression. In the lower and middle parts, there occur only lower sublittoral molluscan assemblages (inhabiting from 50-60 to 200-250 m in depth), while the upper part is dominated by upper sublittoral molluscan assemblages (dwelling from low tide mark to 50-60 m in depth).

At least three sedimentary cycles are recognized in the middle part. Each cycle is lithologically divided into three facies; facies G (bioturbated calcareous fine sandstone), facies D (massive calcareous fine sandstone) and facies F (calcareous fine to medium sandstone with indurated bed) in ascending order. The vertical change of the molluscan fossil assemblages coincides with that of these facies distribution; *Acila nakazimai* assemblage within facies G and D, and *Conchocele - Venericardia* assemblage within facies F.

In the upper part occur at least four sedimentary cycles; they consist of five lithofacies; facies A (well-sorted fine sandstone), facies B (poorly-sorted very fine sandstone), facies C (calcareous medium sandstone), facies D (massive calcareous fine sandstone) and facies E (calcareous coarse sandstone) in ascending order. A typical cycle in this part (*e.g.* Cycle 3) indicates change in sedimentary environments from lower shoreface (in the maximum regression stage) to outer shelf (in the maximum transgression stage).

Study of magnetostratigraphic polarity confirms that (1) the Plio-Pleistocene boundary is located in the upper portion of the middle part of the Junicho Formation, and (2) the lower to middle parts characterized with the normal polarity are assigned to the Olduvai Subchron in the Matuyama Chron. Based on this age assignment, sedimentation rate is reestimated to be about 30 cm/1000 y under the assumption of its constancy.

Sedimentary cycles of the Junicho Formation, which demonstrate rapid rises and falls in sea-level are most likely ascribed to have formed under a major control of glacio-eustatic sea-level change. A depositional model of the non-tropical (temperate) carbonate and mixed-sediments on shelf is proposed with respect to glacio-eustacy.

In addition, stratigraphical changes of rock-magnetic properties (*e.g.* susceptibility) of the cyclic sediments of the middle part (Cycle I and II) reveal a much higher-frequency cycle than that of the litho- and bio-facies. It is expected that this analysis can be used as a sensitive and effective indicator for temporal variations of sedimentary component (especially of ferromagnetic minerals).

1. Introduction

Eustatic sea-level change should tend to leave some variation in sediments and sedimentary facies. The concept of sequence stratigraphy has made remarkable progress in recent years, and benefitted to establish semi-quantitative, eustatic sea-level charts based on the onlap of depositional sequences onto passive continental margins (*e.g.* VAIL *et al.*, 1977; HAQ and VAIL, 1987). Although periodicity and amplitude of first- to third-order cycles of the eustatic sea-level changes are well documented by onlap of stratigraphic sequence, it is generally difficult to detect cycles higher than the third-order, based on indistinct boundaries of seismostratigraphic profiles.

Pleistocene Epoch is characterized by the worldwide climatic changes and the consequent glacio-eustatic sea-level change with periodicity and amplitude of such higher orders (which are often compared with the periods of the Milankovitch cycles by some authors). The glacio-eustatic sea-level change during the Pleistocene has been examined by geochemical signatures and paleomagnetic parameters of deep-sea cores (*e.g.* SHACKELETON and OPDYKE, 1973; PRELL, 1982; WILLIAMS, 1988), and, for late Pleistocene, by multidisciplinary studies of marine terraces, especially of coral reefs.

Shallow marine cyclic sedimentary sequence on and off shelf, now preserved in outcrop on active continental margins (*e.g.* Japan and New Zealand) can be utilized to construct these high-frequency sea-level change, based on the concept of sequence stratigraphy. Though apart from sequence stratigraphy, for instance, the cyclic sedimentary sequence of the Shimosa Group, a representative of the middle to late Pleistocene, of Central Honshu, Japan, was described by several authors (*e.g.* AOKI and BABA, 1973, 1980; TOKUHASHI and KONDO, 1989). Early Pleistocene glacio-eustatic sea-level changes also have been documented from a limited number of marine shelf deposits both in New Zealand (BEU and EDWARDS, 1984) and Japan (Central Honshu; KITAMURA and KONDO, 1990 and Northeast Honshu; KANAZAWA, 1990).

The present study was intended to document the similar high-frequency cycles in shallow marine sequence of non-tropical carbonate and mixed-sediments, exemplified by the Junicho Formation (late Pliocene to early Pleistocene) of Central Honshu, Japan, with a background of sequence stratigraphy. Other than litho- and molluscan bio-facies analyses in detail, paleomagnetic studies were attempted with two-fold purposes; (1) to clarify an ambiguous rate of sedimentation reported for a part of the formation, and (2) to test feasibility of sedimentary cyclicity assignment with magnetic properties (*e.g.* susceptibility) for shallow-water deposits.

2. The Junicho Formation

The Junicho Formation was first named and described by HASEGAWA (1979), after its type locality, Junicho in southwestern area of Himi City, where it is exposed in the area of about 25 km^2 (Fig. 1). This formation unconformably overlies the Ao Formation (latest Miocene to early Pliocene) that consists of massive siltstone, and is overlain with the "Hanyu" Formation (Pleistocene) mainly composed of an alternation of sandy siltstone and fine sandstone (HASEGAWA and KOBAYASHI, 1986).

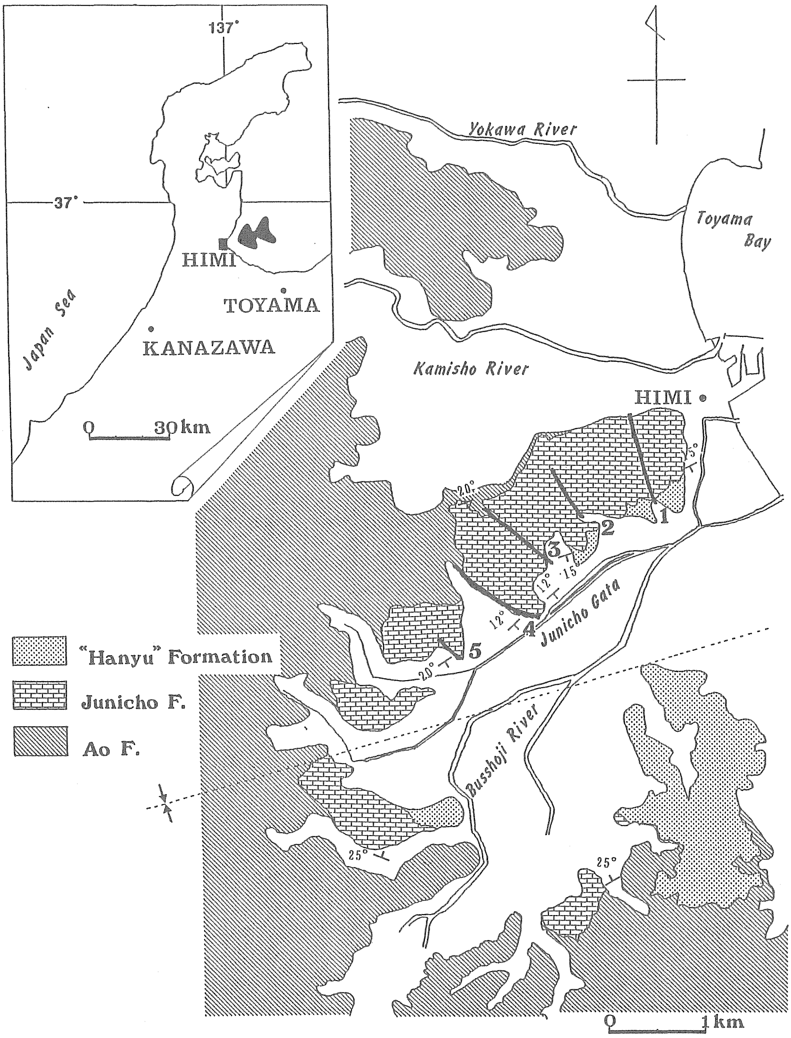


Fig. 1. Index and generalized geologic map showing the studied area and five routes (1-5), where detailed stratigraphy is carried out.

Thickness of the formation attains to 160 m in the northern part of the studied area, where it has attitude of strikes of N45°E and dips of 15-20° SE. In this part it is composed mainly of calcareous coarse sandstone and calcareous fine sandstone with a wide variety of sedimentary facies. Many tuff beds (10 cm to 1 m in thickness) are intercalated in this formation.

In the southern part of the surveyed area, the formation decreasing its thickness to only 30 m has strikes of N45°E and dips of 20-25° NW. It is composed of calcareous coarse sandstone with planar foreset beds up to 1-2 m thick in sets. Direction of paleo-currents deduced from these planar cross stratifications, trends to northeast. No key tuff beds equivalent to those in the northern part have been discernible in this part, most probably due to intermittent destruction by high energy environments.

The following descriptions as well as discussions are essentially focused at the northern part. There, this formation is lithologically divided into three parts: the lower part less than 20 m thick, is largely made up of calcareous fine sandstone; the middle part 50-80 m thick, is also composed of calcareous fine sandstone but much predominant in many indurated beds as compared with the lower part; and the upper part 50-60 m thick, is made up alternation of well-sorted fine sandstone, poorly-sorted very fine sandstone and calcareous fine, medium and coarse sandstone.

The cyclic changes of litho- and bio-facies are characteristically recognized in the middle and upper part of the Junicho Formation. At least three cycles are distinguished in the middle part, whereas yet varied cyclicities defined with well-sorted fine sandstone at base are observed at least four times in the upper part. Generalized characteristics of sedimentary cycles of the formation are explained separately in the section, "Sedimentary Cyclicities" (p. 65).

As the previous works have dealt with the planktonic biostratigraphy and preliminary paleomagnetic analysis (YAMAZAKI *et al.,* 1983), emphasis is placed on the litho-stratigraphy to clarify sedimentary cyclicities and also on high-resolution magnetostratigraphy to solve the contradiction between the previous paleomagnetic and planktonic dating. The Junicho Formation has been dated to range from late Pliocene to early Pleistocene, based on planktonic foraminifer (HASEGAWA, 1979; MOROZUMI and ISHIGAKI, 1981) and nannoplankton (TAKAYAMA *et al.,* 1988) biostratigraphy (Fig. 2).

3. Method of Study

3 . 1 Field study

In order to establish a complete, yet composite, stratigraphic succession of the Junicho Formation, five routes were chosen (1 - 5 of Fig. 1). Partial successions along the five routes are correlated by tracing the four tuff beds (ARAI, 1989MS). Columnar sections (Fig. 3) are constructed based on careful survey of these routes, and a particular attention was paid to vertical change in lithologies, sedimentary structures, and components of molluscs and ichnofossils.

3 . 2 Magnetostratigraphy

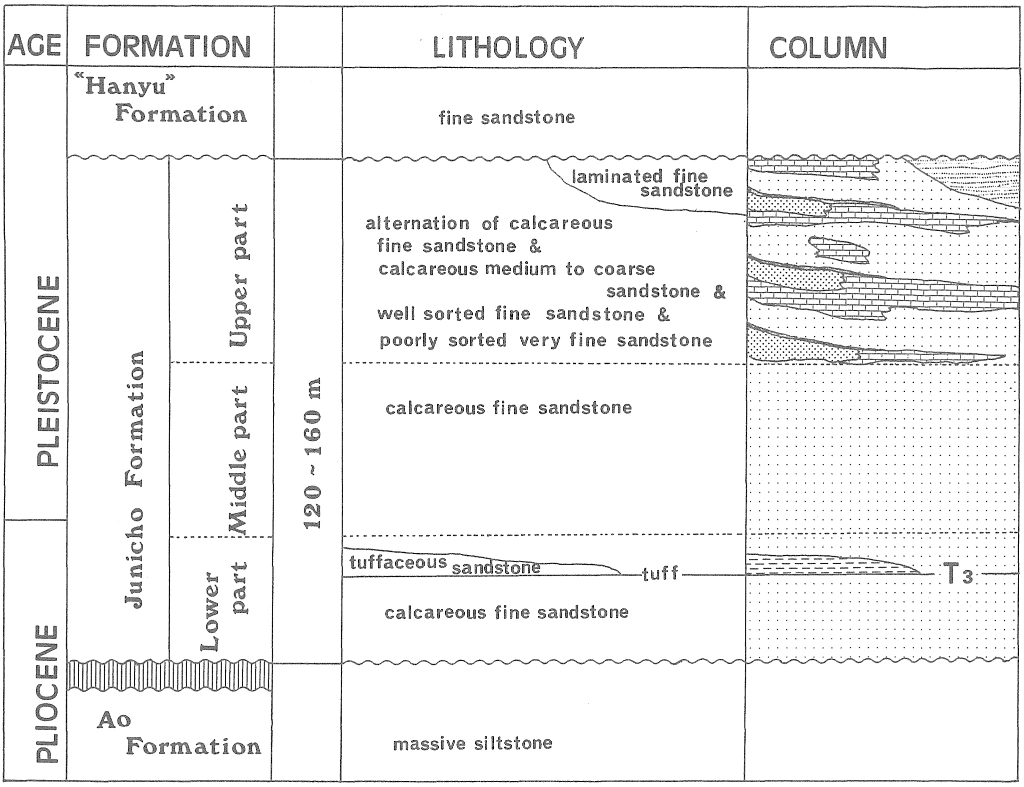


Fig. 2. Stratigraphic summary of the Junicho Formation in the area studied.

