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Mid-Quaternary Paleoceanographic Trend in Near-shore Waters of the Northwest Pacific

— A Case Study Based on an Offshore Well —

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ABSTRACT

An exploratory oil and gas well was drilled on the continental shelf in water 38 m deep at lat. 36°9'33.8"N., long. 140°43'49.3"E., 13 km off the coast of Kashima, Ibaraki Prefecture, Kanto District, Japan. This well sank to the total subbottom depth of 2100 m penetrated sediments ranging back to Late Cretaceous in age. The upper 500 m of well sequence which comprises largely Quaternary sediments was subjected to paleoenvironmental analyses by jointly analyzing microfossils (calcareous nannoplankton and benthic and planktonic foraminifera), mineral content, and oxygen and carbon isotope stratigraphies. Three dated horizons, 0.128, 0.27 and 0.46 Ma, were established by recognizing one marked excursion to negative values in the oxygen isotope record and two calcareous nannoplankton datum levels in the well sequence. A possible hiatus at about 465 m depth terminates this mid-Quaternary sequence which is underlain by late Pliocene strata of about 1.9 Ma and older.

Mid-Quaternary paleobathymetric trends were reconstructed for the well site area mainly on the basis of Q-mode cluster analysis of benthic foraminiferal faunas. Deposition of the mid-Quaternary sequence began in the upper bathyal zone and a steady shallowing followed through outer shelf environments to the present-day inner neritic zone. Other paleo-depth indicators such as abundance variations of nannoplankton *Florisphaera profunda* and planktonic versus total foraminifera ratios, and variations of ¹³C isotope record are all supportive of this benthic foraminifera-based depth-trend.

Paleotemperature fluctuations were estimated by analyzing oxygen isotope compositions of benthic and planktonic foraminifera and by calculating with the aid of paleoecological transfer functions quantitative estimates of past winter temperatures. The paleotemperature fluctuations estimated for the well site area by these two methods agree well for the lower part of the well sequence, but begin to diverge from the mid-sequence and upwards, probably reflecting increasing effects of local water masses to the oxygen isotope variation. In the Quaternary isotope record of Kashima SK-1 well, no definite interval correlatable with the even-numbered isotope stages was observed. In view of the fact that distinct hiatuses occur in the onshore Quaternary record of Kanto District located to the west of the well site, the lack of even-numbered isotope stages is interpreted to signify periods of greatly reduced sedimentation or possibly non-deposition in a broad coastal region encompassing also the continental shelf around the well site. Mid-Quaternary paleoceanography around the well site prior to about 0.35 Ma was under the general influence of cold Oyashio Current with its strength varying greatly from time to time, whereas the latter time period responding to the diminishing Oyashio Current saw a seesaw game of two warm currents, Kuroshio and Tsugaru, expanding and retreating alternatively over a broad region of the sea off Northeast Honshu, Japan.

Key words: Mid-Quaternary, paleoenvironment, near-shore waters, microfossils, mineral content, oxygen isotope, carbon isotope, transfer functions, Ibaraki Prefecture.

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INTRODUCTION

The Quaternary Period is characterized by a remarkable change in global climate with severe glacial modes alternating with more ameliorative interglacial modes. Seas off the coast of North-east Honshu, Japan, where the northward-flowing warm Kuroshio Current meets the southward-flowing cold Oyashio Current, are ideally suited for examining the extent of oceanographic changes responding to the waxing and waning of these two extreme climatic conditions. Compared with a large amount of data available on latest Pleistocene and Holocene paleoenvironments of Japan and its marginal sea, few detailed mid-Pleistocene records exist.

This paper presents a combined paleontologic and mineralogic stratigraphy for middle-upper Pleistocene sediments of the near-shore western Pacific and relates it to a paleoceanographic record as inferred from carbon and oxygen isotopic and faunal methods. In order to elucidate long-range oceanographic changes, a longest possible record of sedimentation is desirable so that changing environments can be reconstructed nearly continuously against a fixed time scale. Our search for a suitable sediment core among various core collections in Japan did not produce any core long enough to penetrate mid-Quaternary sediments, owing to a very high Quaternary sedimentation rate in seas around the Japanese Islands (as high as 230 m/m.y. -Boggs, 1984). We therefore selected, as the next best material, cuttings from "Kashima-oki SK-1 well" (hereafter referred to as Kashima SK-1 well), drilled by Japan Petroleum Exploration Company (JAPEX). This well, sank to the total subbottom depth of 2100 m, is located at 36° 9' 33.8" N., 140° 43' 49.3" E. in the western margin of the Pacific, in the sea

locally known as "Kashima-nada," 13 km off the coast of Kashima, Ibaraki Prefecture, Kanto District, Japan (Fig. 1). The Japanese word "-nada" refers to an open sea prevailed frequently by strong winds and large waves. The well site is in water 38 m deep, and the drilling work was directed from a platform standing at 28 m above sea level. JAPEX labelled all the cuttings of this well from this platform downward; a 66 m-sample is in reality a sea floor sample and 100 m-depth sample comes from a 34 m-subbottom depth. To avoid any undue confusion in regard to sample depth by future workers, this JAPEX system of sample depth designation is adopted in this paper. Preliminary investigation of Maiya, Inoue, and Akiba (1981) showed that the boundary between the Tertiary and Quaternary occurs between 460 m and 470 m depth samples. We therefore sampled well sections from 66 m (sea floor) to 280 m well depth at 5 m-interval and thereafter every 10 m-interval down to the depth of 500 m.

Considerable efforts were expended to date as many horizons as possible in the SK-1 Quaternary sequence by identifying calcareous nannoplankton events which have been calibrated against the absolute time scale. Secondly, sediments were subjected to sedimentological and mineralogical analyses and contained microfossils, including calcareous nannoplankton and benthic and planktonic foraminifera, were examined to establish a paleontological data base with which oceanographic variations during mid-Quaternary times can be interpreted as detailed as possible. In order to reconstruct fluctuations in surface water temperatures and salinities, multiple regression analyses were performed between modern oceano-

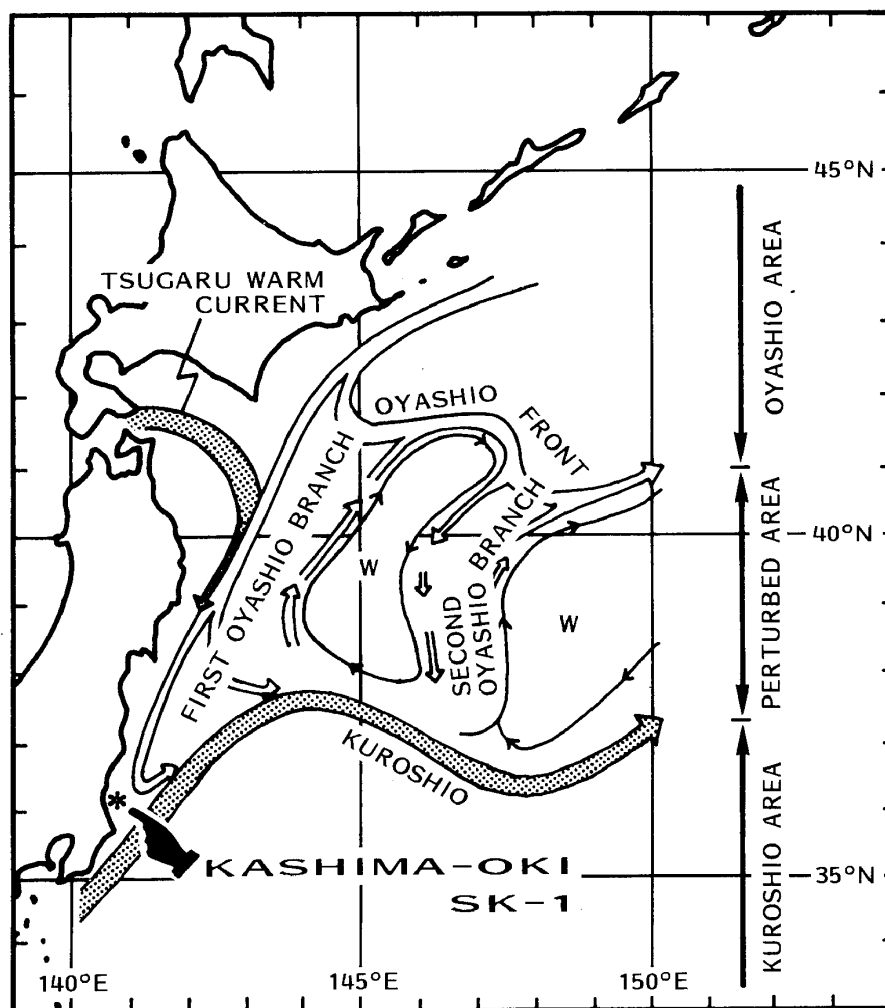


Fig. 1. Location map illustrating the site of Kashima-oki SK-1 well, major current systems and generalized distribution of surface water masses in the sea off Northeast Honshu, Japan. W: areas dominated by warm water masses within the perturbed area. (Modified after Masuzawa (1957) and Kawai (1972)).

graphic data and paleontologic data set derived from Q-mode principal components factor analyses of sea-floor-surface-sediment assemblages of planktonic foraminifera from seas off the coast of Northeast Honshu, Japan. Stable carbon and oxygen isotope compositions of benthic and planktonic foraminifera

were also measured to unravel temporal fluctuations in the nature of bottom and surface waters. All of these lines of investigation are combined to produce a paleoceanographic synthesis from middle Quaternary time onward for the near-shore region of the northwestern Pacific off the coast of Northeast Honshu, Japan.

