Glaucony and carbonate grains as indicators of the condensed section: Omma Formation, Japan

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Abstract

The fifth-order depositional sequences of the Early Pleistocene Omma Formation exposed along the Japan Sea coast of central Japan were formed by glacial-eustasy during oxygen isotope stages 50 to 28. In each depositional sequence, two ecostratigraphic datums are always present: the appearance and disappearance datums of warm-water molluscan species. These datums are independent of sequence stratigraphic concepts, because the establishment of them is based on immigration events of molluscan species associated with glacio-eustatic sea-level changes. Determination of time planes shows that the appearance datum seems to occur near the midpoint of sea-level rise on the glacial to interglacial shift in deep-sea δ18O records. In order to evaluate the significance of the condensed section in sequence stratigraphy and also to facilitate its recognition, this study examines the stratigraphic relationship of the condensed section indicators, glaucony and carbonate grains, with respect to the position of the ecostratigraphic datums in depositional sequences of the Omma Formation. The results show that the maximum concentration of carbonate grains is a more reliable maximum flooding surface indicator than the concentration of glaucony. The combination of indicators of condensed section and ecostratigraphic datums represented by incursion epiboles enables the boundary between transgressive and highstand systems tracts to be recognized in the inner shelf parts of depositional sequences. Moreover, truncation of ecostratigraphic datums during sea-level falls demonstrates significant erosion at the sequence boundaries. Integration of climatic palaeoecology and sequence stratigraphy permits a level of correlational precision of the order of a few thousands of years.

Keywords: Early Pleistocene; sequence stratigraphy; ecostratigraphy; condensed section; maximum flooding surface; sea-level change

1. Introduction

Both type 1 and 2 depositional sequences have transgressive and highstand systems tracts (e.g. Vail et al., 1991). The physical boundary between them is called the maximum flooding surface. This surface commonly occurs within the top of, or at the base of, a condensed section caused by very low sedimentation rates (e.g. Vail et al., 1991; Abbott and Carter, 1994). Stratigraphic condensation on the continental shelf may be characterized by concentrations of planktonic organisms, glaucony, sulphides, phosphate, and airborne particles such as volcanic ash and iridium (e.g. Loutit et al., 1988; Baum and Vail, 1988). Condensed sections usually coincide with zones of maximum diversity and abundance of fossils. On the other hand, condensed sections in epeiric settings are characterized by higher total organic carbon, reduced oxygen values, low concentrations of benthic foraminifera, and minimal or no burrowing, compared with rocks deposited during more elevated sedimentation rates (Pemberton et al., 1992). Although the character of condensed sections varies according to geologic settings, any condensed section is interpreted as a sediment-starved interval that was caused by the trapping of terrigenous sediments during times of relatively rapid sea-level rise and marine flooding. Thus, the distribution of low sedimentation rate indicators has been used to recognize the condensed section, maximum flooding surface and the highstand and transgressive systems tracts.

With the exception of a few studies (e.g. Saito, 1991), most studies have been based on pre-Pliocene sedimentary sequences, where the sea-level signature is not known independently but has to be inferred from the sediments under study. One of the exceptions was a depositional sequence of shelf and upper slope facies formed in response to Late Pleistocene to Holocene sea-level changes but the distribution of indicators of the condensed section were not investigated in detail (Saito, 1991). Thus, the purpose of this paper is to examine the relationship between the distribution of glaucony and carbonate grains as indicators of the condensed section, and true sea-level changes.

The Omma Formation is ideal for this purpose, because its middle part is composed of eleven depositional sequences deposited during glacio-eustatic sea-level changes between about 1.5 and 1.0 Ma (Kitamura and Kondo, 1990; Kitamura et al., 1994). Moreover, each depositional sequence in the Omma Formation contains two chronostratigraphic horizons, namely the appearance and disappearance datums of warm-water molluscan species (Kitamura, 1995). Because these datums are based on the frequency variations of climatically controlled molluscan associations, their recognition is independent of sequence stratigraphic criteria. Thus, using these two horizons the sequence stratigraphic significance of concentrations of glaucony and carbonate grains can be evaluated.

2. Depositional sequences of the Omma Formation

The Omma Formation is exposed around Kanazawa City on the Japan Sea coast of central Japan (Fig. 1). The sedimentary basin is situated in a back-arc position with respect to the subducting plate boundaries between the Pacific, Philippine and Eurasia plates. Eleven cyclothems are recognized in the middle part of the Omma Formation (Kitamura et al., 1994). These cyclothems are numbered upwards in succession from 1 to 11 (Fig. 2). In this paper, cyclothems of the Omma Formation at the type section (Okuwa) and at Yuhidera are examined (Fig. 1).

The type locality of the formation is located in the bed of the Saikawa River, Kanazawa City. Except for cyclothem 9, all sequences can be observed at Okuwa (Fig. 2). The thickness of individual cyclothems exposed at this section is highly variable, ranging from 2 m to 12 m with an average thickness of 7 m. In a representative cycle, the lithofacies present are, in ascending order, a basal shellbed, a well-sorted fine sandstone, a muddy fine to very fine sandstone and a well-sorted fine sandstone (Fig. 3 and Fig. 4; Kitamura et al., 1994).

Although cyclothems 1–4 are identified at Yuhidera, the lower boundary of cyclothem 1 and the upper boundary of cyclothem 4 are obscured due to poor exposure (Fig. 3; Kitamura et al., 1997). Individual cyclothems are about 5 m thick. In cyclothem 2, the lithofacies present are, in ascending order, a basal shellbed, a fine sandstone, a muddy fine to very fine sandstone, an intensely burrowed sandy siltstone and a muddy fine to very fine sandstone (Fig. 3). On the other hand, lithofacies recognized in cyclothem 3 are, in ascending order, a basal shellbed, fine sandstone and muddy very fine sandstone.

A remarkable feature of these cyclothems is that within them they show a cyclicity in the vertical distribution of in-situ molluscan fossil associations. The term 'association' used here is defined as the recurrent autochthonous relicts of former communities (Fürsich, 1984). The faunal changes within an individual cyclothem indicate that the marine conditions changed from cold-water, upper sublittoral (low tide mark to 50–60 m deep) to warm-water, lower sublittoral (50–60 m to 100–120 m deep), followed again by cold-water, upper sublittoral during the deposition of one cyclothem (Kitamura et al., 1994). Therefore, these cyclothems are believed to have formed during glacio-eustatic sea-level changes. In terms of sequence stratigraphy, the cyclothems of the Omma Formation each represent one depositional sequence at fifth-order scale (see below).