11 sites were chosen ; 4 from the route 1, and 7 from the route 2, referring to the previous studies by YAMAZAKI *et al.* (1983). 5 or 6 block samples were taken at each site in the field (Fig. 5) for paleomagnetic study. 116 samples were extracted into plastic cubes (7 cm^3 in volume) from the total blocks at laboratory.

Measurement of the remanent magnetization in discrete samples was made by the cryogenic magnetometer (CCL GM - 401) at Toyama University. Remanent stability was examined by progressive demagnetization as follows:

(1) Natural remanent magnetization (NRM) was determined with the cryogenic magnetometer.

(2) At each site, 3 samples were chosen as a pilot sample. They were demagnetized systematically in alternating field (AF) with steps of 50, 100, 150, 200, 250, 300, 400, 500 œ. Then, the characteristic direction for each sample was determined by the diagonal vector analysis (ZIJDERVELD, 1967).

(3) At each site, 1 sample was provided to the thermal demagnetization.

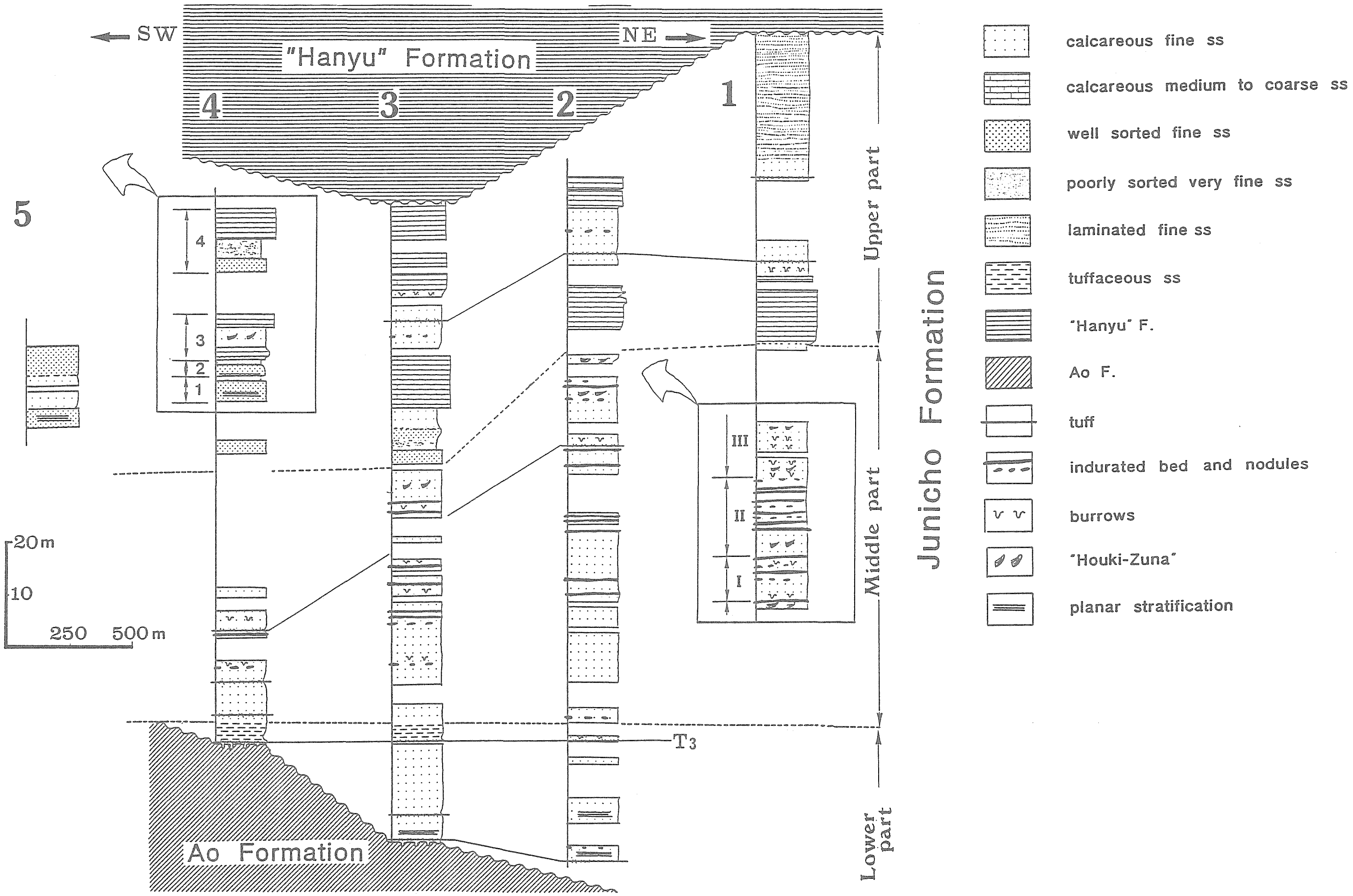


Fig. 3. Columnar section of the Junicho Formation. Gothic figure (1-5) corresponds with each route. 1-4; number of sedimentary cycles in the upper part. I-III; number of sedimentary cycles in the middle part.

(4) Other samples were measured based on optimum demagnetizing field (ODF). For these data, a mean direction and a vector measure of scatter were calculated using Fisher statistics (FISHER, 1953).

3 . 3 Molluscan assemblage analysis

The Junicho Formation yields a variety of molluscs belonging to the "Omma-Manganji Fauna" (*e.g.* OGASAWARA, 1981). In order to reconstruct paleoenvironments, the stratigraphical distribution of molluscan fossils in the whole succession of the Junicho Formation was determined in detail at both outcrops and laboratory. As to the middle part of the formation, a special care was paid for sampling in the field, as described in the next section.

3 . 4 Sedimentological and magnetic analysis of the middle part

Detailed field observations were made at the typical outcrops of the formation, along the Himi Bypass Highway, and also along the road-cut north of the " Himi Bypass Tunnel ", and resulted in establishment of three sedimentary cyclicities in the middle part of the Junicho Formation, as follows:

(1) Field study

A detailed columnar section was constructed (Fig. 8), in order to reveal the stratigraphic variation of lithofacies and molluscan fossils in the middle part. Whole molluscan individuals were identified and counted and their mode of occurrence, especially their shell orientation relative to the life position was examined on the 1 m wide and 50 cm thick section, perpendicular to bedding plane. Relative abundance of burrows per unit area (50 cm wide and 25 cm thick) perpendicular to bedding plane was also determined with tracing them on vinyl sheet.

Samples for measurement of mud content and $CaCO_3$ content were taken at 1 m of stratigraphic interval, except for indurated beds. Rock samples parallel to bedding plane were obtained from the both indurated beds and other lithofacies of the representative sedimentary cycle, *i.e.* the Cycle I (Fig. 3) for modal analysis of mineralogical and biotic composition.

(2) Laboratory work

Mud content was examined, in order to demonstrate a detailed change of lithofacies in each cycle and to study the nature of substrate as an environmental factor affecting the molluscan distribution. After dried in an oven below 50°C, each sample (about 50 g in dry weight) was macerated using an ultrasonic cleaner, and was dry-sieved for grain size analysis. Mud content is expressed in weight percentage of the particles less than 63 μ in diameter.

Thin sections were prepared from the rock samples of each lithofacies in order to study the rate and type of sedimentation. The thin sections cut parallel to bedding plane were used to determine relative abundance of skeletal grain components and of glauconitic mineral grains.

(3) Magnetic intensity and susceptibility

In order to examine the change of the magnetic intensity and susceptibility, high density samples were collected by pressing the two kinds of copper pipes (large type with cross-section of 7.57 cm^2, and small type with 0.969 cm^2) into sediments. Sediments were successively sampled in the cycles of the middle part (Cycle I and II); the large type samples were usually taken at 25 cm of stratigraphic interval, except for indurated beds, while the small type samples were usually taken at 12.5 cm of stratigraphic interval, also excluding indurated beds. Magnetic analysis was carried out by the following procedure:

1. Measurement of NRM intensity was made by the cryogenic magnetometer at Toyama University. Then all the measured samples were removed out from the copper pipes and placed into plastic cubes, and packed with paper to stabilize the sample in the cube.
2. These samples are placed in ferromagnetism field for 1 minute that was made 11000œ AF. Intensity of saturation isothermal remanent magnetization (SIRM) was measured by the cryogenic magnetometer. After these samples were AF-demagnetized of 150œ, SIRM-150 were also determined by the cryogenic magnetometer. Before measurement of magnetic susceptibility, samples were AF-demagnetized 800œ.
3. The unit magnetic susceptibility was measured by magnetic-susceptibility meter at Kyoto University.

3 . 5 Sedimentological analysis of the upper part

Detailed field observation with special reference to four sedimentary cycles was made for the upper part of the formation at the outcrops of Shimazaki, the southernmost part of the Sakatu route (Route 4).

In order to define the stratigraphical distribution of lithofacies and molluscan fossils a special columnar section similar to the one from the middle part was prepared for the upper part. Whole molluscan individuals embedded in the poorly-sorted fine sandstone and calcareous fine sandstone were identified and counted, besides their mode of occurrence was examined with special attention relative to the life position.

Modal abundance of skeletal components was determined from petrographic thin sections of selected rock samples from each lithofacies.

4. Description of Lithofacies

This formation 160 m thick has a wide variety of the lithofacies (ARAI, 1989MS; 1991MS), and consists mainly of six lithofacies; calcareous fine sandstone, calcareous medium to coarse sandstone, well-sorted fine sandstone, poorly-sorted very fine sandstone, laminated fine sandstone and tuffaceous sandstone. Partial successions in route columnar sections are correlated by tracing four useful tuff beds, T_1, T_3, T_6 and T_9 in ascending order, and the vertical as well as horizontal distribution of the six lithofacies is delineated (Fig. 3).

4 . 1 The route 1 and 2 (in the northeastern area)

The lower part of these sections along the two routes consists calcareous fine sandstone with rare nodules and planar stratification, and is less than 20 m in thickness. The middle part of this section is about 70 m thick and also characterized with calcareous fine sandstone partially indurated, which merges into the underlying tuffaceous sandstone (just above T_3 tuff bed). A distinct change of lithofacies referred to much shallow environment predominates in the upper part of the sections. It is about 60 m thick and composed of calcareous fine sandstone with intercalation of two calcareous coarse sandstone beds (about 10-20 m thick). Besides, the upper part of the route 1 section is mostly composed of laminated fine sandstone (non-calcareous).