ACKNOWLEDGEMENTS

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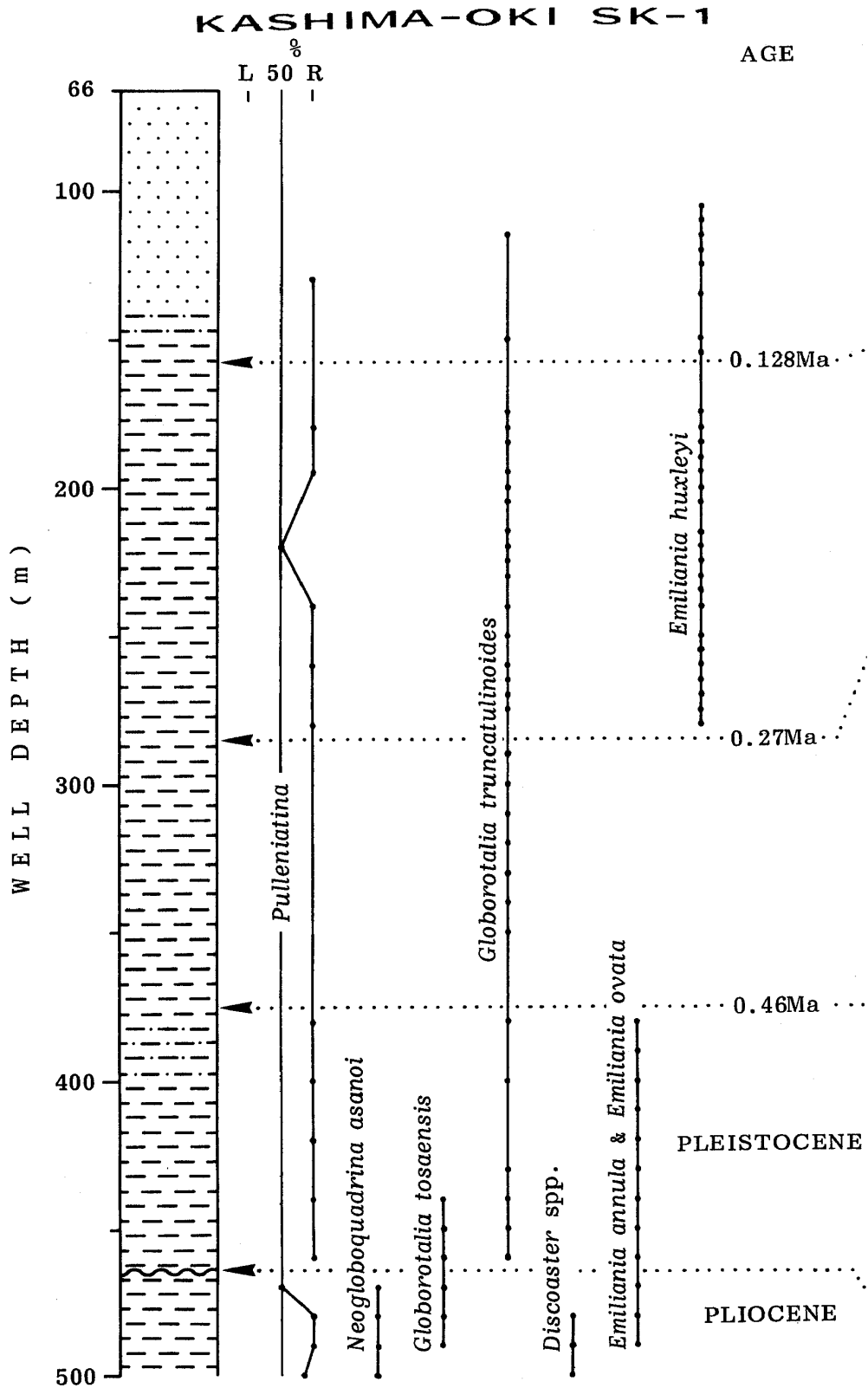
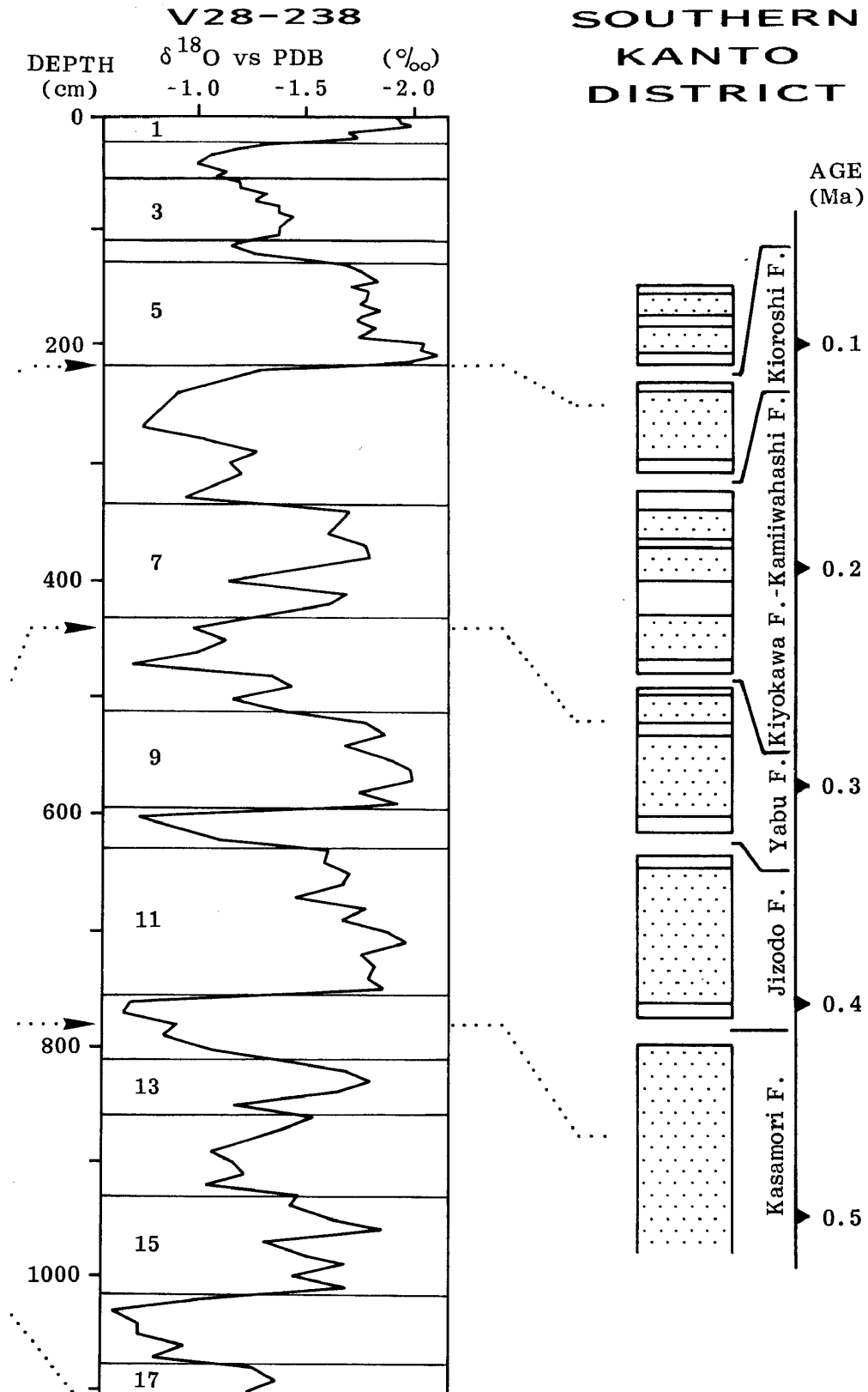


Fig. 2. Lithologic succession of Kashima SK-1 well, stratigraphic distribution of selected species of with oxygen isotope stages and on-shore Quaternary sequence of Kanto District, central Japan. levels (0.46 and 0.27 Ma) and marked shift of oxygen isotope values which is interpreted as that Shackleton and Opdyke (1973).



planktonic foraminifera and calcareous nannoplankton, and correlation of the well sequence. Note that correlation is established largely on the basis of two calcareous nannoplankton datum corresponding to the Stage 5 (0.128 Ma). Oxygen isotope stratigraphy of V 28-238 follows

of this well and who also made numerous helpful suggestions. We are particularly grateful to the following authorities for providing us with sea-floor-surface sediment samples from seas off the coast of Northeast Honshu, Japan: Geological Institute, University of Tokyo; Geological Survey of Japan; Institute of Geosciences, Shizuoka University; and Hydrographic Department, Maritime

Safety Agency of Japan.

Necessary computation was made through NEAC-ACOS model 700 computer in the Tohoku University Computer Center.