Sequence boundaries underlie the basal shellbed at the bottom of the deepening-upward succession in each sequence. The sharp erosive base of each shellbed indicates that the lower sequence boundary coincides with a ravinement surface formed by coastal shoreface erosion during a transgression (Bruun, 1962). The basal shellbeds grade upward into less condensed well-sorted sandstone. Based on these factors, the shellbeds are interpreted as transgressive lag deposits (Kidwell, 1991). Consequently, depositional sequences in the middle part of the Omma Formation contain no lowstand systems tract sediment.

Many studies (e.g., Saito, 1991) indicate that the depth of shoreface erosion is less than 40 m, thus the range of 0–40 m is estimated as the shallowest water depth recorded within the depositional sequences of the middle part of the Omma Formation. According to Dwyer et al. (1995), the glacial to interglacial sea-level fluctuated on average 60 to 70 m between 2.8 and 2.3 Ma. Naish (1998) reports fluctuations of between 25 and 90 m during oxygen iosotope stages 100–72. Therefore, in this paper, the sea-level change associated with climatic cycles during the deposition of the middle part is regarded as 60 to 90 m because the magnitude of δ18O fluctuations during the Early and middle Pleistocene are similar to these Pliocene eustatic estimates. Application of these estimates of eustatic sea-level change to the Omma Formation depositional sequences implies that the coarser-grained sediments accumulated on the inner shelf in water depths of 0–40 and finer-grained sediments accumulated on the mid- and outer shelf between 60 and 100 m (Fig. 4) (Kitamura et al., 1997). This range does not contradict significantly with the palaeobathymetric range of the constituent molluscan fossil associations (Kitamura et al., 1994).

The eleven depositional sequences of the middle part of the Omma Formation correspond to fifth-order sequences equivalent to oxygen isotope stages 50 to 28 (Kitamura et al., 1994) (Fig. 2). The 75-m-thick middle part of the Omma Formation at Okuwa shows no progressive shift in facies towards deeper or shallower deposits. In addition, if the oxygen isotope record (e.g., Ruddiman et al., 1989; Shackleton et al., 1990) is regarded as a proxy for the glacio-eustatic sea-level record, there is no significant trend in average sea-level during the deposition of the middle part (Fig. 2) (1.5–1.0 Ma). The constancy of facies in the middle part of the Omma Formation implies a balance between sedimentation and subsidence. Using both biostratigraphic and magnetostratigraphic data (Ohmura et al., 1989; Takayama et al., 1988; Sato and Takayama, 1992; Kitamura et al., 1993), average rates of sedimentation are estimated to be about 16 cm/ka.

3. Ecostratigraphic datums

The Japan Sea is a semi-enclosed marginal sea and is connected to the East China Sea through the Tsushima Strait, to the Pacific Ocean through the Tsugaru Strait, and to the Sea of Okhotsk through the Soya and Mamiya Straits. At present, the only current flowing into the Japan Sea is the Tsushima Current, a branch of the warm Kuroshio Current that enters the Japan Sea through the Tsushima Strait (Fig. 1). The current transports planktotrophic larvae of benthic molluscs that live in the water mass influenced by the Kuroshio Current. Such warm-water organisms (incursion epiboles; Brett, 1995) occur cyclically in Quaternary sediments of the Japan Sea. Kitamura (1995) compared the stratigraphic pattern of these species during the last 1.5 Ma with the published oxygen isotope record (Ruddiman et al., 1989). The comparison suggested that warm-water organisms such as molluscs and diatoms expanded their range into the Japan Sea during all interglacial stages from 1 to 49, except for stages 3 and 23, and apparently were locally exterminated by the succeeding glacial period, implying that they were killed off by cooling marine temperatures. These phenomena were synchronous within one local region, 10×10 km2 in area. Moreover, the molluscan fossils (time planes indicators) are considered to be in situ in living associations (biocoenoses), and resedimentation of fossils from underlying sediments is not a concern in the interpretation. Therefore, the appearance and disappearance datums of warm-water molluscs have utility as chronostratigraphic datums that can be used to interpret depositional sequences of the Omma Formation (Kitamura, 1995). Indeed, the parallel relationship between volcanic ash layer O4 and the appearance datum of warm-water molluscs within depositional sequence 2 demonstrates the synchroneity of the ecostratigraphic datums (Fig. 3). However, there is a distinct difference between contemporaneous molluscan fossil associations between Okuwa and Yuhidera. For example, at Okuwa, layer O4 occurs at the boundary between the Tugurium–Paphia I Association and the Tugurium–Paphia II Association. In contrast, the O4 layer occurs within the horizon yielding the Tugurium–Paphia II Association at Yuhidera. In addition, molluscan associations above the appearance datum of warm-water molluscs within depositional sequence 4 are different between both sites: Okuwa contains the Barnea Association, Yuhidera is Transitional I Association (Fig. 3). On the basis of the recent distribution of molluscan species (Kitamura et al., 1997), these differences indicate that the sequence at Yuhidera may have been deposited in water a few tens of metres deeper than that at Okuwa. The variation in lithofacies between the two sections can be explained by the difference in inferred water depths between the two sites.

These ecostratigraphic datums are always present in each of the depositional sequences in the middle part of the Omma Formation, although in some sequences the disappearance datum of warm-water species coincides with the upper sequence boundary (Fig. 3). For example, comparison between depositional sequences 2 and 3 at Okuwa and Yuhidera shows that the disappearance datum merges into an upper sequence boundary towards the shoreline (Fig. 3). This implies that the upper portion is largely truncated at the upper sequence boundary and this portion is more complete in thicker, more basinward sections.

4. Sea-level change and ecostratigraphic datums

Because ecostratigraphic datums within each depositional sequence in the Omma Formation are based on biogeographic changes controlled by interglacial–glacial cycles, these datums are independent of sequence stratigraphic concepts. Thus, analysis of the relationship between these datums and sequence and systems tract boundaries may help clarify some concepts of sequence stratigraphy. In the following section, I focus on the stratigraphic distribution of ecostratigraphic datums and of the indicators of the condensed section such as glaucony and carbonate grains. Before doing this, however, the temporal relationship must be established between sea-level change and the appearance and disappearance datums of warm-water molluscs.