4 . 2 The route 3, 4 and 5 (in the southwestern area)

The lower part of the sections along these routes is almost characterized by calcareous fine sandstone, and ranges from base of the Junicho Formation to tuffaceous sandstone just above T_3 tuff bed. The T_3 tuff bed in the route 3 section is stratigraphically situated about 20 m above the base of the Junicho Formation, while it occurs 0.7 m above the base in the route 4 section. The middle part of these sections is about 60 m thick and composed of calcareous fine sandstone, up to its upper boundary where occurs a well-sorted fine sandstone. Alternation of well-sorted fine sandstone, poorly-sorted very fine sandstone, calcareous fine sandstone and calcareous coarse sandstone (in the order of meters thick), represents the upper part of these sections and it attains to a thickness of about 60 m.

The fact that the T_3 tuff bed is present about 20 m above the base of the Junicho Formation in the routes 2 and 3, but at 0.7 m above the base in the route 4, and that the T_1 tuff bed occurs only along the routes 2 and 3, suggests onlap relation of the lower part from northeast to southwest, during the initial expansion of the sedimentary basin of the Junicho Formation.

5. Magnetostratigraphy

Periodicity of cyclic sedimentation is estimated from the thickness of each cycle and sedimentation rate. TAKAYAMA *et al.* (1988) described the datum of the first appearance of *Gephyrocapsa caribbeanica,* which is to date 1.66 Ma, and the datum of the first appearance of *Gephyrocapsa oceanica,* which is to date 1.57 Ma. There is a discrepancy in stratigraphic assignment among workers (*e.g.* HASEGAWA, 1979; TAKAYAMA *et al.*, 1988). This present study also has resulted in a different correlation between key tuff beds at routes 1 and 2. If the sedimentation rate of the Junicho Formation is accepted based on the previous biostratigraphical data, it becomes too large (about 60 cm/1000 y) to be a shallow marine non-tropical carbonate sediments, as compared with the modern analogues.

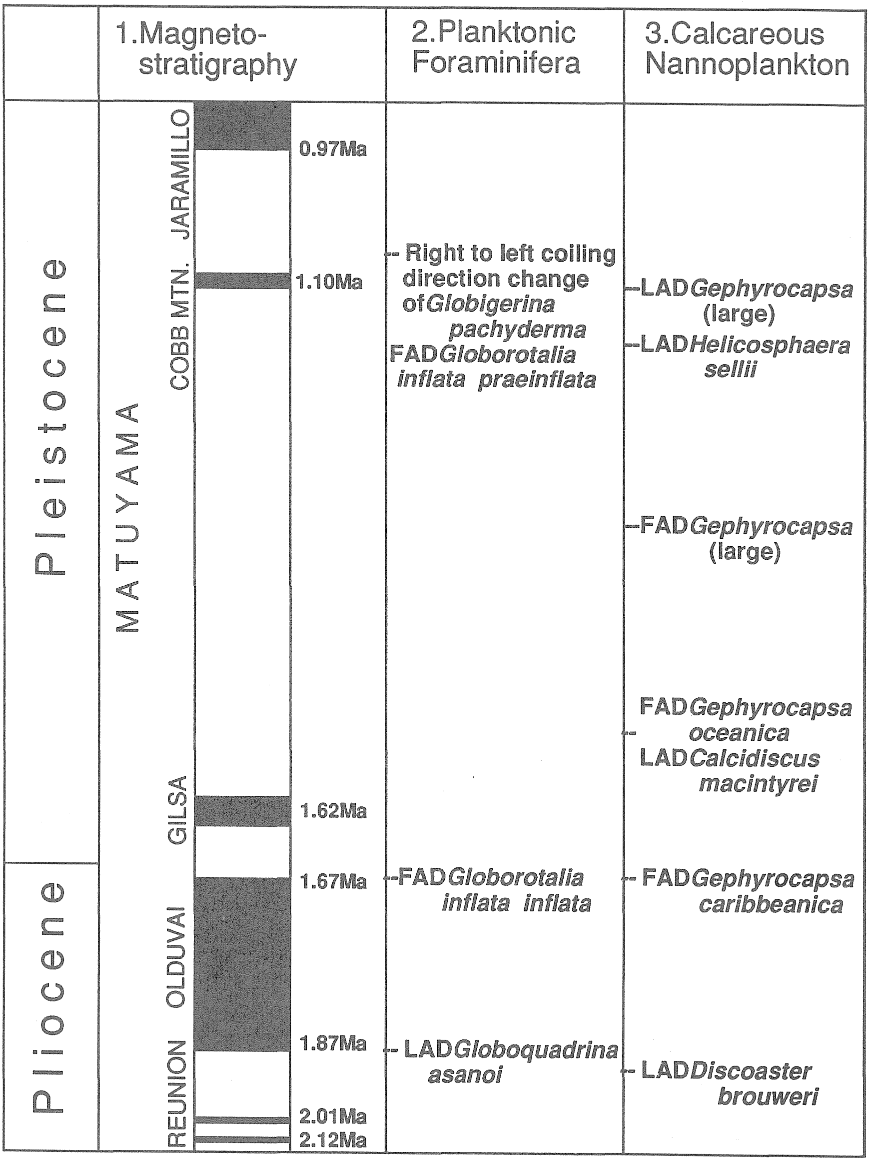
NRM intensity in the Junicho Formation is mostly weak and in the order ranging from 10^{-6} to 10^{-7} e.m.u/gr. As most of the samples have overprinted component in NRM, they have to be removed by AF or thermal demagnetization . The assignment of the magnetozones was done by both a mean direction and diagonal vector analysis (Table 1).

Table 1. The result of magnetic measurements, N; numbers, D; declination, I; inclination, K; precision parameter, ∂_{95}; 95 % confidence angle, and ODF; optimum demagnetizing field and (e) indicates AF demagnetization.

Site name	N	D(°E)	I(°)	K	∂_{95}	ODF(œ)
JNM1	9	10.6	50.4	26.37	26.37	200(e)
JNM2	9	9.9	51.2	51.68	7.23	150(e)
JNM3	5	167.0	-29.2	10.28	25.05	300
JNM4	6	193.6	-36.0	7.01	27.21	200
JNM5	4	219.4	12.3	9.13	32.17	300
JNM6	7	-10.6	43.3	14.98	16.12	300(e)
JNM7	4	230.5	13.5	2.22	82.93	200
JNM8	9	-11.8	47.0	40.93	8.14	150(e)
JNM9	5	174.2	-55.9	4.51	40.6	150
JNM10	4	160.5	-57.5	10.84	29.24	300
JNM11	6	-20.1	27.6	16.72	16.87	200(e)

An attempt was made to correlate the magnetozone with the magnetic polarity intervals so far reported in the deep sea sediments (MCDOUGALL, 1979; BERGGREN *et al.*, 1985; MANKINEN and COX, 1988), referring to the latest knowledge of biostratigraphy (planktonic foraminifers; MAIYA *et al.*, 1976 and calcareous nannoplankton; SATO *et al.*, 1988 and TAKAYAMA *et al.*, 1988) combined with magnetostratigraphy. Fig. 4 shows the relation of biostratigraphic datum levels of planktonic foraminifers and calcareous nannoplankton with the paleomagnetic time scale, as proposed by MAIYA *et al* (1976) and SATO *et al.* (1988).

Fig. 5 shows our interpretation of the magnetostratigraphy of the Junicho Formation. Judging from the present paleomagnetic study with the aid of biostratigraphy (HASEGAWA, 1979 and TAKAYAMA *et al.*, 1988), it is now clear that the whole Junicho Formation characterized by reversal polarity is assigned to the Matuyama Chron. The dominant normal polarity from the lower to middle parts of the formation is assigned to the Olduvai Subchron in the Matuyama Chron. Furthermore, it is highly possible that the normal zone



1.Mcdougall(1979)
Mankinen & Cox(1988)

2.Maiya *et al.*(1976)

3.Sato *et al.*(1988)
Takayama *et al.*(1988)

Fig. 4. Relation of datum levels of planktonic foraminifers and calcareous nannoplankton with the paleomagnetic time scale. Time scale after McDougall (1979) and Mankinen and Cox (1988).

of the lower part below the Olduvai Subchron may well be correlated to the Reunion Subchron. However, further analysis is necessary to confirm the Reunion Subchron in this section.

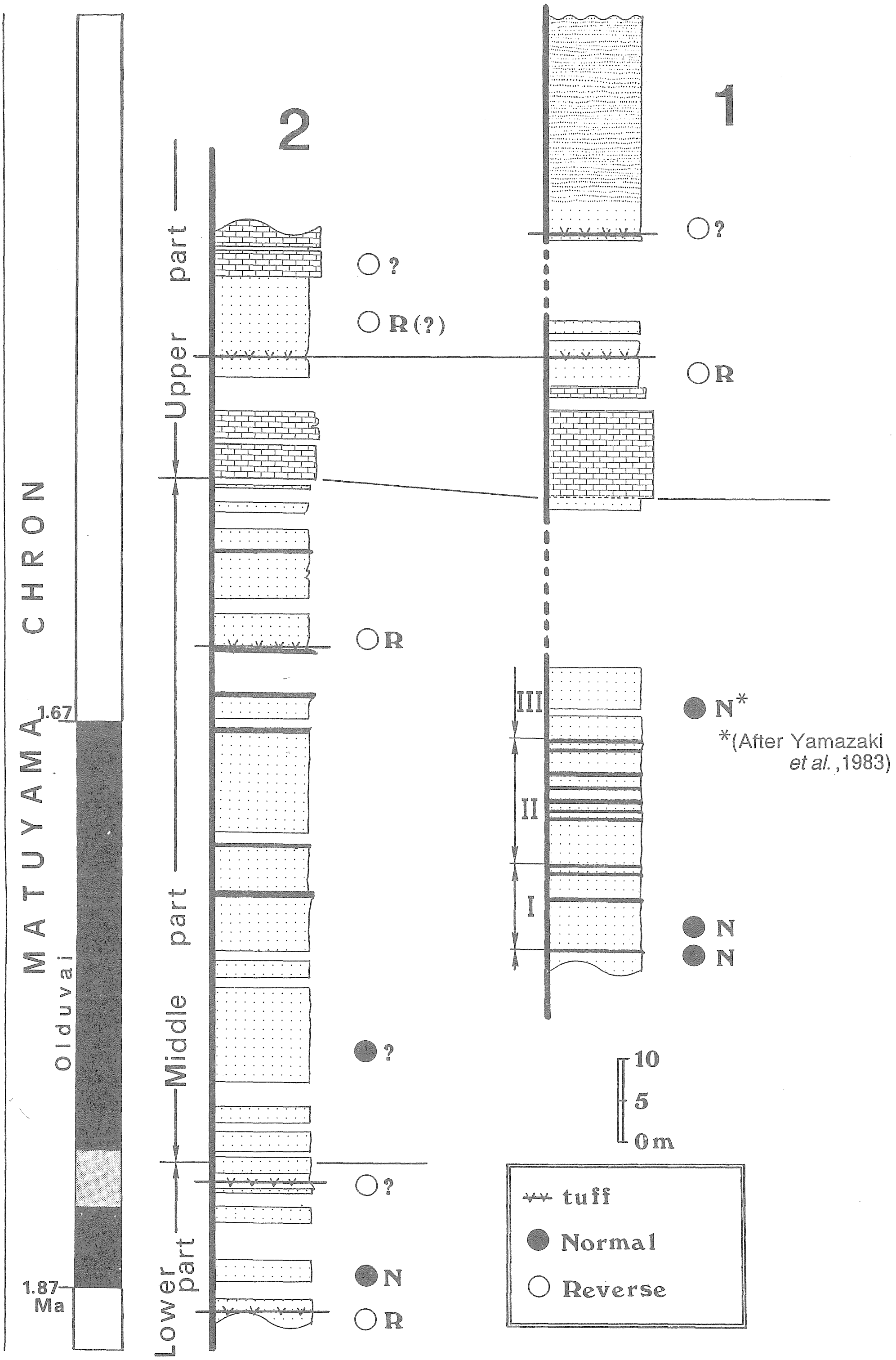


Fig. 5. The result of magnetostratigraphy of the Junicho Formation, based on eleven magnetic measurements. Time scale after MANKINEN and COX (1988). **1**, **2**; number of the surveyed route.