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BIOSTRATIGRAPHY OF KASHIMA-OKI SK-1 WELL

Biostratigraphic studies of planktonic microfossils during the past decades have established a high-resolution stratigraphic record which would allow resolution of time down to 100,000 years in low-to-mid-latitude Quaternary sequences (Berggren et al., 1980). To establish time lines for the Quaternary sequence recovered from SK-1 well and to define any meaningful pattern of sedimentation and paleoenvironmental changes, we examined the stratigraphic distribution of planktonic microfossils. Such calcareous microfossils as planktonic foraminifera and calcareous nannoplankton are well represented in the SK-1 well sequence, whereas siliceous microfossils including diatoms and Radiolaria are only rarely encountered (Fig. 2).

The calcareous nannoplankton biostratigraphy gives three datum levels for which absolute dates are available through calibration with magnetic-reversal or oxygen-isotope time scales. These are: (a) the latest occurrence of all species belonging to the genus *Discoaster* at 480 m well depth; (b) the latest occurrence of both *Emiliana annula* and *E. ovata* at 380 m well depth (some reworked specimens of the latter species occur up to 340 m depth); and (c) the first appearance of *Emiliana huxleyi* at 280 m depth. The extinction datum of the genus *Discoaster* has been determined to occur at 1.77 Ma (Berggren

et al., 1980), thus establishing a Tertiary age for the well section below 480 m well depth. Thierstein et al. (1977) dated precisely the global extinction level of *Pseudoemiliana lacunosa* relative to oxygen-isotope time scales. According to Bukry (1973, p. 678), *P. lacunosa* of authors actually comprises two different taxa, *annula* and *ovata*, which should really be classified under the genus *Emiliana* insofar as the genus *Pseudoemiliana* is taxonomically invalid. Notwithstanding this taxonomic revision, the stratigraphic importance of "*P. lacunosa*" of authors (= *E. annula* and *E. ovata* of this paper) is still valid with its extinction level establishing the date of 0.46 Ma. The global synchronicity of the first appearance datum of *Emiliana huxleyi* has been established at 0.275 Ma also by Thierstein et al. (1977).

Planktonic foraminifera provide three datum levels: (a) the latest occurrence of *Neogloboquadrina asanoi* at 470 m well depth; (b) the first appearance of *Globorotalia truncatulinoides* at 460 m well depth; and (c) the latest occurrence of *Globorotalia tosaensis* at 440 m well depth.

Since *G. truncatulinoides* is known to first appear near the beginning of the Pleistocene (Haq et al., 1977), its occurrence in the well section above 460 m depth establishes a correlation of that part of the section with the Quaternary. Biostratigraphic studies in Japan have

shown that there is a brief overlapping of ranges of *G. truncatulinoides* and *N. asanoi* which is a Pliocene species (Oda, 1979). The non-overlapping ranges of these two species in SK-1 well appear to suggest that this overlapping interval is missing due to the presence of a hiatus in which the Tertiary sequence is unconformably overlain by Quaternary sediments. By correlating the well section with late Cenozoic sequences of the nearby Boso Peninsula, the time gap represented by the hiatus is estimated to span at minimum from the Olduvai Subchron of Matuyama Polarity Chron (1.67–1.87 Ma) to the Jaramillo Subchron (0.92–0.97 Ma). Since 380 m depth level is as young as 0.46 Ma, however, the hiatus could extend up to the beginning

of Brunhes Chron with the entire Quaternary sequence of SK-1 well being a Brunhes Chron age younger than 0.73 Ma.

If we rely on the pattern of coiling direction changes of *Pulleniatina* for correlation, an upward transition from the dominantly dextral to somewhat random coiling populations between 570 and 580 m depth may equate this level with the level L8 coiling-direction change of Saito (1977). If this is the case, a late Pliocene interval corresponding to the lower Matuyama Polarity Chronozone must also be missing at the unconformity. These planktonic foraminiferal age estimates do not contradict dates suggested by the nanofossil evidence.

SEDIMENTOLOGY

Samples were studied sedimentologically and mineralogically by using several analytical techniques. First, a smear slide of sediment sample is made for all the sampling depths and thin section is made when indurated rocks were encountered. The smear slide and thin section were examined by using a polarizing microscope. Pelitic samples are subjected to X-ray diffraction analysis, differential thermal analysis and electron microscopic examination for the identification of clay mineralogy.

Down to 90 m well depth, sediments consist largely of coarse-grained sands bearing some granules and the section below that depth is largely composed of pelitic sediments. The upper part (90–175 m) of this pelitic sedimentary sequence occasionally contains grains of coarse-grained sand and granule. Stratigraphic variations in the abundance of principal clay mineral constituents are shown in Fig. 3 for the sequence below 175 m well depth. Some of the more significant characteristics of Quaternary sediments of SK-1 well include the fol-

lowing:

(1) Stratigraphic variations in the abundance of quartz and plagioclase show a similar trend and minimum values occur between 360 and 420 m well depth. Generally, the amount of quartz tends to increase toward shallower well depth. High peaks in the proportions of plagioclase to quartz possibly reflect active island arc volcanisms at the time of deposition.

(2) The clay mineral composition is characterized as a whole by chlorite, illite, smectite and mixed-layer derivatives. Among these minerals, mixed-layer derivatives are restricted to well depths shallower than 300 m. The clay minerals that occur most commonly are chlorite and illite, and they together with smectite are weathering products of rocks exposed on land.

The absence of kaolinite is noteworthy. Kaolinite is a product of chemical weathering under warm and humid climates in the tropics and is dispersed in the ocean by surficial currents (Aoki, 1976). In Shikoku Basin,

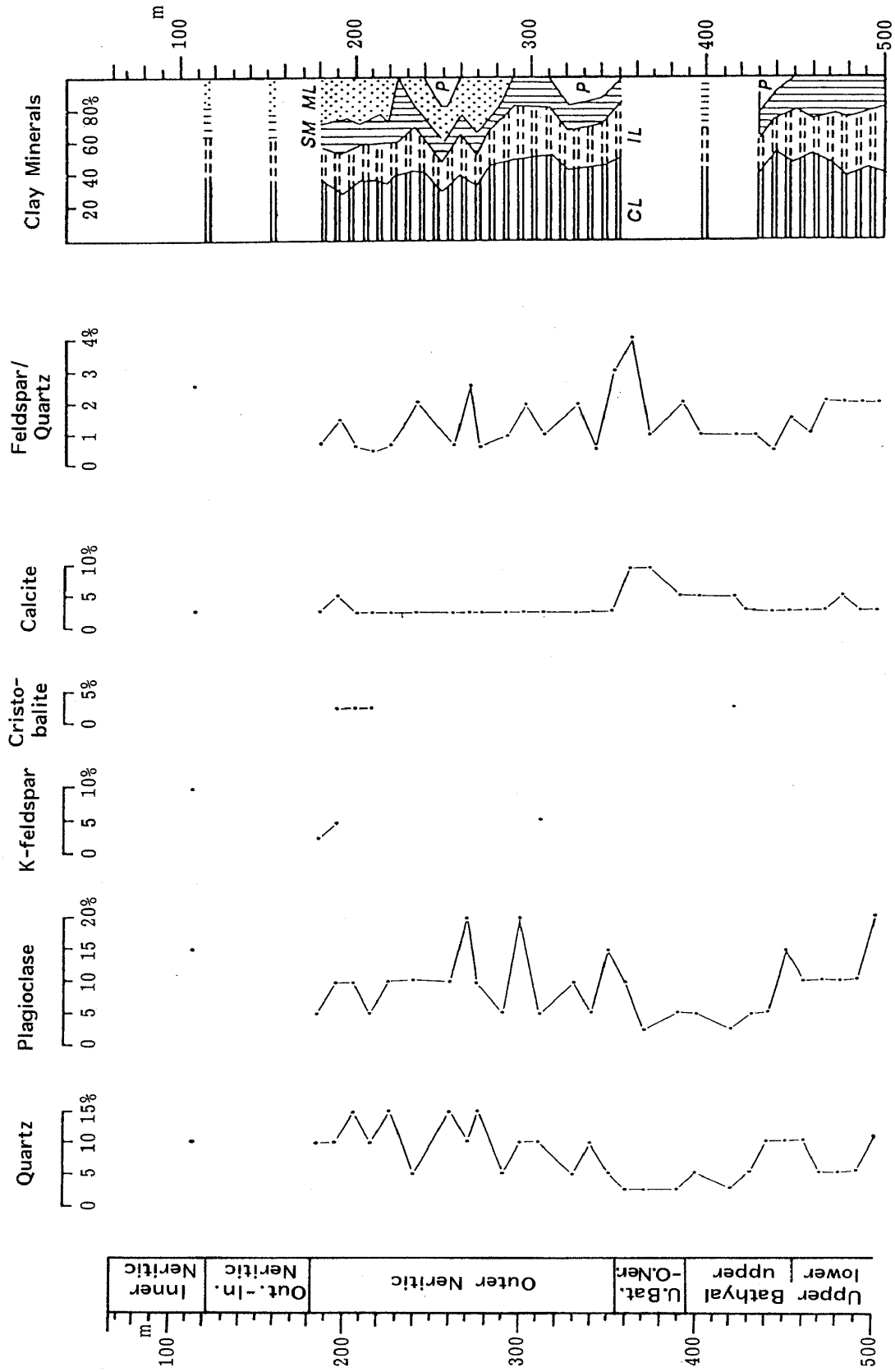


Fig. 3. Percentage changes with depth of principal clay minerals and other major mineral constituents in the Kashima SK-1 well sequence. Data are plotted against paleoenvironmental trends as interpreted from benthic foraminiferal analyses.

off the coast of southwestern Japan, the kaolinite content decreases from southwest to northeast along the course of Kuroshio Current (Chamley, 1980). In the Kashima-nada region, kaolinite was not deposited owing to the existence of a barrier island to the south of the area. This barrier island which later evolved to be the present-day Boso Peninsula formed a remarkably effective deterrent to the northward flow of the major part of warm Kuroshio Current that would carry kaolinite across and over the

Kashima-nada region.