Since the depositional sequences in the Omma Formation were formed by glacio-eustasy, the oxygen isotope record in deep-sea cores can be regarded as a proxy for contemporaneous sea-level change. The temporal position of the ecostratigraphic datums on the sea-level curve can be established by dating the datums precisely then by establishing their correlations with the oxygen isotope curve.

The age of the youngest appearance datum in cores from the Japan Sea is shown by 14C dating to be about 10 ka (Oba et al., 1991 and Oba et al., 1995). The age of the appearance datum within depositional sequence 10 of the Omma Formation can be dated by magnetostratigraphy. The base of the Jaramillo Subchron is placed about 50 cm above the appearance datum of warm-water molluscs in this sequence (Fig. 4) (Kitamura et al., 1994). Thus, the datum age corresponds approximately to the base of the Jaramillo Subchron. On the basis of the benthic oxygen isotope record from North Atlantic core V30-97 (Ruddiman and McIntyre, 1984) and ODP site 659 (Tiedemann et al., 1994), the δ18O value at 10 ka was about 3.5‰. Also, according to the benthic oxygen isotope record from ODP site 659 (Tiedemann et al., 1994), and at DSDP Site 607 (Ruddiman et al., 1989) which is quite near core V30-97, the δ18O value at the base of the Jaramillo Subchron was about 3.4‰ (Fig. 4). As the appearance datum of warm-water molluscs is placed about 50 cm below the base of the Jaramillo Subchron, the δ18O value at this period also can be regarded as 3.5‰. These correlations suggest that a δ18O value of 3.5‰ is a threshold value for physical conditions that control the timing of initiation of inflow of the Tsushima Current. It appears that these physical conditions have been consistent since 1.5 Ma, because except for stages 3, 23 and 39, the δ18O values of all interglacial stages after the oxygen isotope stage 50 became lighter than 3.5‰ in the benthic δ18O records from DSDP site 607 and ODP site 659. Thus, I use this δ18O value of the glacial–interglacial shift to estimate the ages of the appearance datums of warm-water molluscs, although the physical conditions that control ocean currents in the Japan Sea during the Quaternary remain poorly understood.

According to the oxygen isotope records corresponding to deposition of the middle part of the Omma Formation, δ18O values of 3.5‰ fall near midpoints between interglacial and glacial peaks (Fig. 2). Also, the appearance datum of warm-water molluscs seems to have fallen midway along glacial to interglacial δ18O shifts.

5. Relationship of ecostratigraphic datums to indicators of condensed section in siliciclastic sequences

To document the stratigraphic distributions of glaucony and carbonate grains in each depositional sequence, thin sections of sandstone were made from samples without megafossils and trace fossils, and 500 sand-size grains were identified from each thin section. These results are shown in Fig. 5 and Fig. 6.

Cementation was not observed in any of the analyzed samples. Most of the glaucony comprises pale green, well rounded grains. Glaucony occurs throughout the depositional sequences and the content of glaucony in most samples ranges from 10 to 20% of the total rock (Fig. 5 and Fig. 6). A systematic pattern within depositional sequences is not recognized in the stratigraphic distribution of glaucony.

Sand-size carbonate grains dominate samples, and occur as both benthic and planktonic foraminifers, with a lesser contribution from fragmented grains of echinoids and other carbonate detritus. The content of carbonate grains in all samples is less than 10% of the total rock, except for one sample with 14%. The abundance of carbonate grains shows a systematic change within depositional sequences; these generally increase upwards (to a point identified as the maximum flooding surface) and then decrease (Fig. 5 and Fig. 6). Typically, the stratigraphic level of maximum concentration of carbonate grains occurs between the appearance and disappearance datums of warm-water molluscs (Fig. 5 and Fig. 6). However, depositional sequences 3 and 4 at

Okuwa do not have zones with upward-decreasing carbonate grains. This is caused by erosion of the upper part of the sequence, judging from the disappearance datum of warm-water species which coincides with the upper sequence boundary in these sequences.

6. Discussion and conclusions

From the analytical results described above, the distribution of glaucony and carbonate grains can be used to evaluate sequence stratigraphic concepts. In this use the stratigraphic relationship between glaucony grains and ecostratigraphic datums indicates that the distribution of glaucony is not diagnostic of the condensed section or a particular systems tract in a depositional sequence (Fig. 5 and Fig. 6). Thus, in the case of the Omma Formation, the maximum flooding surface associated with the condensed section cannot be identified uniquely by the distribution of glaucony alone. The sequence stratigraphic interpretation of many glaucony-bearing units is confused by the mixing of allochthonous and autochthonous glaucony. For example, in the lower part of the TST, allochthonous glaucony is supplied by erosion during shoreline retreat (Amorosi, 1995). This mixing may obscure the expected distribution of glaucony in depositional sequences of the Omma Formation. The detailed documentation in this paper suggests that fuller information on glaucony, including spatial distribution, maturity and genetic attributes, are required for the sequence stratigraphic interpretation of glaucony-bearing successions (Amorosi, 1995).

Carbonate grains change in abundance in a regular pattern through each depositional sequence. Moreover, the temporal pattern of change of carbonate grains within depositional sequence 2 at Okuwa is similar to those at Yuhidera. These facts imply that the concentration of carbonate grains provides a criterion to help identify the maximum flooding surface associated with the condensed section. The horizon of maximum concentration is placed above the appearance datum of the warm-water molluscs in most depositional sequences (Fig. 5 and Fig. 6). Thus, the horizon of maximum concentration of carbonate grains may correspond to the part of the oxygen isotope curve representing the mid-point of the sea-level rise to the highest stand of sea-level, and thus is a good indicator of stratigraphic condensation during rapid drowning of the shelf.

From the results described above, the distribution of carbonate grains seems to be more effective as an indicator of the condensed section than glaucony. In all depositional sequences of the Omma Formation except for depositional sequences 3 and 4 at Okuwa, the maximum flooding surface can be defined at the horizon of the maximum concentration of carbonate grains (Fig. 5 and Fig. 6). In the case of depositional sequence 2 at both Okuwa and Yuhidera, the difference in values between the horizon of the maximum concentration and the neighbouring horizons is less than 1%. Thus, I place the maximum flooding surface at a midpoint between the two horizons. Although there is an exception (depositional sequence 4 at Yuhidera), the maximum flooding surface is between the appearance and disappearance datums of warm-water molluscs. This suggests that incursion epiboles of warm-water molluscs may occur in the upper parts of the transgressive systems tracts and the early highstand systems tracts of depositional sequences in the Quaternary Japan Sea basin.