Based on this magnetostratigraphy, the averaged sedimentation rate of the Junicho Formation is reestimated to be about 30 cm/1000 y under the assumption of constant rate of sedimentation. Considering a possibility to assign the lower part to the Reunion Subchron, sedimentation rate can be reappraised to be about 15 cm/1000 y. These values seem reasonable for a shallow marine non-tropical carbonate sediments. It is also confirmed that the Plio-Pleistocene boundary is demarcated within the middle part of the Junicho Formation.

6. Molluscan Assemblages

The molluscs-bearing sediments of the Junicho Formation can be grouped into three types, very fine, fine and coarse sand, with respect to substrata of benthic molluscs. The species found with life position in the very fine and fine sand type are limited to deep burrowers, such as *Lucinoma acutilineatum* and *Conchocele bisecta*. The most other bivalves are, though well preserved, not in life position and disarticulated postmortemly. The common presence of the well preserved shells of these species implies that they were not subjected to either a long-term strong current or wave action, and that the probability of whether a shell being preserved in its life position or not depends on its depth of burrowing. Accordingly the molluscan fossils in the very fine and fine sand type are considered essentially to be autochthonous (semi-autochthonous) which retain their original composition, although reworking and even transportation for a short distance may have taken place.

The species in the coarse sand type are not only disarticulated but also are remarkably abraded and destroyed, except for *Mizuhopecten yessoensis yokoyamai*. *M. y. yokoyamai* is usually found well preserved lying parallel to bedding plane with the right valve concave-upward, suggesting autochthonous in origin. Except for this species, the presence of the defaced or destroyed shells implies that they were subjected to a long-term strong current.

Environmental characters of the assemblages as to the nature of the sea water, and approximate water depth of their habitat are inferred from available information concerning the distribution range geographic (KURODA and HABE, 1952; HIGO, 1973) and bathymetric (OYAMA, 1952, 1973) of living species (Fig. 6). The species of the Junicho Formation are exclusively of the cold-water and intermediate elements, and do not contain those of warm-water element.

In this paper, the term "assemblage" is used to indicate a group of fossils similar in species composition that occurs from a bed of about 1 m thick on outcrop. Ten assemblages, one from the lower part, four from the middle part and five from the upper part, are recognized in the Junicho Formation (Fig. 7 shows stratigraphic distribution of these molluscan assemblages), as follow:

- Lower part -

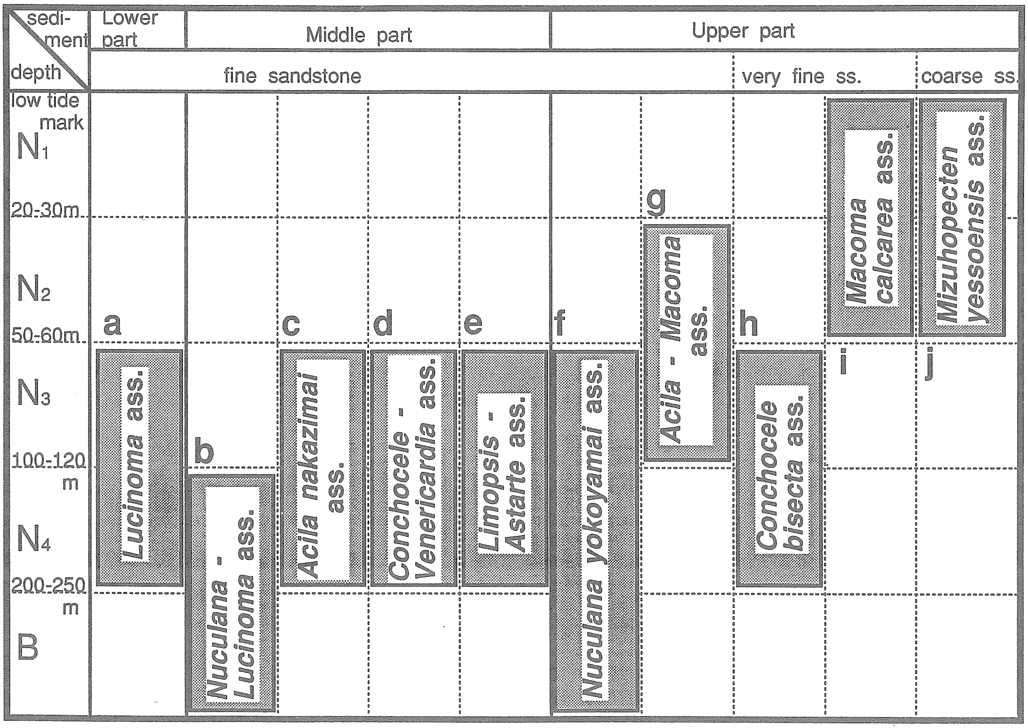


Fig. 6. Relationship between the molluscan assemblages and paleobathymetry of the Junicho Formation. The bathymetric notations are as follows, N_1; euneritic zone, from low tide mark to 20-30 m, N_2; mesoneritic zone, from 20-30 m to 50-60 m, N_3; subneritic zone, from 50-60 m to 100-120 m, N_4; bathyneritic zone, from 100-120 m to 200-250 m, B; bathyal zone, from 200 m to 1000 m.

The lower part of the Junicho Formation consists of calcareous fine sandstone and tuffaceous fine-grained sandstone. The species diversity is so low in the tuffaceous sandstone that only one species, *Lucinoma acutilineatum*, is found. The calcareous fine sandstone in this part is also characterized by the same species. This species occurs articulated in life position that is nearly vertical with the beak upward. The fossil molluscs contained in the lower part are lumped into a single assemblage.

(a) *Lucinoma* assemblage

This assemblage is characterized by dominant occurrence of *Lucinoma acutilineatum*. It is associated with *Nuculana yokoyamai* and *Portlandia* sp. The assemblage seems to have inhabited from subneritic to bathyneritic zone.

- Middle part -

The middle part of the formation consists of calcareous fine sandstone indurated in part. It contains species living in an open ocean environment, such as *Nuculana yokoyamai* and *Astarte alaskensis* that intermittently occur in the middle part. The fossil molluscs in

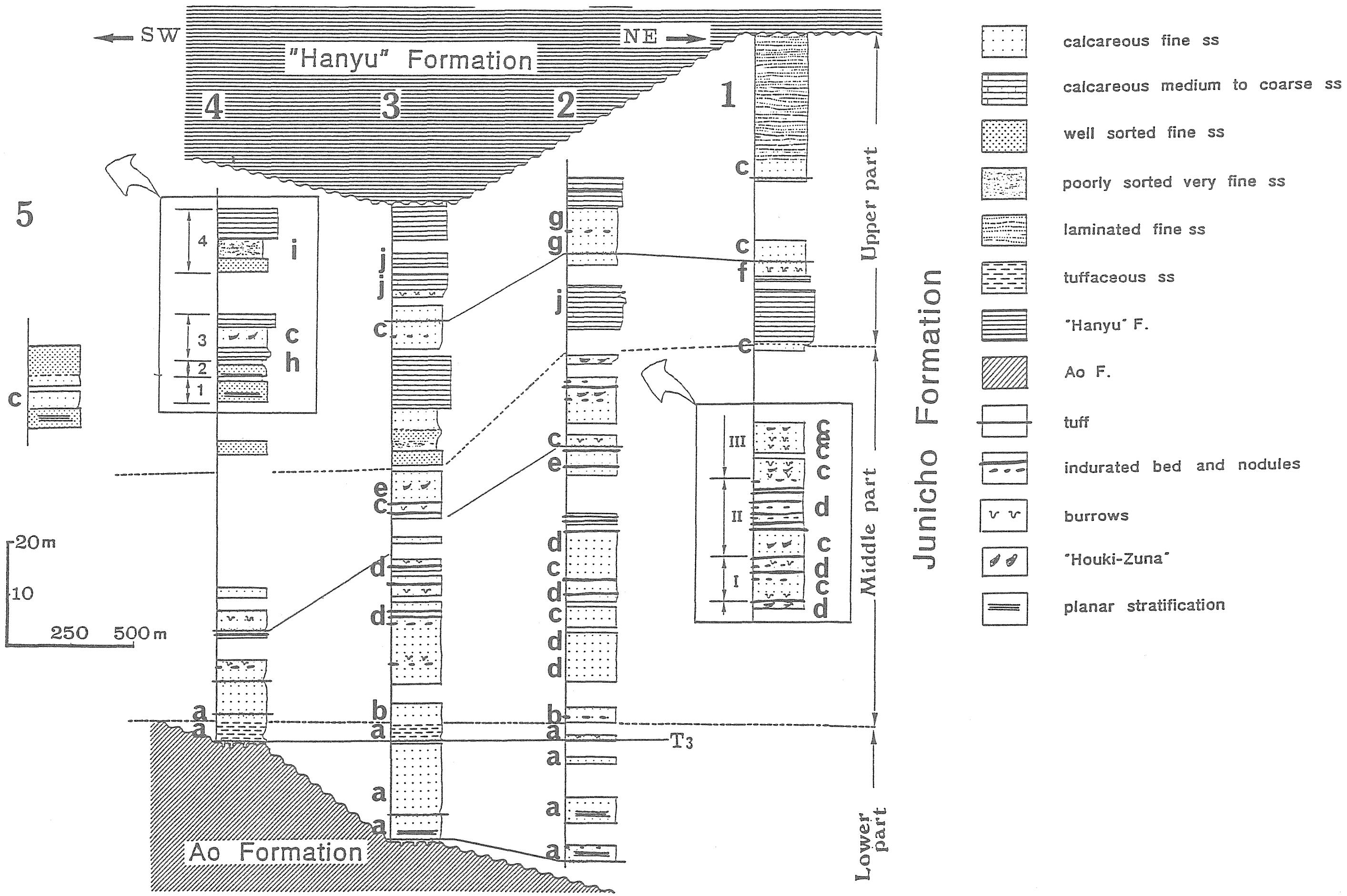


Fig. 7. Stratigraphic distribution of molluscan assemblages. a; *Lucinoma* ass., b; *Nuculana* - *Lucinoma* ass., c; *Acila nakazimai* ass., d; *Conchocele* - *Venericardia* ass., e; *Limopsis* - *Astarte* ass., f; *Nuculana yokoyamai* ass., g; *Acila* - *Macoma* ass., h; *Conchocele bisecta* ass., i; *Macoma calcarea* ass. and j; *Mizuhopecten yessoensis* ass.

the middle part are grouped into the following four assemblages.

(b) *Nuculana* - *Lucinoma* assemblage

The molluscs of this assemblage occur in calcareous fine sandstone, the lowermost portion of the middle part. The assemblage is characterized by dominance of *Nuculana yokoyamai* and subordinate of *Lucinoma acutilineatum,* besides a rare associate of *Limatula japonica, Portlandia* sp. and *Panomya ampla*. This assemblage perhaps dwelled in from bathyneritic to bathyal zone.

(c) *Acila nakazimai* assemblage

The characteristic species of this assemblage are *Acila nakazimai* and *Astarte alaskensis*. They are associated with *Nuculana yokoyamai, Limopsis tokaiensis* and *Conchocele bisecta*. Although *A. nakazimai* is an extinct species, this assemblage represents most probably subneritic to bathyneritic zone, according to the available data of the living associated species.

(d) *Conchocele* - *Venericardia* assemblage

The assemblage is characterized by dominance of *Conchocele bisecta* and *Venericardia ochiaiensis,* besides occasional associate of *Astarte alaskensis*. Judging from the living representatives of this assemblage, it seems to have inhabited from subneritic to bathyneritic zone.

(e) *Limopsis* - *Astarte* assemblage

Dominance of *Limopsis tokaiensis* and *Astarte alaskensis*, and associate of *Glycymeris nipponica, Venericardia ochiaiensis, Acila nakazimai* and a gastropod *Turritella saishuensis motidukii* characterize this assemblage. The molluscs of this assemblage occur in bioturbated calcareous fine sandstone of the upper section of the middle part, and its population density is high. Many species are found well preserved conjoined or in life position in this section. Judging from the living representatives of this assemblage, it seems to characterize subneritic to bathyneritic zone.