(3) An interval between 360 and 420 m well depth forms a mineralogically distinct horizon. Quartz, plagioclase as well as clay minerals are practically absent there and, instead, the sequence is dominated by calcite possibly derived from foraminifera and calcareous nannoplankton. This mineral composition is interpreted to indicate a period of high organic productivity coupled with a greatly reduced supply of terrigenous materials.

BENTHIC FORAMINIFERA

Samples were disaggregated by sequentially applying two types of rock maceration techniques, one with Glauber's salt (Na_2SO_4) and the other with petroleum solvent called Varsol or naphtha. The former maceration technique is described in detail by Kirchner (1958) and the latter with petroleum solvent by Maiya and Inoue (1973) and Saito (1985).

For total faunal analyses, the $>74 \mu\text{m}$ fraction of each washed sample residue was repeatedly divided by a micro-splitter to obtain an aliquot of at least 300 foraminiferal specimens. In these aliquots, abundance counts of planktonic and benthic foraminifera were made, and planktonic versus total foraminiferal specimen ratio was calculated for each sample (Fig. 4). With the exception of the shallowest well-depth sample (75 m) which was barren of foraminifera, all the samples yielded foraminifera. Particularly, samples from well depth deeper than 95 m yielded sufficient numbers of foraminifera for statistical treatment of the assemblage. A total of 229 species belonging to 113 genera were enumerated. The stratigraphic distribution of abundance variations of important benthic taxa and of planktonic/total foraminiferal specimen ratios (P/T ratio) are shown in Fig. 4.

Benthic foraminifera are known to

have a broad distribution from embayment to abyssal depths, but their abundance is greatest in shallow waters and decreases beyond the edge of the continental shelf (Walton, 1955). On the other hand, planktonic foraminifera live principally in the surficial layers of the open ocean and their numbers in bottom sediments generally increase with depth and distance away from the shore. Thus, the ratio between the number of planktonic specimens and the number of total foraminifera in a given sample gives a measure of water depth (Grimsdale and Morkhoven, 1955). In SK-1 well, the P/T ratio tends to decrease upwards in the well sequence. The ratio is about 70% between 380 and 500 m well depth, about 50% between 190 and 370 m depth except for part of the section where it drops to 30%, and about 20% between 100 and 190 m depth.

Distinct changes are also recognizable in the benthic faunal composition (species composition and their abundance) which shows a trend similar to that demonstrated by the P/T ratio changes. Paleocological significance of the 56 assemblages between 100 and 500 m well depth is interpreted by recognizing major and minor assemblages with the help of Q-mode cluster analysis of the raw census data of abundances of 110

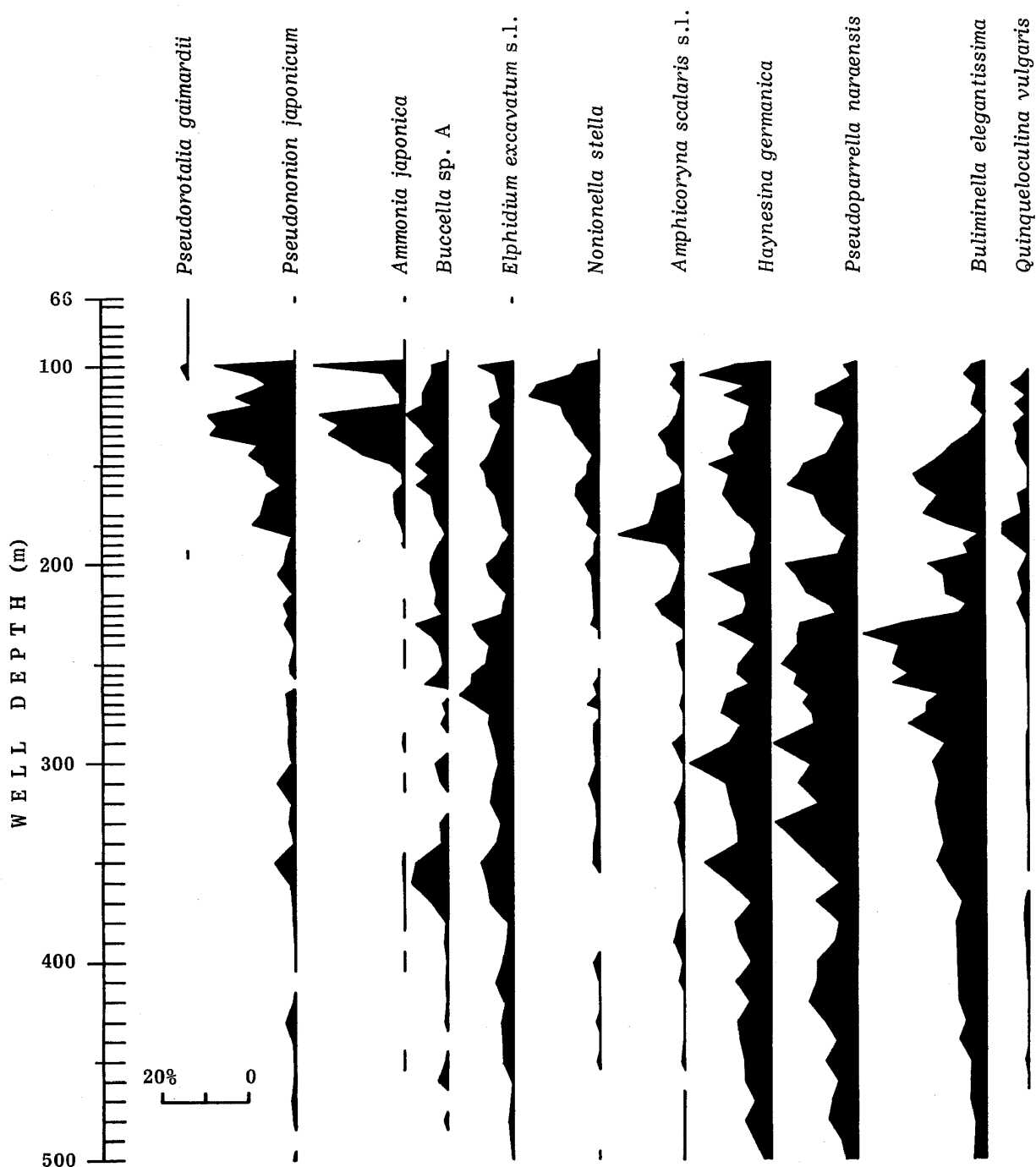
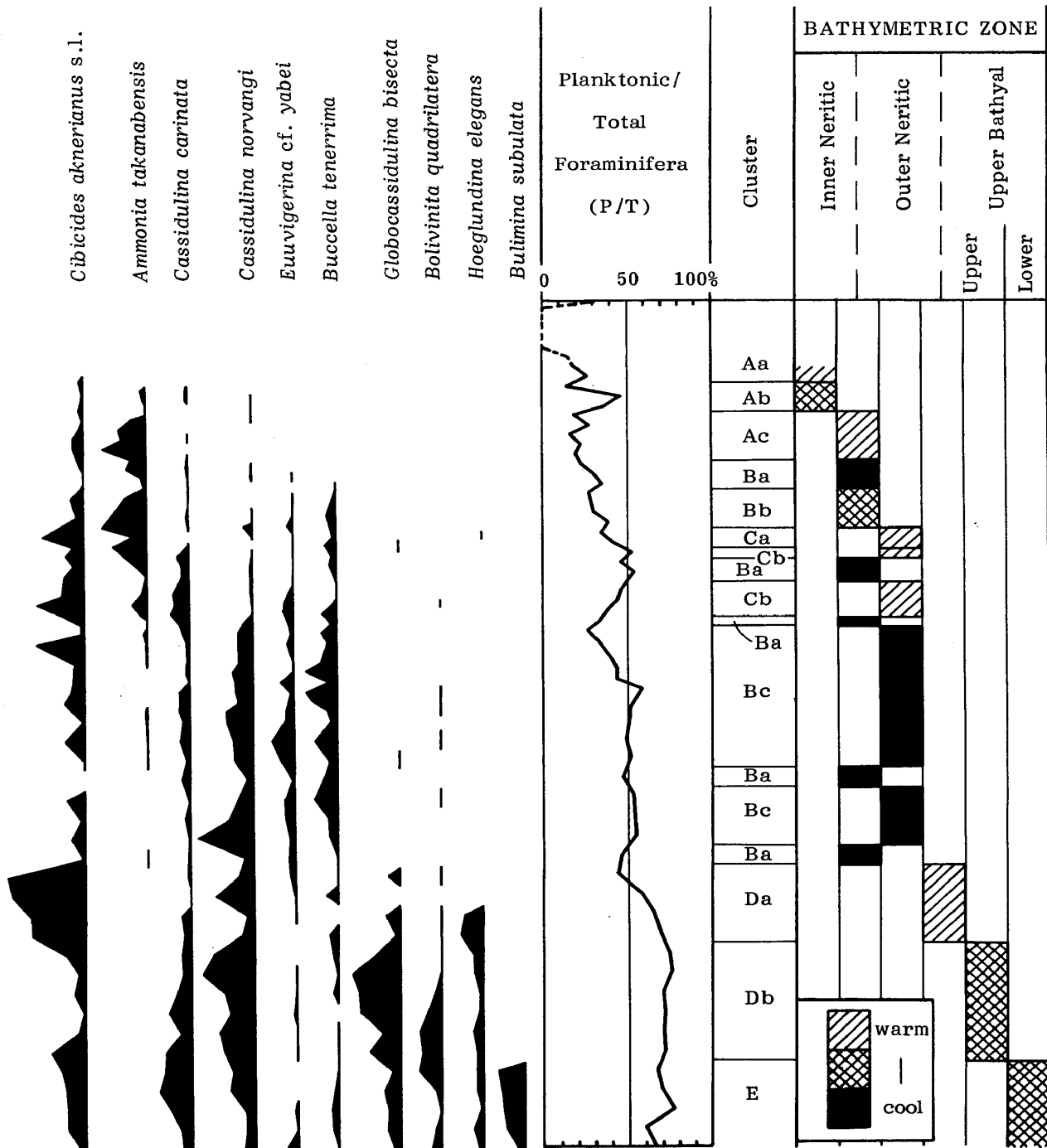