In the case of depositional sequences 3 and 4 at Okuwa, the maximum flooding surface is not defined. On the basis of ecostratigraphic datums and carbonate grains, the upper portions of these sequences were missing due to erosion at an upper sequence boundary. Thus, these sequences at Okuwa contain the transgressive systems tracts alone. Such incomplete depositional sequences were reported by other workers (e.g., Pasley and Hazel, 1995).

Plio–Pleistocene depositional sequences derived from the 40-ka cycle of interglacial–glacial sea-level change are found in Wanganui in western North Island, New Zealand (Abbott and Carter, 1994; Naish and Kamp, 1997). In these sequences, a condensed shellbed is recognized near the maximum flooding surface. The shellbeds comprise a rich in-situ and near-situm fauna of shallow infaunal and epifaunal invertebrates and their mean thicknesses are 16 cm. The shellbeds probably formed at 20–40 m depth in a few thousand years (Abbott and Carter, 1994). In contrast, they are not present in the Omma Formation, although the water depth at the maximum flooding surface was as much as 50–100 m. The development of a condensed shellbed requires both the absence of a major supply of sediment and the presence of an in-situ fauna. Molluscan species are preserved in situ or near situm within the horizon near the maximum flooding surface in each depositional sequence of the Omma Formation. The lack of a condensed shellbed is therefore interpreted as a highly siliciclastic sediment supply during a transgressive phase. In fact, the average transgressive sediment thickness of the Omma Formation (Okuwa 4.74 m, Yuhidera 2.37 m) is thicker than that of depositional sequences at Wanganui (1.96 m). The discharge of rivers into the Japan Sea during the inflow of the Tsushima Current was far greater than that during glacial periods (Yasuda, 1982). This is because the warm Tsushima Current would have caused heavy snowfalls on the Japan Sea coast of the Japanese islands. At present, the annual rainfall at Kanazawa is more than 2600 mm/yr, of which more than half is contributed by winter snowfall. The interglacial sediment influx accompanied by such heavy precipitation seems to have prevented a condensed shellbed from forming.

The depositional sequences of the Omma Formation seem to be a special case, because conditions of relative sediment starvation associated with sea-level rise did not take place at the deposition site. Regardless of the degree of change, such local and/or regional environmental changes such as climate paralleling sea-level rise took place in all sedimentary basins. Thus, the local and/or regional environmental factors must be considered when the concepts of sequence stratigraphy are applied. Climatic fluctuations associated with sea-level changes may carry incursion epiboles that have utility as local time markers (Martin et al., 1993; Brett, 1995). The ecostratigraphic datums represented by such incursion epiboles are very helpful in the recognition of systems tracts and sequence boundaries (Martin et al., 1993; Brett, 1995). Moreover, integration of climatic palaeoecology (ecostratigraphic datums) and sequence stratigraphy permits a level of correlational precision on the order of a few tens of thousands of years (Martin et al., 1993; Kitamura, 1995).

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Fig. 1. Map of the Japan Sea and its surrounding region, and geological map and studied section of the Omma Formation around Kanazawa City, central Japan. Modified from Imai (1959) and Tada et al. (1992).

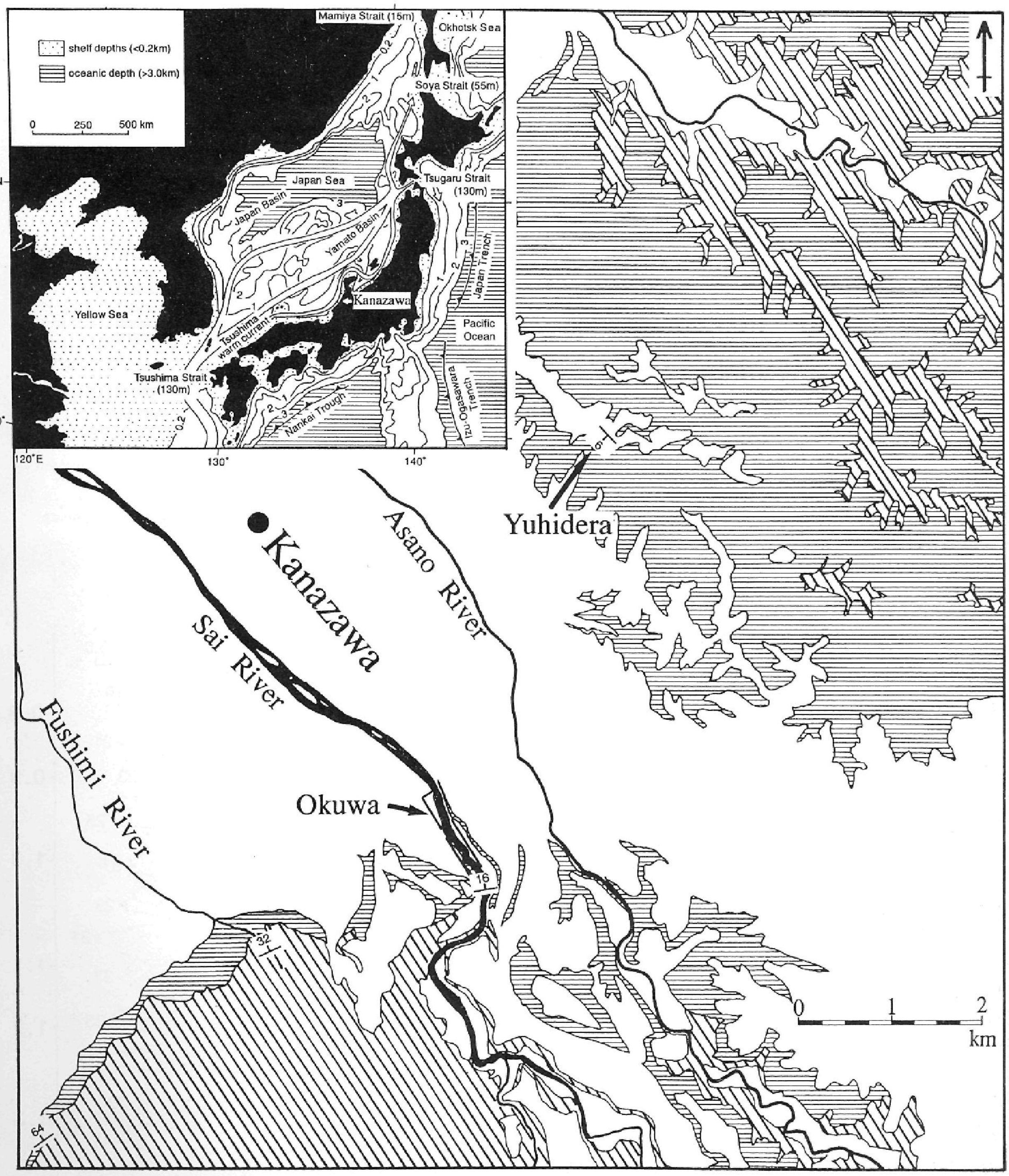
Fig. 2. Comparison of stratigraphic distribution of warm-water species in the Omma Formation at the type section and another section located in the bed of the Fushimi River (Fig. 1) with the oxygen isotope record from DSDP Site 607 (Ruddiman et al., 1989). Biostratigraphic datums are after Takayama et al. (1988) and Sato and Takayama (1992); magnetostratigraphic data are from Ohmura et al. (1989) and Kitamura et al. (1993); time scale of oxygen isotope record of DSDP Site 607 and ages of biostratigraphic datums and magnetic polarity changes are based on chronology of Berger et al. (1994). SB = sequence boundary; 1–11, I–III = numbers of depositional sequences.