- Upper part -

The fossiliferous strata of the upper part of the Junicho Formation are grouped into three lithofacies. Three assemblages occur in calcareous fine sandstone facies; *Acila nakazimai* assemblage (already described from the middle part), *Nuculana yokoyamai* assemblage and *Acila* - *Macoma* assemblage. Two assemblages are found from a poorly-sorted very fine sandstone facies; *Conchocele bisecta* assemblage and *Macoma calcarea* assemblage. *Mizuhopecten yessoensis* assemblage is known in calcareous coarse sandstone facies.

(f) *Nuculana yokoyamai* assemblage

This assemblage is found from a road-side cliff, beside the northern entrance of Himi Nambu Junior High School. It is characterized by exclusive occurrence of *Nuculana yokoyamai*. Judging from the living representatives, this assemblage seems to occur from subneritic to bathyal zone.

(g) *Acila* - *Macoma* assemblage

This assemblage occurs at a stream-cut cliff, located about 100 m NW of Yazaki in the lower section of the upper part of route 2. The assemblage is dominated by *Acila nakazimai* and *Macoma* sp., associated with *Acila insignis* and a gastropod *Cryptonatica janthostomoides*. The assemblage seems to live in from mesoneritic to subneritic zone, as judged from the living associates.

(h) *Conchocele bisecta* assemblage

This assemblage found from poorly-sorted very fine sandstone at a road-side cliff of Shimazaki at the lower section of the upper part of route 4. The characteristic species of the assemblage are *Conchocele bisecta*, *Nuculana yokoyamai* and *Clinocardium* sp. The living representatives of this assemblage suggest that it dwelled from subneritic to bathyneritic zone.

(i) *Macoma calcarea* assemblage

This assemblage is known from poorly-sorted very fine sandstone at the uppermost outcrop of Shimazaki (route 4). The characteristic species of the assemblage are *Macoma calcarea* and *Acila nakazimai*, associated with *Lucinoma annulata* and *Conchocele bisecta*. The assemblage seems to live from euneritic to mesoneritic zone.

(j) *Mizuhopecten yessoensis* assemblage

The characteristic species of the assemblage is *Mizuhopecten yessoensis yokoyamai*. Although it is an extinct species, this assemblage seems to occur both euneritic and mesoneritic zones, as the associated living species indicate.

7. Sedimentary Cyclicities

Both the middle and upper parts of the Junicho Formation demonstrate distinctly sedimentary cycles based on facies characteristics (Table 2), which, however, differ considerably between the two parts. At least three cycles are recognized in the middle part, whereas four cycles variable yet always defined with the base of well-sorted fine sandstone occur in the upper part. Each sedimentary cycle will be described in detail respectively.

Table 2. Sedimentary facies forming cyclicities of the Junicho Formation.

FACIES	LITHOLOGY	SEDIMENTARY STRUCTURES	BIOFACIES	ENVIRON-MENTS
A	well sorted fine sandstone	HCS planar stratification	burrows(*Skolithos* sp.)	upper -lower shoreface
A'	well sorted fine sandstone with thin mud layer			
B	poorly sorted very fine ss.		*Conchocele bisecta* ass. *Macoma calcarea* ass.	inner - outer shelf
C	calcareous medium sandstone		lithoskels	
D	massive calcareous fine sandstone	"Houki-Zuna"	*Acila nakazimai* ass.	outer shelf
E	calcareous coarse sandstone	cross stratified	*Mizuhopecten y.* ass. Bryozoa dominated	inner shelf
F	calcareous fine to medium ss. with indurated bed	indurated bed	*Conchocele - Venericardia* ass.	outer shelf above storm w. b.
G	bioturbated calcareous fine sandstone	burrows	*Acila nakazimai* ass.	outer shelf

7 . 1 Middle part

Fig. 8 shows the summary of field observation at the typical outcrops of the middle part. Each of the three cycles is lithologically quite similar but divided into three facies; facies G (bioturbated calcareous fine sandstone), facies D (massive calcareous fine sandstone), and facies F (calcareous fine to medium sandstone with indurated beds) in ascending order. The "boundary" between the cycles of the middle part is defined as the distinct contact between facies F and G.

The vertical distribution of the molluscan fossil assemblages is well correlated with these lithofacies; *Acila nakazimai*, the characteristic species of *Acila nakazimai* assemblage, occurs only within facies G and D, whereas *Conchocele bisecta* does almost exclusively in facies F (Fig. 8).

The Cycle I 10 m thick consists of the following three facies which are conformably merged into one above the other, in ascending order; facies G of 2.5 m thick, facies D of 1.5 m thick and facies F of 6 m thick. Thickness of the Cycle II is 13.5 m, and the identical upward change in facies is observed from facies G of 1 m thick, to facies D of 4 m thick and finally to facies F of thick 8.5 m. The Cycle III partially exposed shows facies G of 6 m thick and overlying facies D at least 2 m thickness, but no facies F due to unexposure.

Relative abundance of each kind of skeletal grains expressed as a percentage of the total grains is determined from point-counting of petrographic thin sections in the Cycle I and the result is summarized as Fig. 9. The terrigenous grains in the Junicho Formation are composed mainly of quartz and feldspars. Planktonic and benthic foraminifers are the

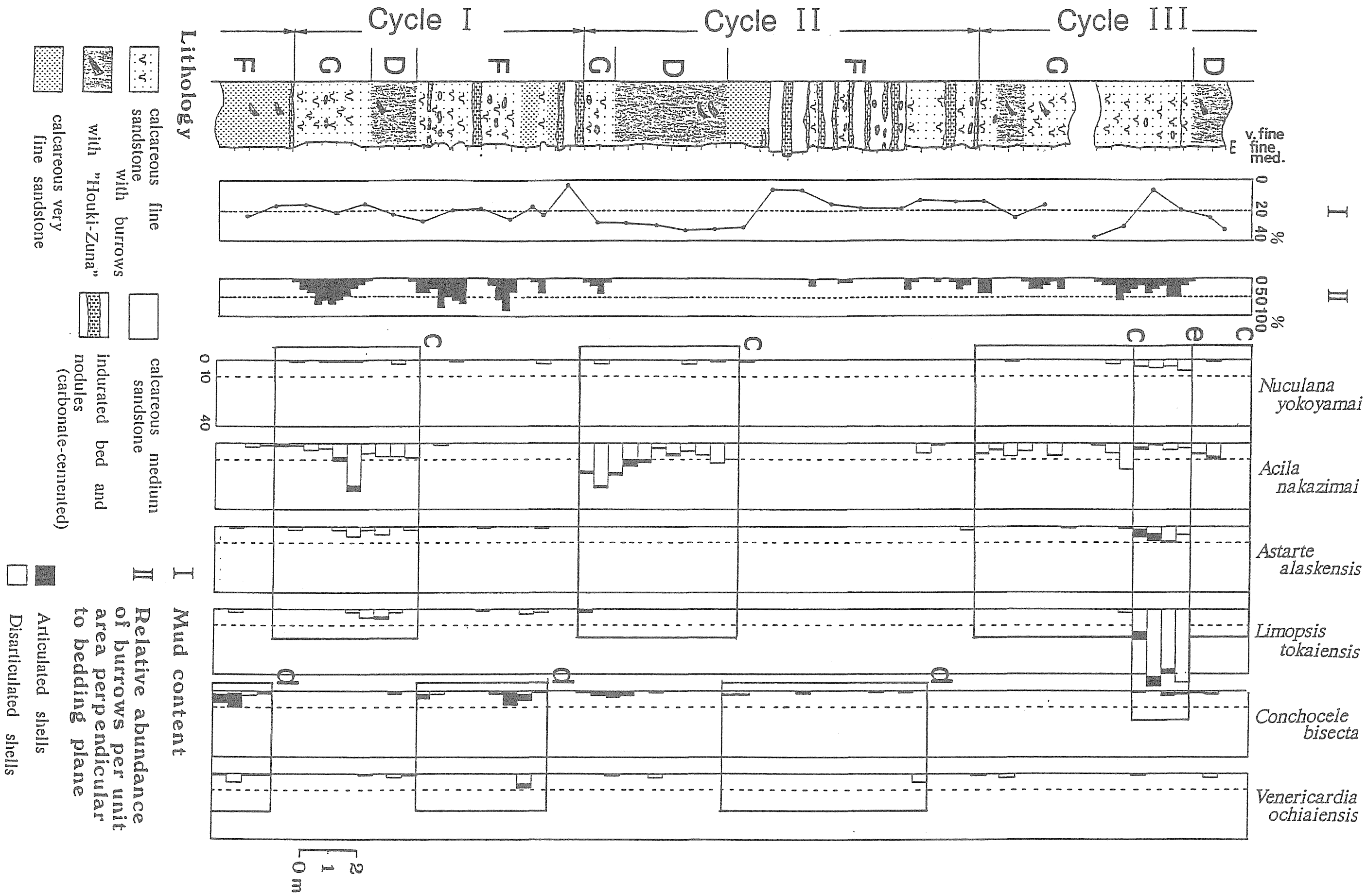


Fig. 8. Columnar section of the middle part along the Himi Bypass Highway (route 1), and also along the road-cut north of the "Himi Bypass Tunnel". D; massive calcareous fine sandstone, F; calcareous fine to medium sandstone with indurated bed, G; bioturbated calcareous fine sandstone, c; *Acila nakazimai* ass., d; *Conchocele - Venericardia* ass. and e; *Limopsis - Astarte* ass.

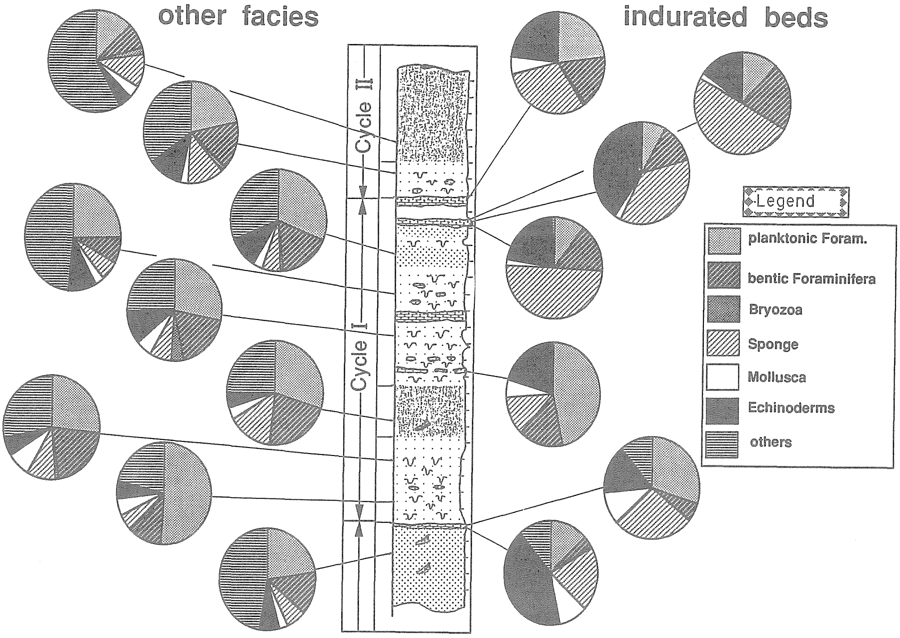


Fig. 9. Pie diagrams of skeletal composition in the Cycle I of the middle part, as determined from point counting of thin section.