Fig. 4. Frequency distribution of depth-index species, planktonic versus total foraminifera (P/T) clustered groups of depth-index species.

relatively common taxa. For a similarity index, Horn's index of overlap (Horn, 1966) is adopted. The analysis was performed by using the weighted pair group method with simple arithmetic averages. This analysis yielded

five clusters, A-E, and A to D clusters were further divided into two or three subclusters (Table 1). The present-day environmental data of those species whose fossil counterparts characterize these clustered assemblages are used to



ratios, and paleo-bathymetric interpretation for the Kashima SK-1 well site on the basis of five

reconstruct depositional environment for each cluster group (Fig. 4; Table 1).

These data reveal the following paleo-depositional trend for the SK-1 well section: Between 400 and 500 m, sediments were laid in the upper bathyal

zone of the upper continental slope environment. An ecologic change to a shallower, outer shelf environment must have taken place between 360 and 400 m well depth. Further shallowing occurred between 130 and 180 m well

Table 1. Five major and 10 subordinate clustered groups of benthic foraminifera which are used to interpret paleobathymetry of the Kashima SK-1 well site. Dominant and subordinately dominant species for each clustered group are enumerated. The column "Distribution" indicates those depth intervals in which particular clustered groups occur. Bottom water temperature trends and bathymetric zones indicated by each clustered group are also shown in the two right-hand columns.

CLUSTER	DOMINANT SPECIES	SUBORDINATE SPECIES	DISTRIBUTION	TEMPERATURE	BATHYMETRIC ZONE
Aa	<i>Pseudononion japonicum</i>	<i>Buccella</i> sp. A	100-105 m	warmer	inner neritic
	<i>Ammonia japonica</i>	<i>Porosotalia makoyamai</i>			
	<i>Hayesina germanica</i>	<i>Pseudosotalia gaimardii</i>			
Ab	<i>Nonionella stella</i>	<i>Buccella</i> sp. A	110-120 m	cooler	inner neritic
	<i>Pseudoparrella naraensis</i>	<i>Murrayinella takayanagi</i>			
		<i>Pseudoparrella tamana</i>			
Ac	<i>Pseudononion japonicum</i>	<i>Ammonia takanabensis</i>	125-145 m	warmer	inner (to outer) neritic
	<i>Ammonia japonica</i>	<i>Buccella</i> sp. A			
		<i>Amphicoryna scalaris</i>			
Ba	<i>Buliminella elegantissima</i>	<i>Elphidium excavatum</i> s.l.	150-160,	cooler	(inner to) outer neritic
	<i>Pseudoparrella naraensis</i>	<i>Buccella</i> sp. A	200-205,		
	<i>Hayesina germanica</i>	<i>Pseudononion japonicum</i>	230, 310, 350 m		
	<i>Buliminella elegantissima</i>	<i>Pseudoparrella naraensis</i>	165-180 m	cooler	(inner to) outer neritic
	<i>Pseudononion japonicum</i>	<i>Hayesina germanica</i>			
Bb	<i>Ammonia takanabensis</i>	<i>Amphicoryna scalaris</i>			
	<i>Buliminella elegantissima</i>	<i>Hayesina germanica</i>	235-300,	cold	outer neritic
	<i>Pseudoparrella naraensis</i>	<i>Buccella tenerima</i>	320-340 m		
	<i>Euvigera</i> cf. <i>yabei</i>				
Ca	<i>Amphicoryna scalaris</i>	<i>Cibicides aknerianus</i> s.l.	185-190 m	warmer	outer neritic
		<i>Ammonia takanabensis</i>			
		<i>Quinqueloculina vulgaris</i>			
		<i>Buliminella elegantissima</i>	195,	warmer	outer neritic
	<i>Hayesina germanica</i>	215-225 m			
	<i>Amphicoryna scalaris</i>				
Da	<i>Cibicides aknerianus</i>	<i>Pseudoparrella naraensis</i>	360-390 m	warmer	outer neritic to upper bathyal
	<i>Hayesina germanica</i>	<i>Cassidulina norvangi</i>			
	<i>Buliminella elegantissima</i>	<i>Hoeglundina elegans</i>			
	<i>Cassidulina norcrossi</i>	<i>Buliminella elegantissima</i>	400-450 m	cooler	upper bathyal (upper part)
Db	<i>Pseudoparrella naraensis</i>	<i>Cassidulina carinata</i>			
	<i>Globocassidulina bisecta</i>	<i>Bolivinita quadrilatera</i>			
	<i>Bulimina subulata</i>	<i>Cassidulina carinata</i>	460-500 m	cooler	upper bathyal (lower part)
E	<i>Pseudoparrella naraensis</i>	<i>Hayesina germanica</i>			
		<i>Cassidulina norvangi</i>			

depth. Above 125 m well depth, the site reached water depths of the inner neritic zone which characterizes the well site today. Temperature regimes indicated by the benthic foraminifera appear to have been nearly the same as those of today with water-masses bearing a mixed nature of both the warm Kuroshio and cold Oyashio Currents influencing the region of well site. A close scrutiny,

however, reveals minor fluctuations in temperature. There is a warming trend from 500 to 360 m well depth, which corresponds to the shoaling trend of depositional depth. Cold waters prevailed between 350 and 230 m and somewhat frequent temperature fluctuations characterized the uppermost section.