Fig. 3. Correlation of depositional sequences 1 to 6 of the middle part of the Omma Formation between the Okuwa and Yuhidera sections by ecostratigraphic datums and a volcanic ash layer.

Fig. 4. Correlation for the Jaramillo Subchron between the oxygen isotope record of North Atlantic DSDP site 607 (Ruddiman et al., 1989) and the inferred changes in water depth and stratigraphic distribution of ecostratigraphic datums in the Omma Formation. See legend to Fig. 2 and Fig. 3 for explanation of symbols.

Fig. 5. Glaucony, carbonate grains and sequence stratigraphic interpretation of depositional sequences 1 to 6 of the middle part of the Omma Formation in the Okuwa and Yuhidera sections. See legend to Fig. 3 for explanation of symbols. SB = sequence boundaries; TS = transgressive surface; RS = ravinement surface; TST = transgressive systems tract; HST = highstand systems tract.

Fig. 6. Distribution of glaucony and carbonate grains and sequence stratigraphic interpretation of depositional sequences 8 and 10 of the middle part of the Omma Formation in the Okuwa section. See legend in Fig. 3 and Fig. 5 for explanation of symbols.



overlying formations Omma Formation

underlying formations

Fig. 1

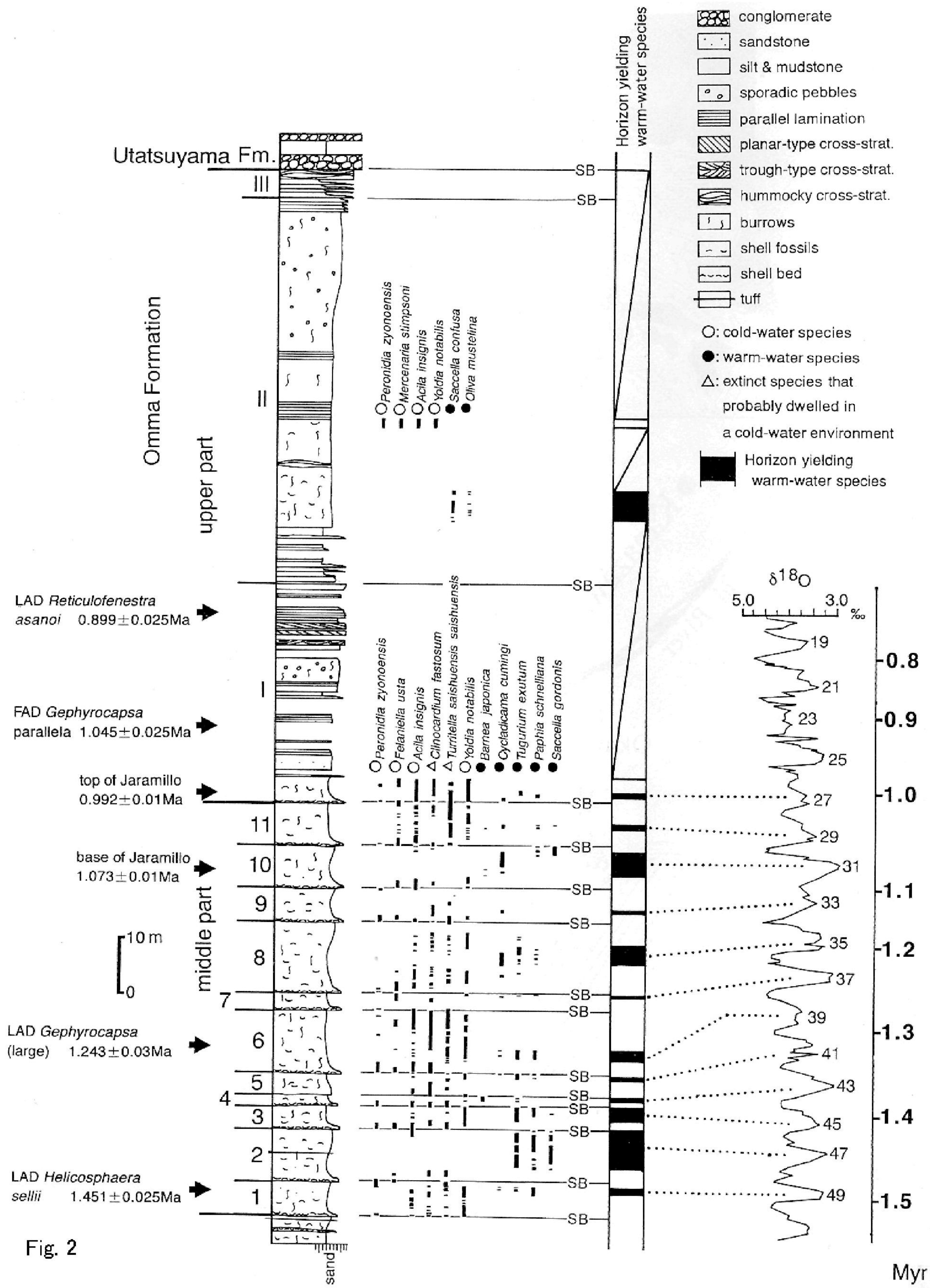

Utatsuyama Fm.
Omma Formation
upper part
middle part
LAD Reticulofenestra asanoi 0.899±0.025Ma
FAD Gephyrocapsa parallela 1.045±0.025Ma
top of Jaramillo 0.992±0.01Ma
base of Jaramillo 1.073±0.01Ma
LAD Gephyrocapsa (large) 1.243±0.03Ma
LAD Helicosphaera sellii 1.451±0.025Ma
10 m
0
sand
SB
Horizon yielding warm-water species
Peronidia zyonoensis
Mercenaria stimpsoni
Acila insignis
Yoldia notabilis
Saccella confusa
Oliva mustelina
Felaniella usta
Clinocardium fastosum
Turritella saishuensis saishuensis
Barnea japonica
Cycladicama cumingi
Tugurium exutum
Paphia schnelliana
Saccella gordonis
conglomerate
sandstone
silt & mudstone
sporadic pebbles
parallel lamination
planar-type cross-strat.
trough-type cross-strat.
hummocky cross-strat.
burrows
shell fossils
shell bed
tuff
O: cold-water species
●: warm-water species
△: extinct species that probably dwelled in a cold-water environment
Horizon yielding warm-water species
δ18O
5.0
3.0
‰
Myr

Fig. 2

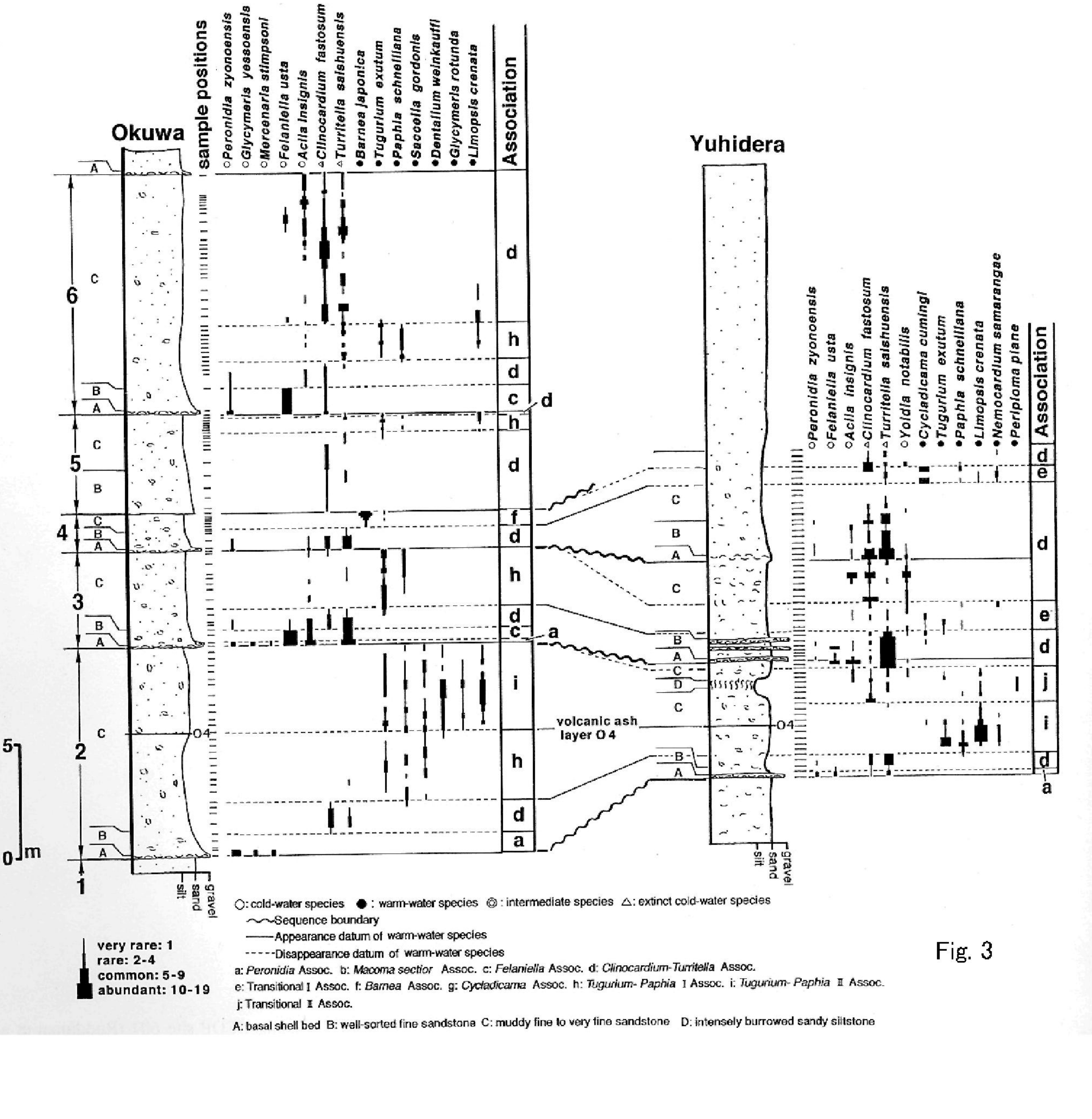
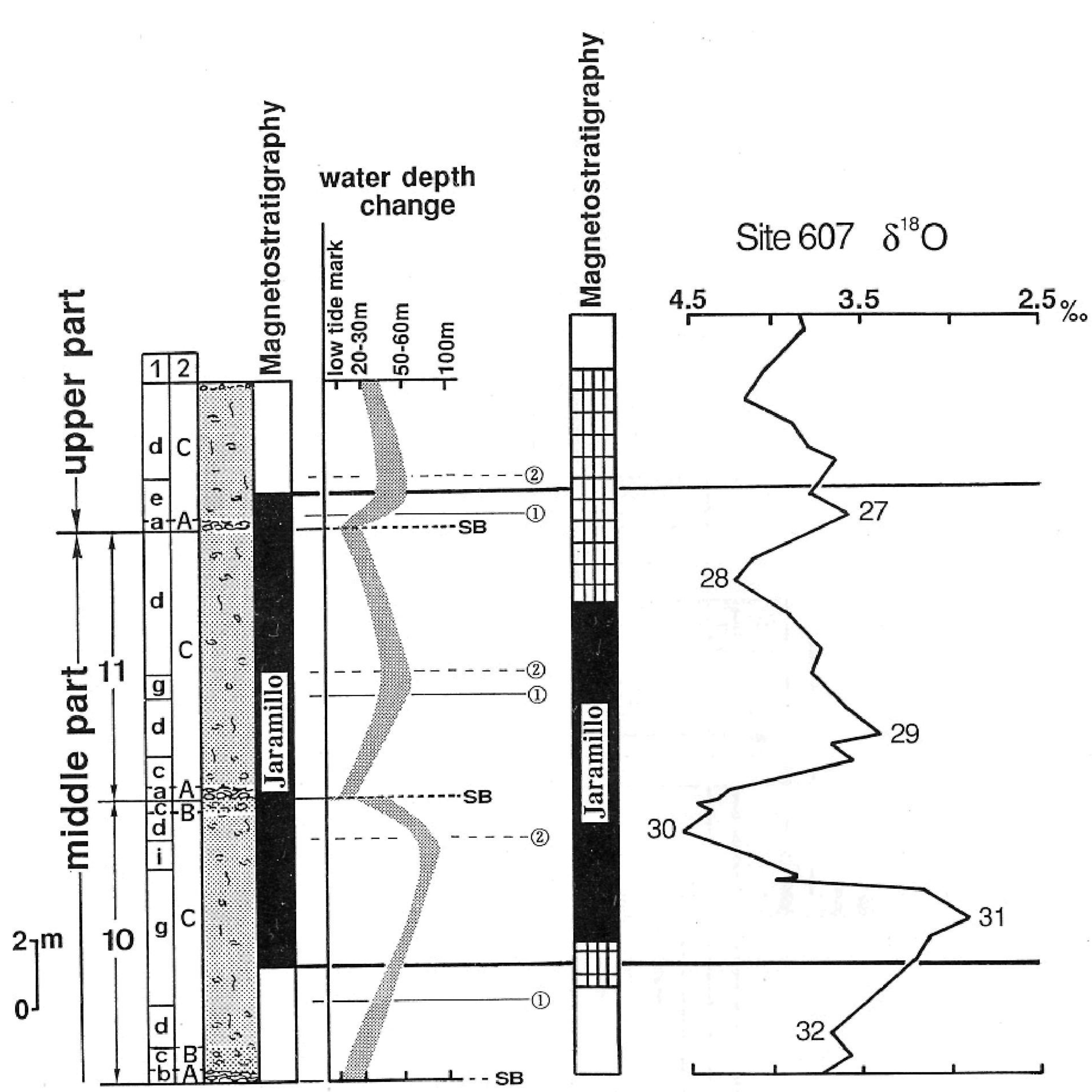