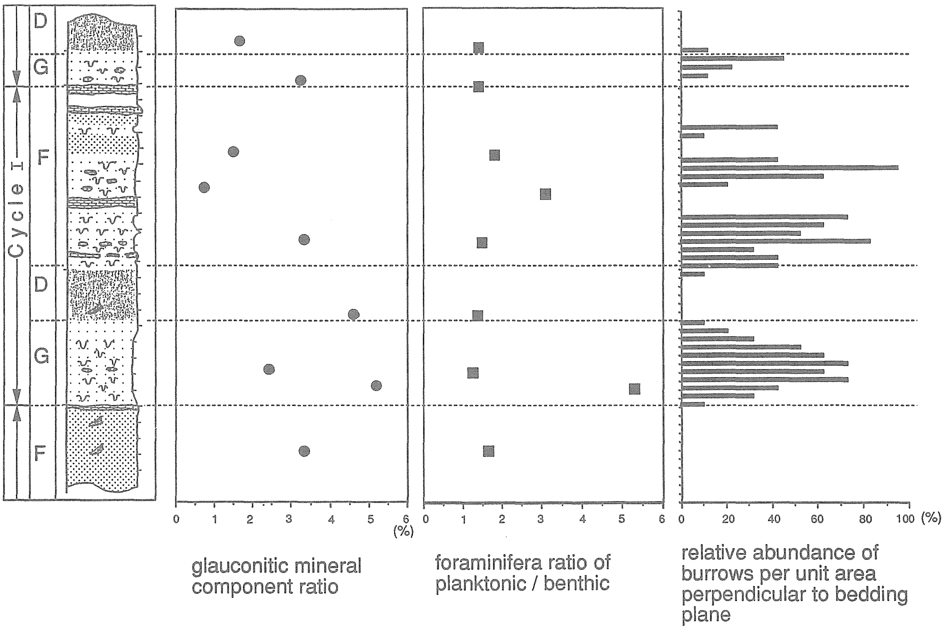


Fig. 10. The abundance of the glauconitic mineral grains and of foraminiferal ratio of planktonic/benthic in the Cycle I of the middle part (from point counting of thin section). ; and number of burrows per unit area perpendicular to bedding plane.

major skeletal contributors, with minor but consistent additions from bryozoans, sponges, molluscs and echinoids in calcareous fine sandstone facies. The principal skeletal grains in the indurated beds of the facies F are sponges or echinoids.

Compared with the rest, this indurated beds seem to have characteristic features other than the dominance of sponge or echinoid debris, as follows; larger grain size (specially, in terrigenous grains), frequent occurrence of rock-fragments, and conspicuous fining-upward structure.

The relative abundance of glauconitic mineral grains in the Cycle I, is summarized in Fig. 10. It indicates a peak in the facies G, and tends to decrease upward from facies G to facies F. The considerable occurrence of the glauconitic minerals in facies G is ascribed to the very low rate of sedimentation (ODIN and MATTER, 1981).

7 . 2 Upper part

At least four cycles are designated in the upper part : each cycle is ubiquitously defined with the base of well-sorted fine sandstone (Fig. 11), but lithologically differentiated into five facies; facies A (well-sorted fine sandstone), facies B (poorly-sorted very fine sandstone), facies C (calcareous medium sandstone), facies D (massive calcareous fine sandstone), and facies E (calcareous coarse sandstone) in ascending order. Stratigraphical succession of the lithologies and molluscan fossil assemblages in each cycle is documented

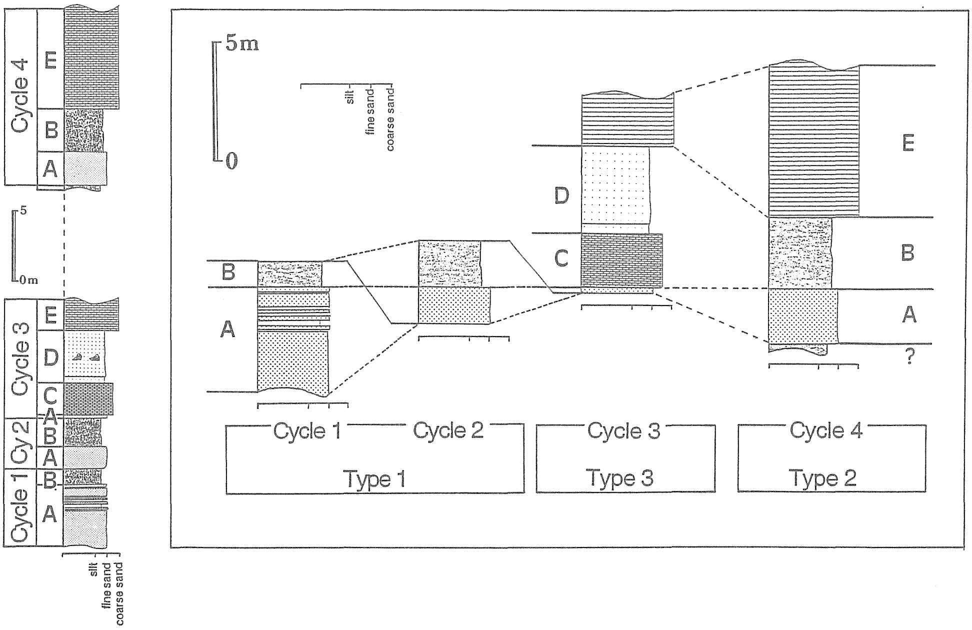


Fig. 11. Columnar section of the upper part along the route 4. A; well sorted fine sandstone, B; poorly-sorted very fine sandstone, C; calcareous medium sandstone, D; massive calcareous fine sandstone and E; calcareous coarse sandstone.

in detail as follows. Except for the boundary between Cycle 3 and 4, where no exposures are observable, the boundary between cycles is well defined with a sharp contact. The facies boundary in each cycle also tends to be defined clearly (Fig. 11).

(1) Cycle 1

This cycle at least 6 m thick is composed of facies A of 2.5 m thick, facies A' (well-sorted fine sandstone with thin mud layer) of 1.5 m thick and facies B of 1 m thick in ascending order. Hummocky cross-stratification (HCS) is observed in facies A, while many burrows (*Skolithos* sp.) appear in facies A'.

(2) Cycle 2

This cycle 3.5 m thick, consists of facies A of 1.5 m thick which is overlain by facies B of 2 m thick. Alternations of thin (about 5 cm) layered planar stratification and wave ripple are observed in the lower section of facies A. *Conchocele bisecta* assemblage appears in facies B.

(3) Cycle 3

In this cycle at least 8 m in thickness, the facies changes upwards from facies A of 30 cm thick, facies C of 2 m thick, facies D of 4 m thick to facies E of at least 2 m thick. The molluscan species, such as *Chlamys swiftii* and *Mizuhopecten yessoensis* in facies C are remarkably defaced and fragmented. Both "Houki-Zuna" structure and *Acila nakazimai* assemblage appear in facies D. Lithoskels (READ, 1974) in facies C and dominance of bryozoa skeletals in facies E are determined from thin section analysis.

(4) Cycle 4

This cycle with a thickness of at least 10 m, is composed of facies A of 2 m thick, facies B of 2 m thick and facies E of at least 6 m thick. *Macoma calcarea* assemblage appears in facies B. The shells of molluscan species, such as *Limopsis* sp. and *Venericardia ferruginea* in facies E are exceedingly abraded and fragmented. Planar cross stratification is observed in facies E.

Grain size analysis shows each sample in the facies A is fine-grained (2.48 to 2.73 ϕ) and well-sorted (sorting-coefficient is 0.33 to 0.64) with the mud content of 1.08 to 4.26 % (ARAI, 1989MS).

8. Magnetic Intensity and Susceptibility in the Cycles of the Middle Part

Magnetic susceptibility is the ratio of induced magnetization to an applied weak magnetic field. Magnetic susceptibility measurements in deep-sea sediment cores have been utilized as a sensitive indicator of temporal variations in the concentration of terrigenous material supplied to the sea bed (BLOEMENDAL and DEMENCAL, 1989). In this study, magnetic intensity and susceptibility of the sediments are measured in order to interpret a stratigraphical change of the transportation process of terrigenous grains and also to test a correlation between litho- and bio-facies change.

Fig. 12 shows the result of magnetic intensity and susceptibility measurement in the two cycles of the middle part. Intensity of natural remanent magnetization (NRM) depends on the four factors; species, grain size and concentration of magnetic minerals and geomagnetic intensity. Intensity of saturation isothermal remanent magnetization (SIRM) and magnetic susceptibility are affected by the three factors; species, grain size and concentration of magnetic minerals. Surprisingly, each sedimentary cycle seems to be characterized with distinctly similar, but double-peaked magnetic cyclicities.

As the ratio of intensity of SIRM and SIRM-150 that was demagnetized systematically in alternating field (AF) with steps of 150 œ keeps to be constant (Fig. 13), this observed cyclicity seems to substantiate stratigraphical variation of the concentration of magnetic minerals in the sediments.

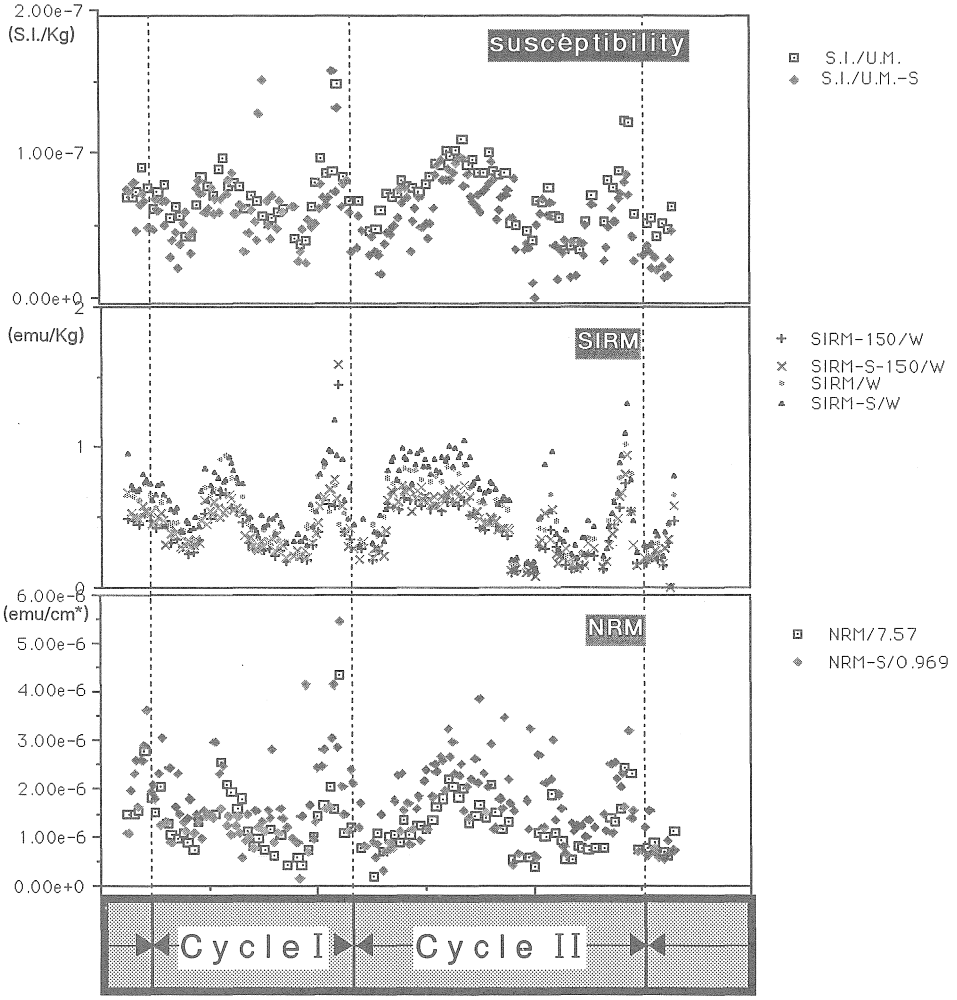


Fig. 12. The rock-magnetic intensity (NRM and SIRM) and susceptibility in the Cycle I and II of the middle part.