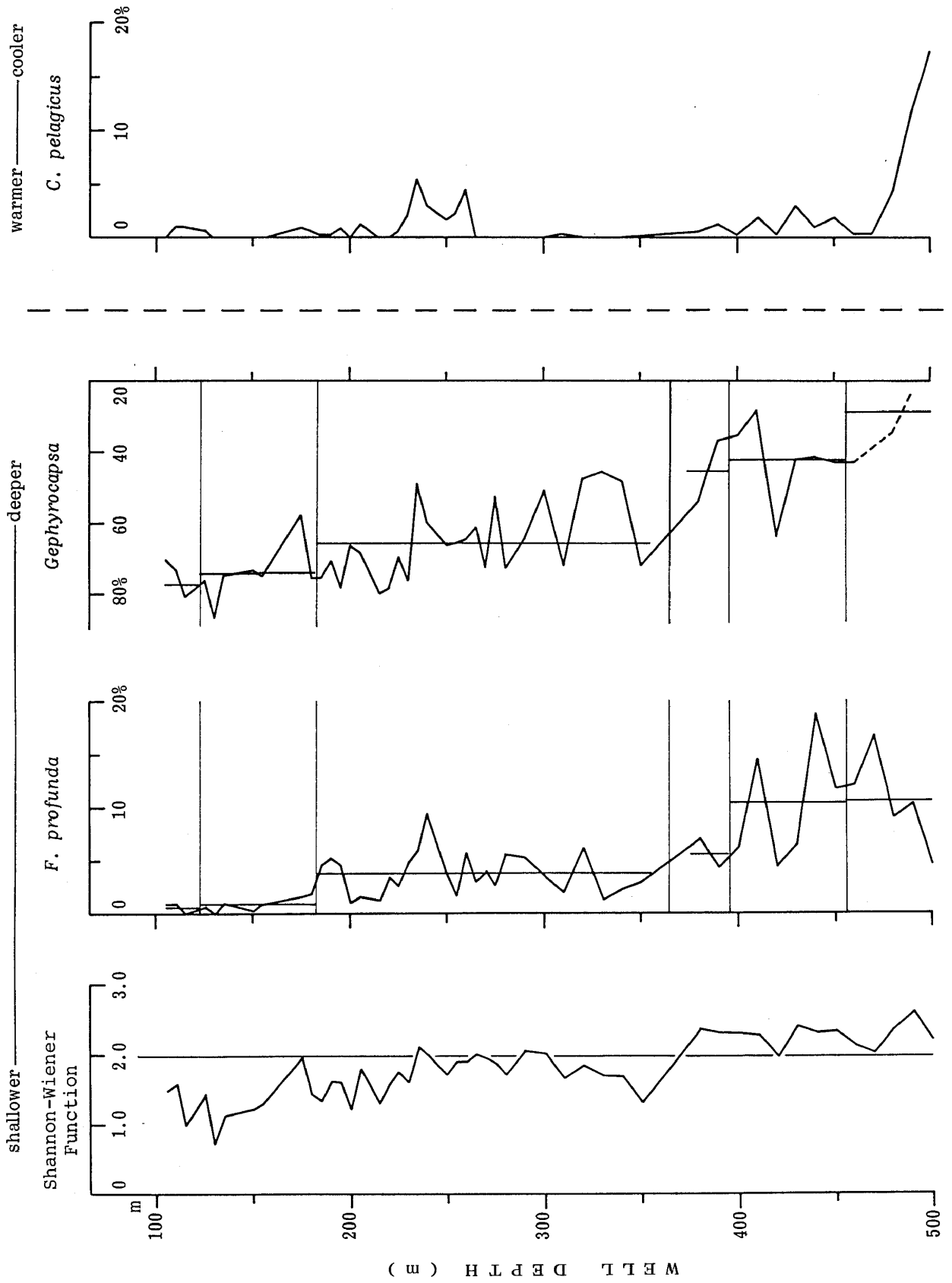
CALCAREOUS NANNOPLANKTON

Three-hundred specimens larger than 3–4 μm are identified for each sample to determine nannofossil assemblages by examining a smear slide under a light microscope. Other age-diagnostic or environmentally restricted species which are smaller than 3 μm are examined taxonomically by using an electron microscope. Of 55 samples examined between 105 and 500 m well depth, 48 yielded common and well-preserved nannofloras.

Diversities of the nannofossil communities consisting of 21 genera and 34 species are expressed by the Shannon-Wiener information function (DH), which was calculated with the method described by Berger and Parker (1970). These community diversities and stratigraphic variations in relative abundances of *Florisphaera profunda* Okada and Honjo, species of the genus *Gephyrocapsa*, and *Coccolithus pelagicus* (Wallich) Shiller are shown in Fig. 5. The Shannon-Wiener information function is influenced by both the number of species and the evenness of their distribution within a given sample. As can be seen in Fig. 5, the spectrum of diversity change among 48 samples with well depth shows an increasing trend with increasing depositional depths that are determined on the basis of the P/T foraminiferal ratio and the compositional change in benthic foraminiferal assemblages.

Modern *Florisphaera profunda* is restricted to the lower part of the euphotic zone, usually below 100 m water depth, of the equatorial to transitional zones and its abundance in sediments shows a positive correlation with increasing water depths (Okada, 1983). On the other hand, species of *Gephyrocapsa*, common elements in the SK-1 well floras, inhabit abundantly coastal waters where other oceanic species tend to diminish. Thus, they also provide an indirect measure of water depth. Abundance fluctuation curves of *F. profunda* and species of *Gephyrocapsa* with well depth are illustrated in Fig. 5 and overlaid on the curves are vertical reference lines showing simple arithmetic averages of abundance values within each interval corresponding to one bathymetric zone defined by benthic foraminifera. Comparison of these two abundance curves marked by the arithmetic average reference lines clearly demonstrates a negative correlation between these two species groups. The paleo-depth trend revealed by these abundance curves is concordant with the trend shown by the information function (Fig. 5).

Coccolithus pelagicus is a cold-water species, but this rather rare species in the Quaternary section of SK-1 well shows little variation except for its brief increased abundance between 230 and 260 m well depth.



PLANKTONIC FORAMINIFERA

The "transfer functions" introduced by Imbrie and Kipp (1971), initially by taking advantage of extensively available fossil planktonic foraminiferal data from deep-sea sediment cores, have become very important in Quaternary research as this technique provides calibrated quantitative estimates of some parameters of a past oceanic environment such as seasonal or monthly air or ocean-surface temperature. These functions are derived simply from the spatial correlations between modern oceanographic data (water temperature, salinity, etc.) and census data for bottom surface sediment assemblages of planktonic foraminifera.

These functions, however, have inherent geographic limits in their applicability because they are entirely based upon biotic and oceanographic parameters available from a given oceanic region which is geographically confined. In order to interpret paleoenvironmental changes as accurate as possible, it is necessary to select transfer functions which are applicable to the region in question. This is evident from the fact that, in most cases, several extracted factors which may differ greatly between various regions are assumed to explain a larger part of the variance of the data set for a given region. Therefore, prior to the analysis of planktonic foraminifera from Kashima SK-1 well, we attempted to formulate our own new multiple regression equations pertinent to the sea off

Northeast Honshu, Japan, by taking steps as shown in the flow chart (Fig. 6: Takayanagi et al., 1985).

(1) Formulation of transfer functions

Among those various samples made available to the present study to examine surface-sediment assemblages of planktonic foraminifera in the sea off Northeast Honshu, Japan (Takayanagi and Oda, 1983), 42 stations yielding nearly 100 or more specimens were used for Q-mode principal components factor analysis (Imbrie and Purdy, 1962; Imbrie and Kipp, 1971). Species identified included 31 taxa and analysis was done with a data matrix consisting of 42 columns by 31 rows.

The calculated eigenvalues indicate that the first four factors account for more than 97 percent of the total variance (Oda et al., 1983). The distribution of the varimax factor loadings of the first four factors is depicted in Fig. 7, which clearly demonstrates that the first factor reflects the relative importance of the Tsugaru Warm Current. The second factor manifests the association with the Oyashio. The loadings of the third factor are high off Choshi, suggesting some plausible effects of the Kuroshio. In regard to the fourth factor loadings, no positive value is detected and only negative ones become apparent in the offshore area north of Choshi. The distribution of these fourth factor

Fig. 5. Variations with depth of four factors indicative of water depth and a general climatic trend for the well site. Both the Shannon-Wiener Function, species diversity indices, and the relative abundance of *Florisphaera profunda* Okada and Honjo are known to decrease in shallower waters, whereas *Gephyrocapsa* species tend to increase in coastal waters (Okada, 1983). Vertical lines in *F. profunda* and *Gephyrocapsa* abundance plots indicate their average abundances within each stratigraphic interval corresponding to different paleo-depositional depths that are determined by benthic foraminifera (see Fig. 4). The relative abundance of *Coccolithus pelagicus* (Wallich) Schiller is also known to increase generally in cooler waters, especially during the latter part of the Quaternary.

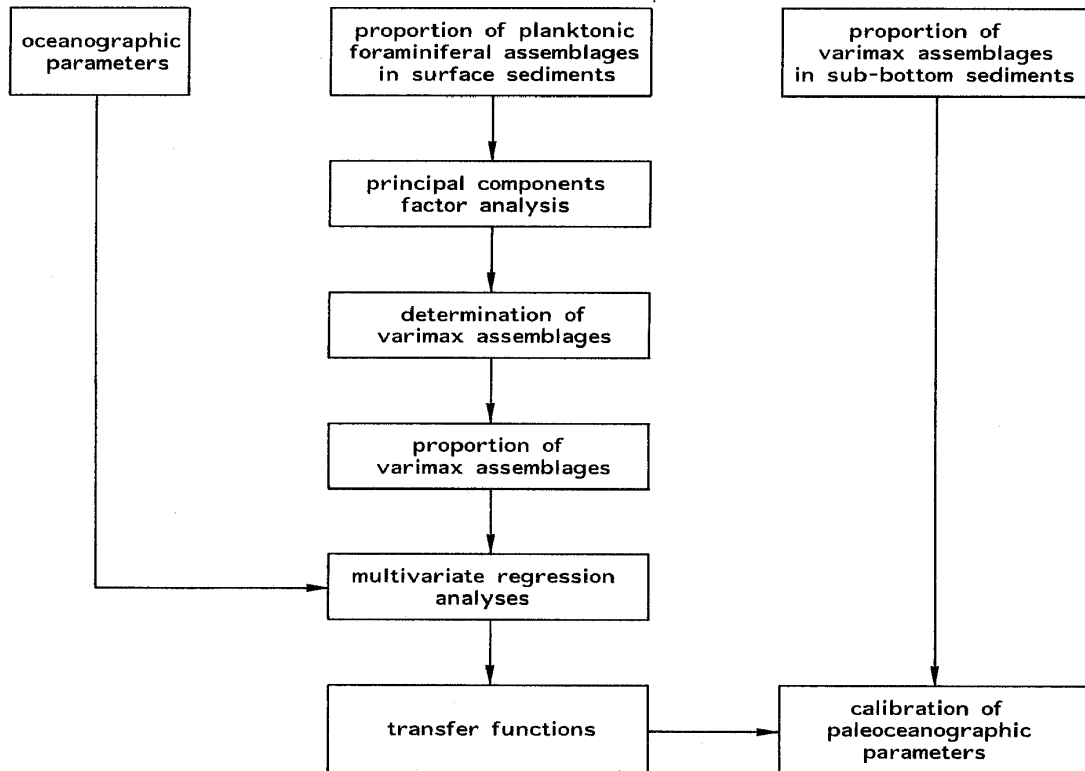


Fig. 6. Flow chart illustrating principal steps in transforming planktonic foraminiferal assemblage data in sea floor surface sediments into temperature or salinity estimates for sub-bottom sediment assemblages.

loadings suggests the degree to which conditions of a particular oceanic region are influenced by the closeness to land, for instance, increasing mixing with low-salinity waters.