Okuwa
sample positions
○Peronidia zyonoensis
○Glycymeris yessoensis
○Mercenaria stimpsoni
○Felaniella usta
○Acila insignis
△Clinocardium fastosum
△Turritella saishuensis
●Barnea japonica
●Tugurium exutum
●Paphia schnelliana
●Saccella gordonis
●Dentalium weinkauffi
●Glycymeris rotunda
●Limopsis crenata
Association
Yuhidera
○Peronidia zyonoensis
○Felaniella usta
○Acila insignis
△Clinocardium fastosum
△Turritella saishuensis
○Yoldia notabilis
●Cycladicama cumingi
●Tugurium exutum
●Paphia schnelliana
●Limopsis crenata
●Nemocardium samarangae
●Periploma plane
Association
volcanic ash layer O 4
silt sand gravel
5
0 m
very rare: 1
rare: 2-4
common: 5-9
abundant: 10-19
○: cold-water species ●: warm-water species ◎: intermediate species △: extinct cold-water species
Sequence boundary
Appearance datum of warm-water species
Disappearance datum of warm-water species
a: Peronidia Assoc. b: Macoma sectior Assoc. c: Felaniella Assoc. d: Clinocardium-Turritella Assoc.
e: Transitional I Assoc. f: Barnea Assoc. g: Cycladicama Assoc. h: Tugurium- Paphia I Assoc. i: Tugurium- Paphia II Assoc.
j: Transitional II Assoc.
A: basal shell bed B: well-sorted fine sandstone C: muddy fine to very fine sandstone D: intensely burrowed sandy siltstone