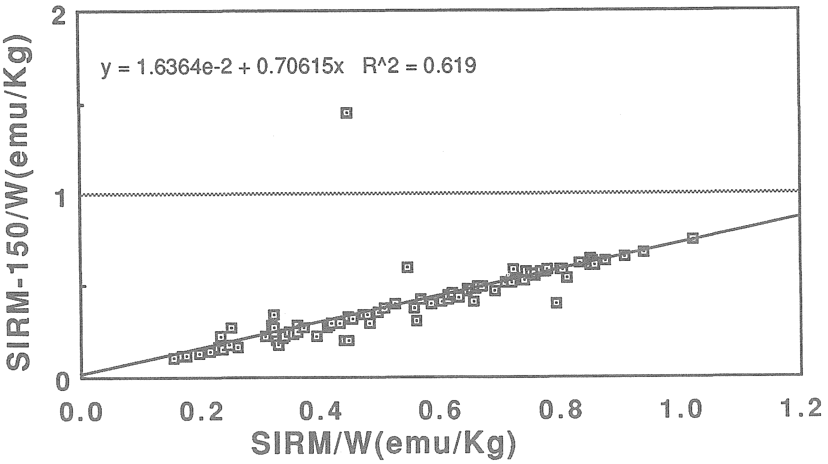
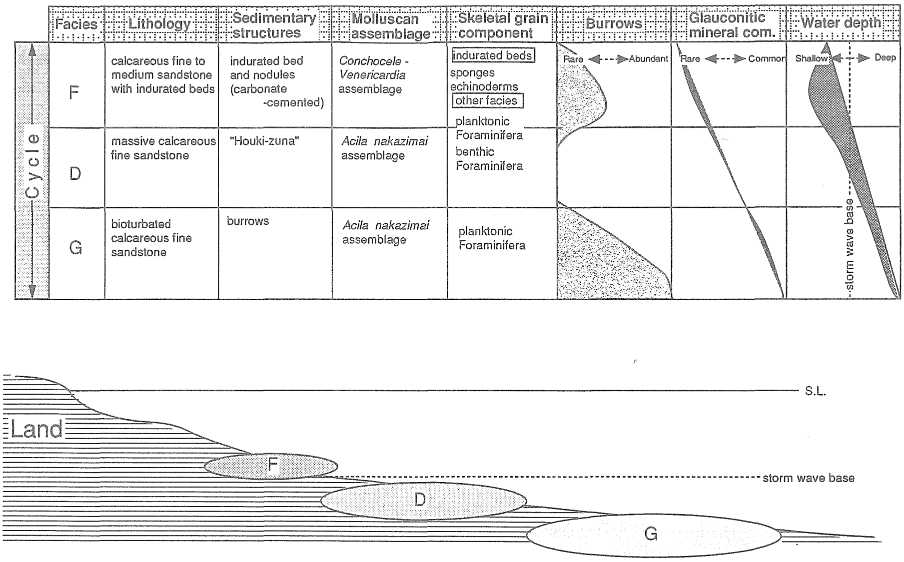


Fig. 13. SIRM-150/W plotted against SIRM/W for samples of large type, showing a linear relationship.

9. Discussions

Fig. 14 shows an idealized scheme of a sedimentary cycle in the middle part of the Junicho Formation and interpreted sedimentary depth of each facies. Facies G represents the maximum transgression stage characterized with the least terrigenous materials and with most abundant hemipelagic and pelagic sediments over a wide area of the shelf,



Facies	Lithology	Sedimentary structures	Molluscan assemblage	Skeletal grain component
F	calcareous fine to medium sandstone with indurated beds	indurated bed and nodules (carbonate -cemented)	*Conchocele - Venericardia* assemblage	indurated beds sponges echinoderms other facies
D	massive calcareous fine sandstone	"Houki-zuna"	*Acila nakazimai* assemblage	planktonic Foraminifera benthic Foraminifera
G	bioturbated calcareous fine sandstone	burrows	*Acila nakazimai* assemblage	planktonic Foraminifera

Fig. 14. Summary showing an idealized schematic sedimentary cycle of the middle part.

initiating the formation of a "condensed section", which is areally most extensive at the time of maximum regional transgression of the shoreline (LOUTIT *et al.*, 1988). Concentration of the glauconitic minerals has a peak in the facies G and seems to reflect a very low sedimentation rate of this facies. In addition, abundance of bioturbation and high ratio of pelagic to benthic foraminifers in the facies support this interpretation. Thus facies G may represent the shelf sediments referable to condensed section during the maximum transgression.

The results of comparison between the indurated beds in the facies F and other fine sandstone beds (in the facies G, D and F) indicate that the indurated beds have unique features as described above (p.69). These characteristic features suggest that the indurated beds should have experienced a sedimentary process different from that of the other fine sandstone facies. Together with these features, conspicuously fining-upward sequence in the indurated bed indicates that intermittent inflow of coarse-grained sand probably as a storm deposit in origin took place during accumulation of the facies F. These porous coarse-grained sands have tended to be indurated selectively by carbonate cement through diagenesis.

Each cycle in the middle part manifests the change of sedimentary environments from the one deeper than the storm wave base (facies G and D) into the shallower one (facies F) as both lithologic and paleontologic evidence verify. This cyclic change of litho- as well as bio-facies (molluscs and foraminifer ratio) can be best explained by relative change of sea-level.

It seems that relative sea-level change affects stratigraphical variation of the concentration of magnetic minerals. In the maximum transgression stage during accumulation facies G, it is anticipated that a supply of terrigenous grains including ferromagnetic minerals tends to decrease and be restricted to more landward regions. The relative sea-level fall following this stage may tend to increase the concentration of ferromagnetic minerals as in the succeeding facies D, and further facies F. Though preliminarily, the present magnetic studies not only vindicate the sedimentary cycles, I and II, in the middle part, which are delineated by the facies analyses, but also seem to reveal a much higher-frequency record of relative sea-level change, which otherwise has not been detected by the conventional means. It can be stressed that this magnetostratigraphy other than paleomagnetic dating is a promising method applicable to unearth fine cyclicities in the stratigraphic columns of sediments on and off shelves. It is expected that magnetic intensity and susceptibility measurements of sediments can be used as a sensitive and effective indicator of temporal variations in the concentration of terrigenous material supplied onto the sea floor, with probably much higher resolution than the sedimentary cycles delineated by the conventional approach to litho- and bio-facies analyses. More extensive analyses both deep sea and shallow marine sediments are necessary to substantiate this concept.

Four sedimentary cycles in the upper part of the Junicho Formation are grouped into three types, with respect to stratigraphical succession of the facies (Fig. 11). Fig. 15 shows paleoenvironmental interpretation of each facies forming three types of the upper part. Facies A thoroughly described above suggests that it is accumulated under a strong wave action above fairweather wave base such as lower to upper shoreface.

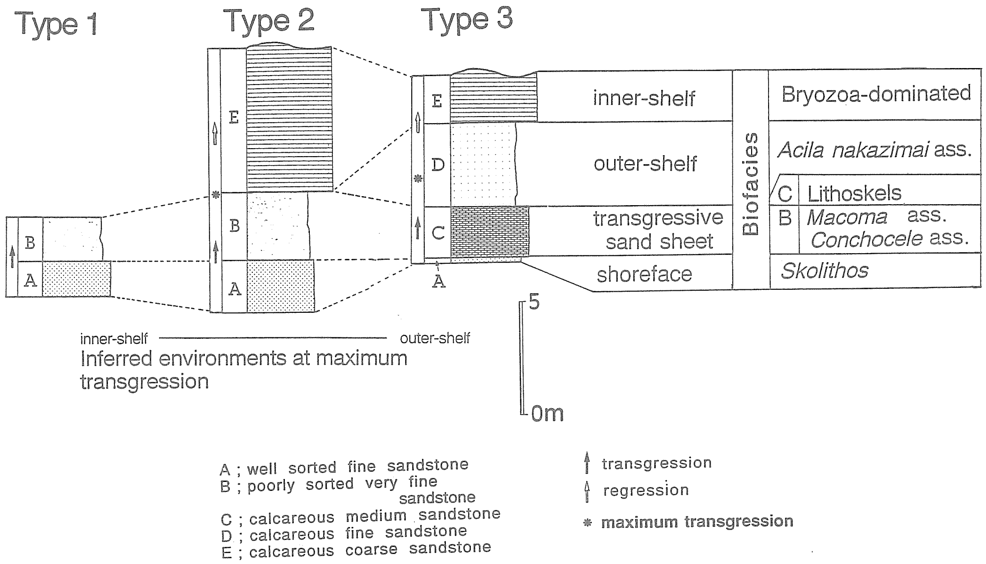


Fig. 15. Environments of Each Type of Sedimentary Cycles inferred by litho- and bio-facies.

Both facies B and C lack sedimentary structures of wave action in origin, and suggest a similar water depth of accumulation, deeper than fairweather wave base, as evidenced by molluscan assemblages. The prominent change in water depth from facies A to facies B and C is attributed to a rapid relative rise of sea-level. Lithoskels abundant in facies C are referred to the reworked origin which have been eroded from older unconsolidated or weakly consolidated deposits from an earlier sedimentary cycle and have been incorporated into younger sediments. Therefore, facies B and C seem to form different parts of a transgressive sand sheet (SWIFT *et al.*, 1971). A modern analogue of such a transgressive sand sheet has been documented in detail from the shelf and the upper slope off Sendai, Northeast Honshu, Japan (SAITO *et al.*, 1989).

Facies D yields *Acila nakazimai* assemblage, which dwelled in from subneritic to bathyneritic zone (from 50-60 to 200-250 m in depth; Fig. 6), and is assigned to be accumulated at outer shelf.

Planar cross stratifications are observed in the bryozoa-dominated facies E. *Mizuhopecten yessoensis* assemblage living from euneritic to mesoneritic zone (from low tide mark to 50-60 m in depth; Fig. 6) has been observed in the same facies at nearby outcrops.

Hence, the facies E was accumulated under high energy regime such as inner shelf.

Thus, each sedimentary cycle in the upper part changes the environmental spectrum from shoreface (facies A) to inner or outer shelf (facies B, D and E). This cyclic change of paleoenvironments can also be best explained by relative sea-level change.

The relevant facts described above may lead to the following conclusions:
(1) The Junicho Formation represents an unconformity-bounded sequence that is a conformable succession of genetically related strata. (2) The lower part of the formation formed under the rapid transgression due to relative sea-level rise. After the transgression is terminated, it turned to regression. (3) The relative sea-level change was of the third-(0.1-1 mys.) and even smaller order, and had an amplitude of at least 100 m. (4) The relative sea-level change is essentially caused by glacio-eustacy affected with the regional tectonic subsidence.

Each sedimentary cycle of the upper and middle parts of the Junicho Formation is equivalent to a parasequence, which is a relatively conformable succession of genetically related beds or bedsets bounded by marine-flooding surfaces and their correlative surfaces (VANWAGONER *et al.*, 1988).

The periodicity of the sedimentary cycles in the upper and middle parts of the Junicho Formation is estimated to be in the order of few tens thousand years on the average based on magnetostratigraphy. These high-frequency sedimentary cycles are most likely ascribed to have formed under a major control of glacio-eustatic sea-level change. The apparent difference in the sedimentary facies between the middle and upper part appears to depend essentially on water depth during the deposition.

The difference in stratigraphical succession among three types of the upper part is also dependent to water depth. Environments at maximum transgression change from inner shelf to outer shelf (from Type 1 to 3), and the thickness of facies A which is characterized by shoreface deposits have tendency to decrease from Type 1 to 3. From this fact it is concluded that the upper part of the Junicho Formation has been formed under the combined influence of relative sea-level change of a smaller order (Fig. 16).

Depth-related facies models have been constructed for modern shallow marine non-tropical carbonate sediments (*e.g.* SCOFFIN *et al.*, 1980; NELSON and BORNHOLD, 1983; COLLINS, 1988). The relative abundance of pelagic foraminifers has a negative correlation with other skeletal components and a positive correlation with water depth. A depositional setting is envisaged for accumulate of the Junicho Formation based on such facies models (Fig 17).