By screening only those species which scored higher than 1.0 (not normalized), four varimax assemblages (end members for the first four factors) are determined. The first varimax assemblage is represented by only one species *Neogloboquadrina incompta*, and the second by the sinistrally coiling form of *Neogloboquadrina pachyderma*. In contrast to these two assemblages, the third varimax assemblage is composed of such a variety of species as *Globigerina bulloides*, *Globigerina quinqueloba*, *Globigerinoides ruber*, *Pulleniatina obliquiloculata*, and *Neogloboquadrina eggeri*. The fourth varimax assemblage is again represented by only one taxon *Neogloboquadrina eggeri*.

Multiple regression analyses were carried out between modern oceanographic data and the paleontologic data set. The oceanographic data include average water temperatures and salinities for both the summer and winter which are read from the marine environmental atlas compiled by the Japan Oceanographic Data Center (1978). The paleontological data set is the proportion of these four varimax assemblages in each faunal assemblage at 42 sample stations. The resultant multiple regression equations are generally called the transfer functions. The following equations give surface water temperatures and salinities in the winter:

$$\begin{aligned}
 Tw(0) &= 17.908 - 15.553 F_1^2 - 28.327 F_1 \cdot F_3 \\
 &\quad - 14.874 F_2^2 - 61.469 F_2 \cdot F_3 \\
 &\quad - 63.651 F_2 \cdot F_4 \\
 Sw(0) &= 34.718 + 1.854 F_2 - 1.421 F_1^2 \\
 &\quad - 3.341 F_1 \cdot F_3 - 3.578 F_2^2 \\
 &\quad - 10.037 F_2 \cdot F_3 - 10.669 F_2 \cdot F_4
 \end{aligned}$$

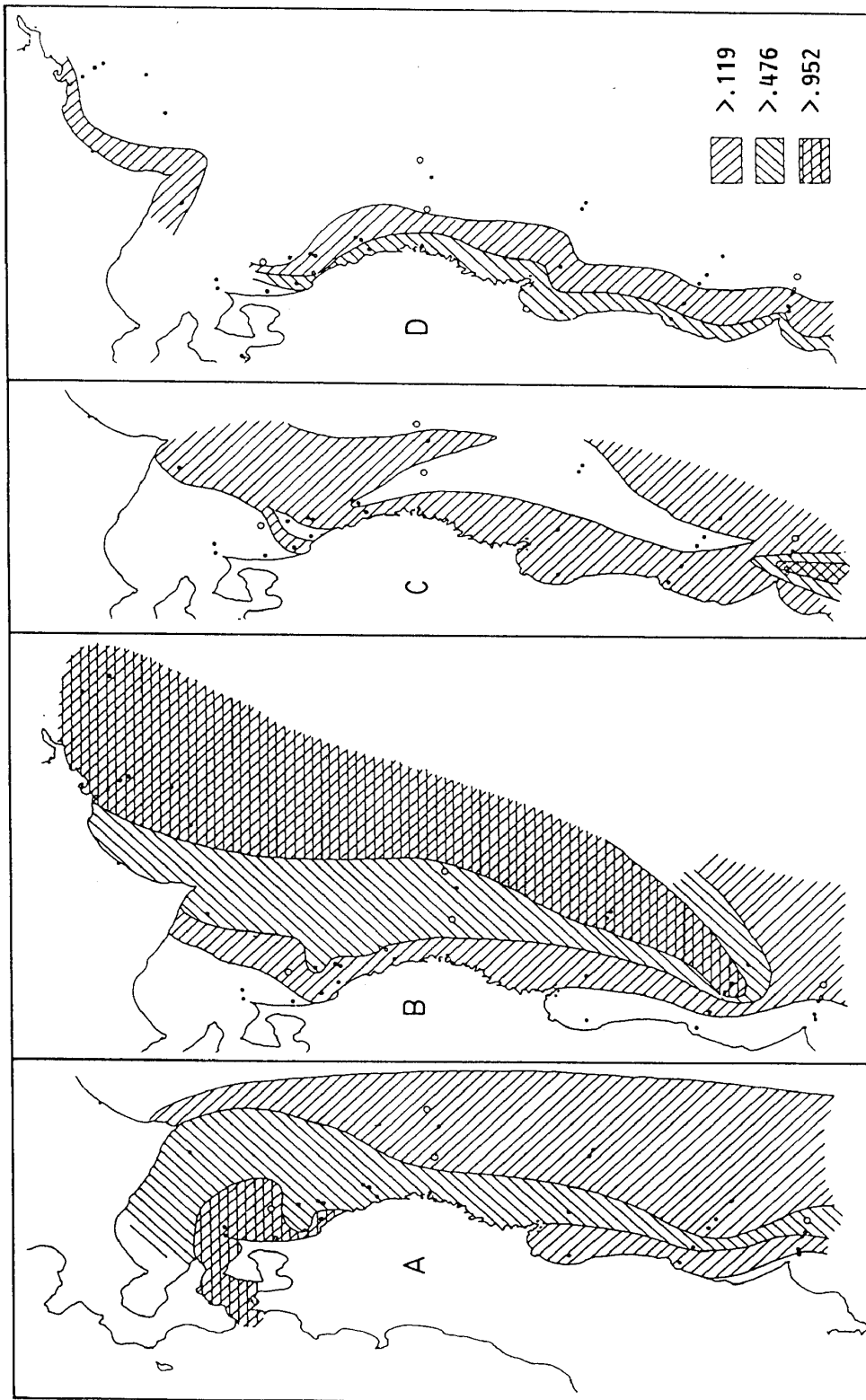


Fig. 7. Geographic distribution of the varimax factor loadings of the first four factors in the sea off Northeast Honshu, Japan, as derived from analyses of planktonic foraminifera from 42 core top samples. A : First factor ; B : Second factor ; C : Third factor ; D : Fourth factor. Note that A to C plot positive values, whereas D negative values.