Fig. 3



1 molluscan fossil associations
2 lithologic units
Magnetostratigraphy

Normal Reversed Undefined

SB: Sequence boundary

①: Appearance datum of warm-water species

②: Disappearance datum of warm-water species

Fig. 4

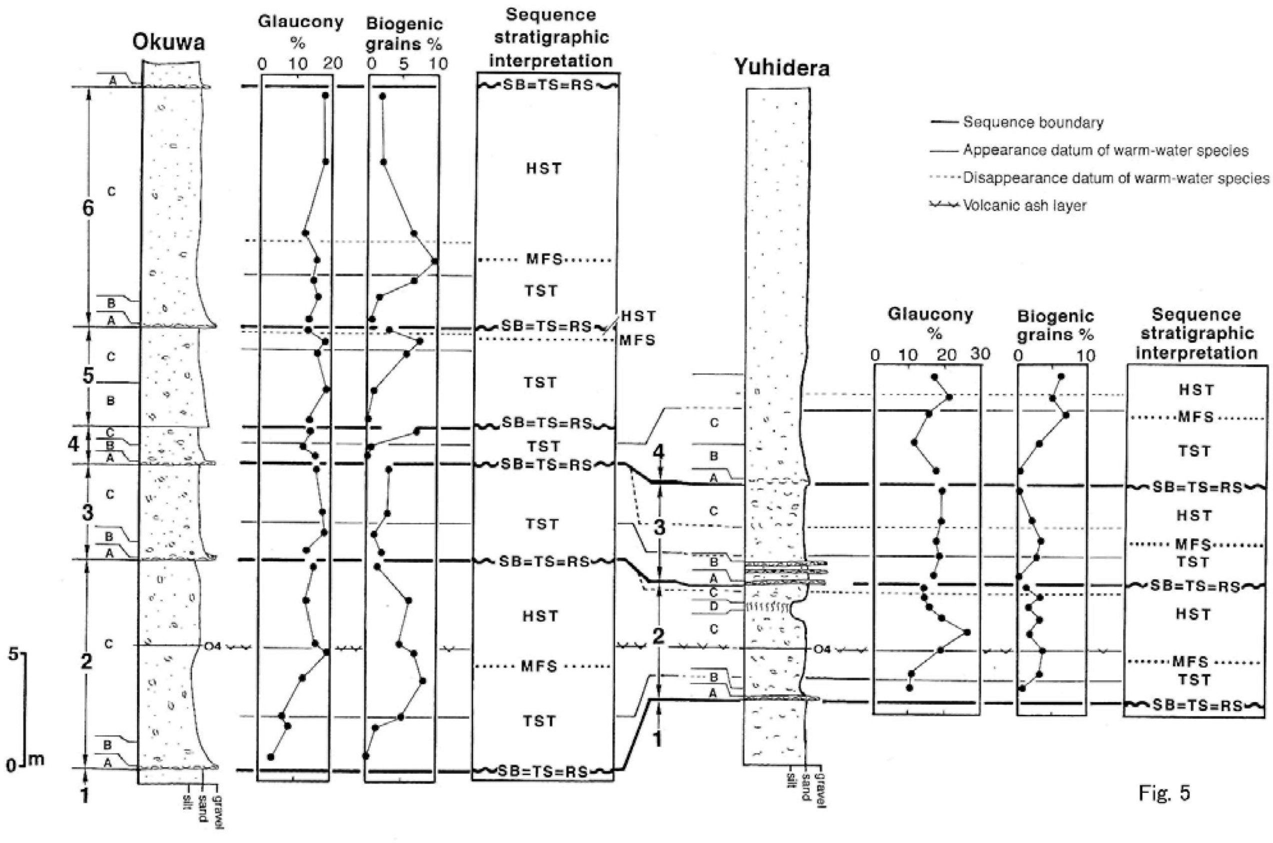
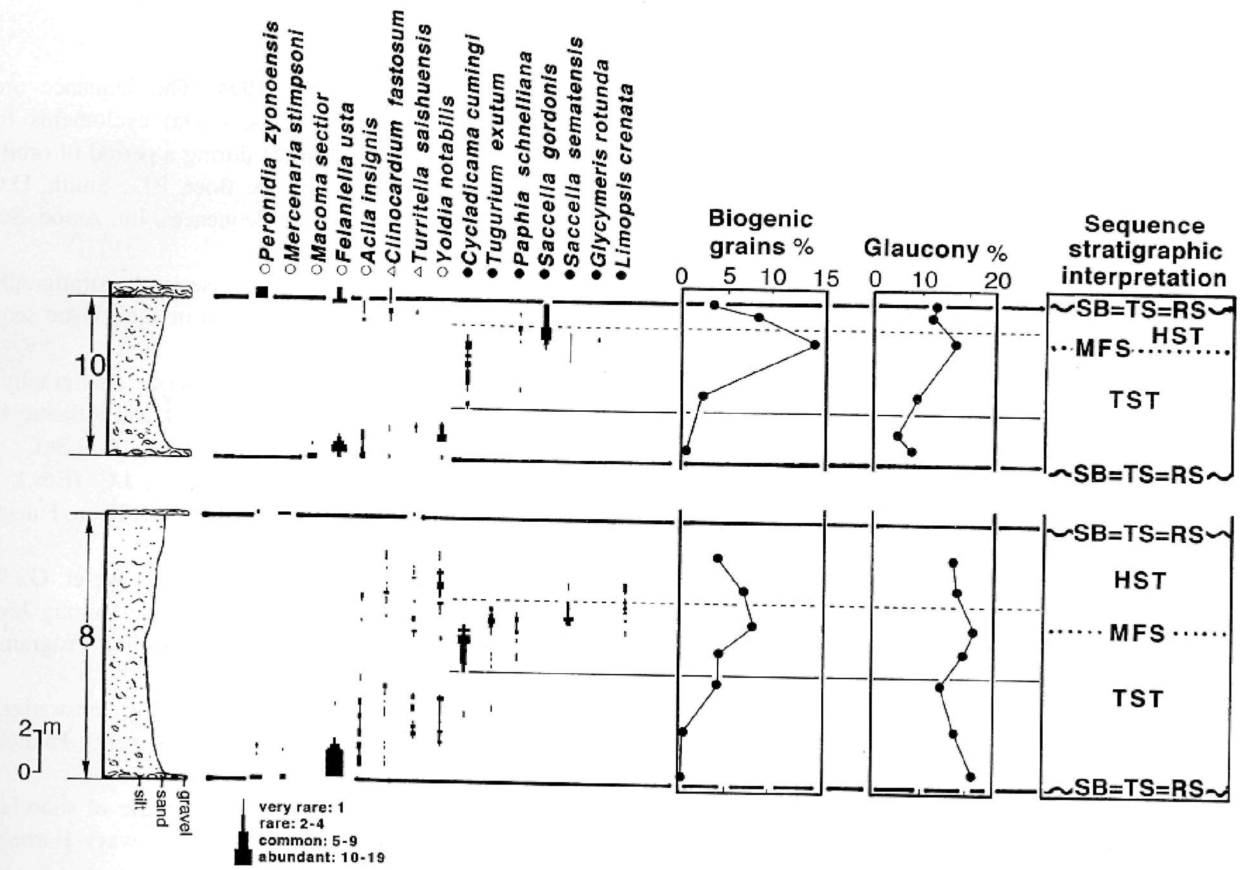

Okuwa
Glaucony %
Biogenic grains %
Sequence stratigraphic interpretation
Yuhidera
Sequence boundary
Appearance datum of warm-water species
Disappearance datum of warm-water species
Volcanic ash layer
SB=TS=RS
HST
MFS
TST
O4
silt
sand
gravel
m

Fig. 5



○Peronidia zyonoensis
○Mercenaria stimpsoni
○Macoma sectior
○Felaniella usta
○Acila insignis
△Clinocardium fastosum
△Turritella saishuensis
○Yoldia notabilis
●Cycladicama cumingi
●Tugurium exutum
●Paphia schnelliana
●Saccella gordonis
●Saccella sematensis
●Glycymeris rotunda
●Limopsis crenata
Biogenic grains %
0 5 10 15
Glaucony %
0 10 20
Sequence stratigraphic interpretation
SB=TS=RS
HST
MFS
TST
SB=TS=RS
SB=TS=RS
HST
MFS
TST
SB=TS=RS
10
8
2 m
0
silt
sand
gravel
very rare: 1
rare: 2-4
common: 5-9
abundant: 10-19