Finally, a depositional model of the non-tropical carbonate and mixed sediments on shelf is preliminarily constructed with respect to the early Pleistocene glacio-eustacy. Three types (Type 1-3 of Fig. 18) of sedimentary cycles in the upper part of the Junicho Formation and that (Type 4 on Fig. 18) in the middle part are adopted as the fundamental source of information. Basic assumptions are that both periodicity and amplitude of the

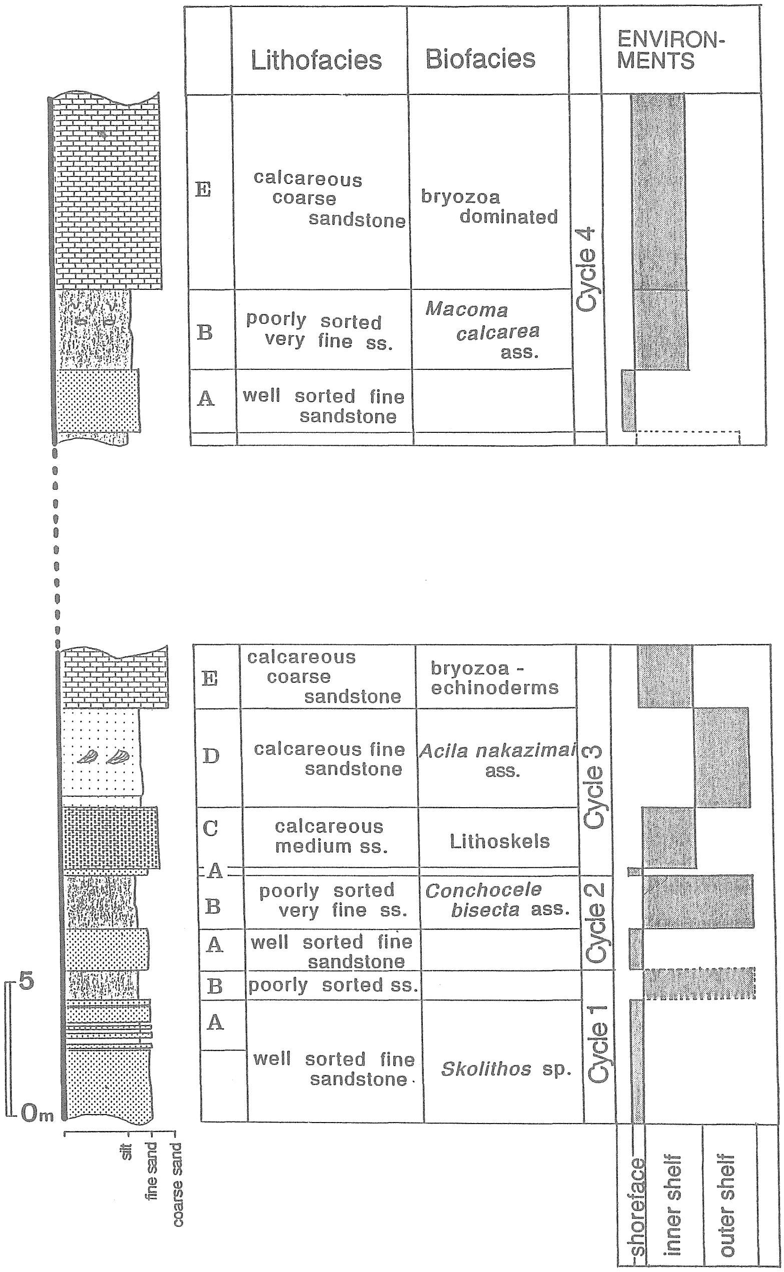


Fig. 16. Summary of cyclic changes of lith- and bio-facies in the upper part.

sea-level fluctuation were similar throughout a given time and that the apparent difference in stratigraphic succession among the four types (Type 1 to 4) was controlled by water depth, as envisaged and compared from the bathymetry of the high stillstand facies in each

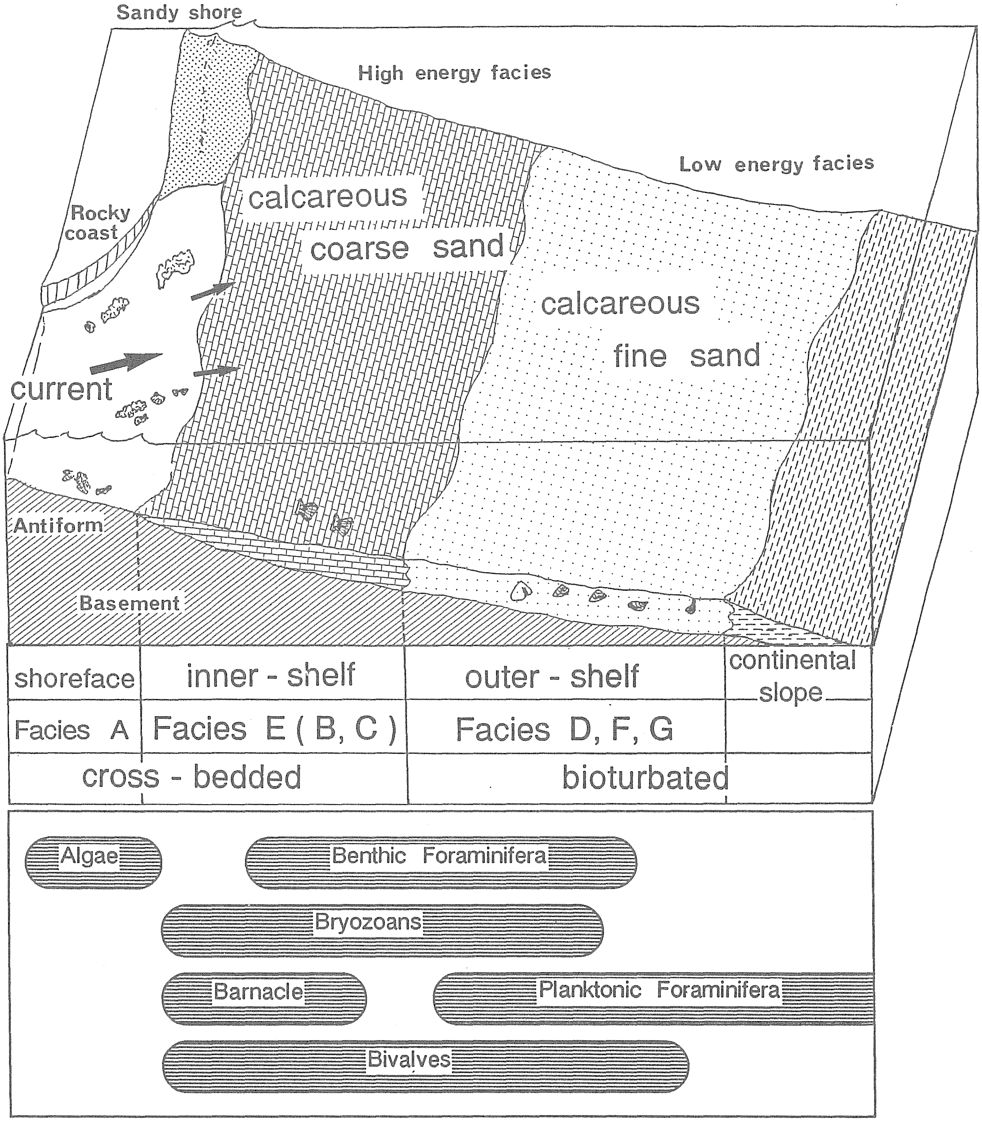


Fig. 17. A model for accumulation of the shallow marine non-tropical carbonate at studied area. Characteristic distribution of bioclastics is based on modern analogues; the Rockall Bank (SCOFFIN *et al.*,1980), the Scott Shelf (NELSON and BORNHOLD, 1983) and the Rottnest Shelf (COLLINS, 1988).

type. Thus, the four types are to represent different water depths on a shelf profile, respectively; from the most "coastal" Type 1 to the most "basinal" Type 4 (Fig. 18). It is also inferred that even the site of Type 1 was not exposed subaerially during the low stillstand.

Prior to initiation of the transgression, shallow marine non-tropical carbonate and

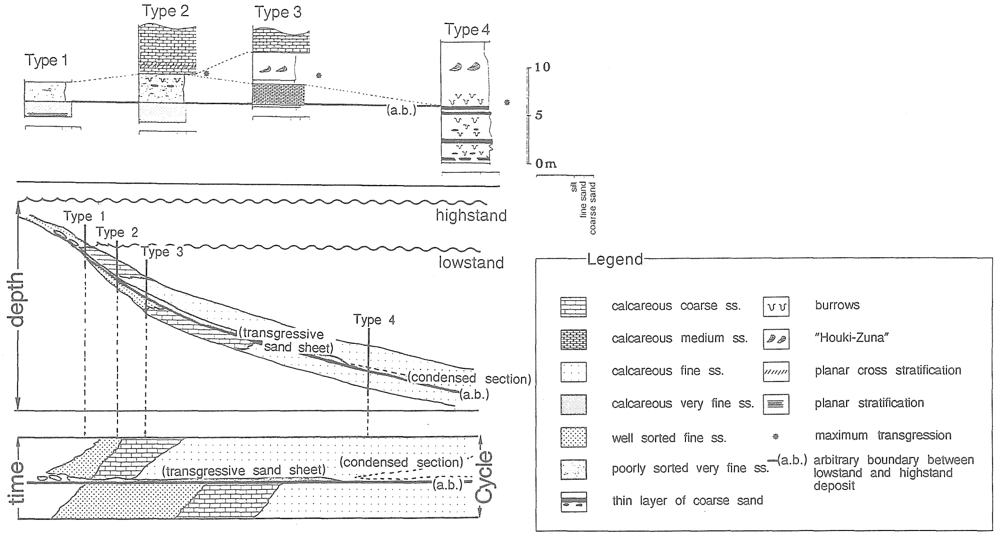


Fig. 18. A schematic diagram of non-tropical carbonate lithofacies distribution in a parasequence framework. Type 1-3; Cycles of the upper part, Type 4; Cycle of the middle part.

mixed sediments characterized the stillstand environment from coastal facies A (well-sorted fine sandstone) to basinal facies F (calcareous fine sandstone), with the facies E (calcareous coarse sandstone) in between. As the transgression commenced rapidly associated with landward retreat of the shoreface, the facies B (poorly-sorted very fine sandstone) and/or facies C (calcareous medium sandstone) covered the inner shelf as a transgressive sand sheet. During a period of the high stillstand, active shoreface erosion by wave continued over the inner shelf, where the substrates were progressively colonized with the contemporary biota (dominant by Bryozoa), which contributed skeletal debris to lag deposits (facies E). The outer shelf substrates are characterized with hemipelagic to pelagic sediments of very low rate of sedimentation (facies G), which are interpreted as condensed section. During as well as right after the maximum high stand, a limited progradation took place reworking and breaking-down the biotic skeletals, together with limited seaward transport of fine sediment (facies D), which formed consequently a shallowing-upward sequence (from facies D to facies F).

10. Conclusions

(1) Stratigraphic relation of sedimentary facies (onlap pattern) and temporal distribution of molluscan assemblages indicate that the Junicho Formation was formed under a rapid regional transgression associated with relative sea-level rise, which then turned to a regression.

(2) Stratigraphically, the Junicho Formation is divided into three parts, and demon-

strates distinct cyclic changes of litho- and bio-facies both in the middle and upper part.

(3) The middle part consists of at least three cycles, each of which demonstrates shoaling upward sequence across the storm wave base.

(4) In the upper part, similar, yet varied cyclicities defined with well-sorted fine sandstone at base, show that fluctuations of relative sea-level change occurred at least four times during its deposition. The apparent difference in the lithofacies between the middle and upper part appears to depend essentially on the depositional depth.

(5) The cycles of the upper part are grouped into three types, of which the difference is also dependent on water depth. The upper part of the Junicho Formation has formed under the combined influence of sea-level change of two different orders.

(6) Magnetostratigraphy of the Junicho Formation confirms that the lower part of the formation is assigned to the Olduvai Subchron in the Matuyama Chron. Based on this magnetostratigraphy, the average sedimentation rate is reestimated to be about 30 cm/1000 y under the assumption of its constancy for the Formation.

(7) The periodicity of the cyclic changes in the middle and upper parts of the Junicho Formation is estimated to be a few ten thousand years. The amplitude of the relative sea-level changes is up to 30 m. These sedimentary cycles of the Junicho Formation with such periodicity and amplitude are most probably attributed to glacio-eustatic sea-level change.

(8) The magnetic intensity and susceptibility measured in each sedimentary cycle of the middle part verify a similar magnetic cyclicity, which is characterized by double peaks. Although no conclusive interpretation is warranted at present, this fact may suggest a positive, most likely causal, correlation between the concentration of ferromagnetic minerals and the relative sea-level fall.

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