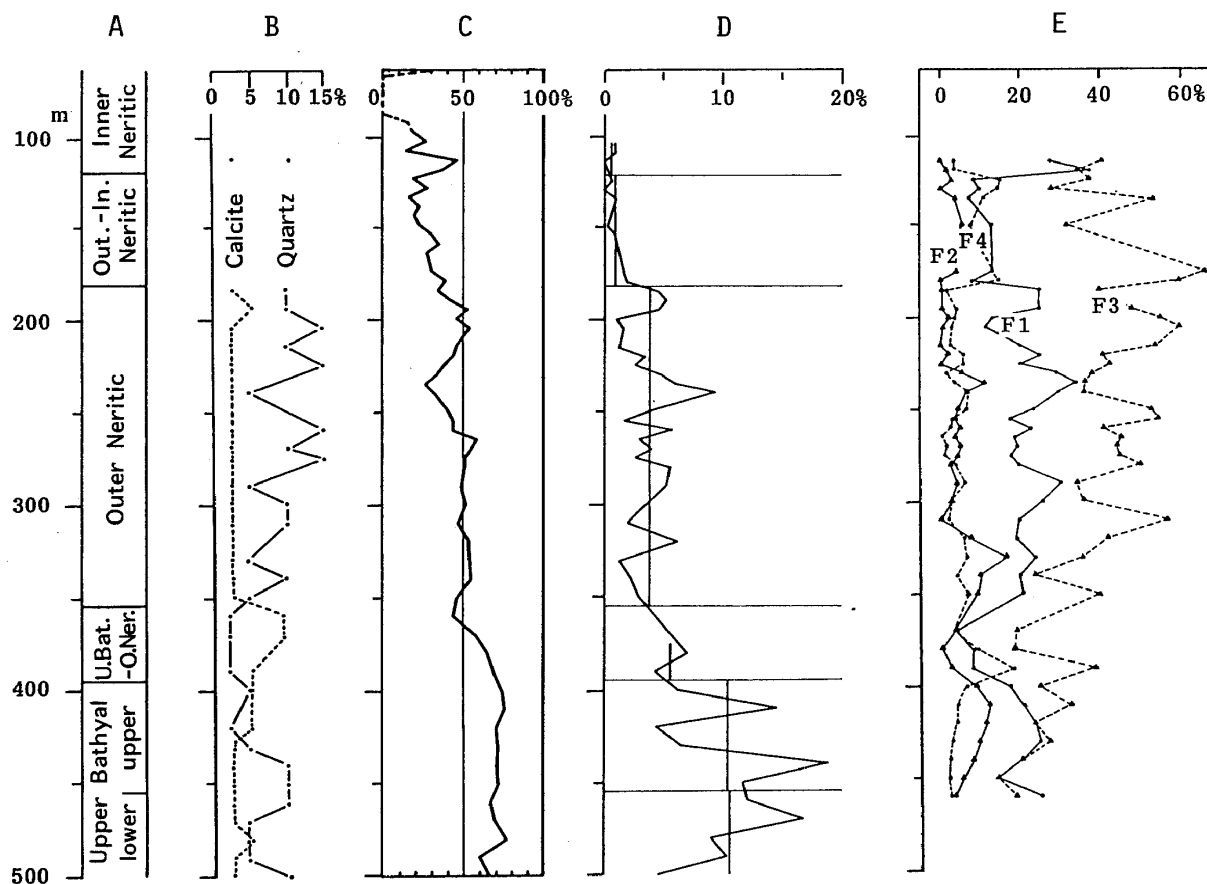


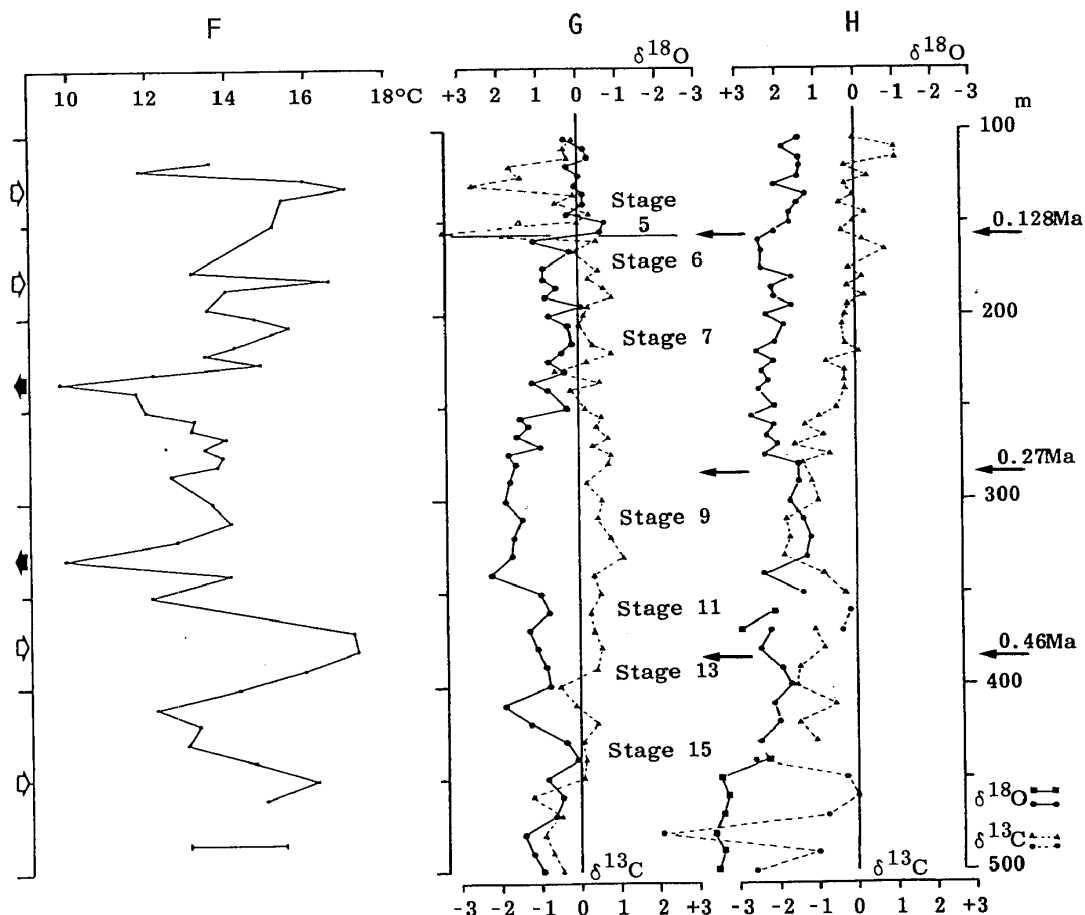
Fig. 8. Intercorrelation of stratigraphies determined by the mineralogical, floral and faunal, SK-1 well sequence. A: paleobathymetric trends of the well site based on biofacies analysis of C: planktonic versus total foraminifera ratios. D: relative abundance variations of calcareous lages. Vertical lines indicate average abundance of *F. profunda* within each stratigraphic E: percentage variations of four varimax factor assemblages, F_1 - F_4 . F: winter temperature functions. Filled-in arrows denote temperature minima and open arrows temperature maxima. (solid line) and carbon (dashed line) isotope record of the planktonic foraminifera *Globorotalia* indicated. H: Oxygen and carbon isotope record of the benthic foraminifera *Amphicoryna* (*Bolivinita quadrilatera*). In both G and H, isotopic composition is expressed as a deviation

(2) Kashima SK-1

Fluctuations in surface water temperatures and salinities back in time for the well section can be calibrated by the above-established equations, where F_1 to F_4 represent the proportion of the first four varimax assemblages (Fig. 8E). The data set used for these analyses is 42 sediment samples taken from well depths between 115 m and 460 m. Fluctuations for the winter only are depicted in Fig. 8F because of their showing wider amplitudes, although surface water

temperatures and salinities for the summer can also be obtained easily from the similar equations.

The rightness of these computed temperatures and salinities for a given geologic time can be examined by comparing the frequency distribution of each of the varimax assemblages because environmental conditions primarily control the frequency distributions (Fig. 8E). The most remarkable among the temporal fluctuations in assemblage compositions are those characterizing the upper section from the top to 330 m well



paleoecological transfer functions, and oxygen isotope methods for the upper 500 m of Kashima benthic foraminiferal faunas. B: percentage changes of calcite and quartz contents with depth. nanno-plankton *Florisphaera profunda* Okada and Honjo in calcareous nannoplankton assemblage interval corresponding to different paleoenvironments as determined by benthic foraminifera estimates (in degrees Centigrade) for surface waters made by the paleoecological transfer function. Horizontal bar shows standard error referring to analytical precision of index. G: oxygen *inflata* (d'Orbigny). Suggested correlation with the standard oxygen isotope stages is also *scalaris* (Batsch) with the exception of 360 m depth (*Cibicides aknerianus*) and 440-500 m depth per mil from the PDB standard.

depth, where the first and third varimax assemblages show an inverse correlation. That is, the first assemblage increases in frequency as the third assemblage decreases and when the third assemblage increases the first assemblage decreases.

The reason for this correlation is that changes in oceanographic conditions near the Kashima SK-1 well and its environs may have been caused by the countervailing effects of the Tsugaru Warm Current and the Kuroshio. The stronger the Kuroshio became, the less extended to the south the Tsugaru Warm

Current would be, and the more feeble the Kuroshio became, the farther extended to the south the Tsugaru Warm Current. The lack of observed evidence of such countervailing effects below 330 m well depth may indicate the prevalence at that time of a somewhat different oceanographic regime in which the influence of Oyashio fluctuated in much larger extent than that prevailed in the subsequent time period.

Of those four peaks of water temperatures indicated by open arrows in Fig. 8F, the upper two correspond to the peak

proportions of the third varimax assemblage and also to the decreased proportions of the first varimax assemblage. These observations suggest that the relative importance of the Tsugaru Warm Current was considerably reduced during such periods because of the stronger effects of the Kuroshio. Two troughs in the water temperature profile, marked by filled-in arrows in Fig. 8F, are interpreted as those time periods when the Oyashio had stronger influences. In contrast, the lower two peaks of water temperatures below 330 m well depth have no corresponding changes in the proportions of varimax assemblage, making them quite distinct from the upper two peaks which had an extraordinary high contribution of the third varimax assemblage.

It is noteworthy that the proportion of the second varimax assemblage fluctuates

in much greater amplitude below 330 m well depth in Kashima SK-1 well, and the two major peaks agree well with the two water temperature minima. In addition, there is a general increasing trend (=trend variation) in the proportion of the third varimax assemblage in upward sequence from the lowest sample to around the well depth of 170 m.

These observed fluctuation patterns in the proportion of the first four varimax assemblages may suggest that oceanographic conditions around Kashima SK-1 well site during the period earlier than 330 m well depth time was quite different from those developed later in that the earlier time period was strongly influenced by the Oyashio fluctuated in much larger extent, whereas the influence of the Kuroshio become stronger as time advanced.

OXYGEN AND CARBON STABLE ISOTOPE STRATIGRAPHY

The stable isotope composition of both planktonic and benthic foraminifera has become an increasingly valuable tool for paleoclimatic and paleoceanographic studies. They also have provided Quaternary geologists with a detailed global chronostratigraphic framework, because variations of oxygen isotope compositions of ocean waters are shown to be synchronous within the mixing time of world oceans (Shackleton and Opdyke, 1973). However, nearly all the isotopic studies published so far relied on sediment cores from deep-sea basins and few workers have examined isotopic records preserved in sedimentary sequences in waters less than 2000 m deep. In recent years, some isotopic analyses were done on cores taken from depths less than 2000 m in the seas around the Japanese Islands (for references see Chinzei and Oba, 1986).

The isotope record from the ocean margin sedimentary sequence of Ka-

shima SK-1 well is quite unique in that the area was influenced during the Quaternary by the most dynamic paleoceanographic processes including migrations of the Kuroshio-Oyashio front, eustatic sea-level fluctuations and varying rate of upwelling. Thus, such factors as the influence of coastal current, input of river waters, changing water depth of the sedimentary basin must be taken into account when interpreting isotope data. Furthermore, very little has been studied regarding the isotope composition of waters of the Oyashio Current since mid-Quaternary times.

As a tool for sea-surface temperature reconstruction in the Pleistocene, *Globigerinoides sacculifer* has been used extensively because this species lives predominantly in waters less than 50 m deep and yields the lowest $^{18}\text{O}/^{16}\text{O}$ ratios among modern planktonic foraminifera. This species is not abundant enough throughout the SK-1 well sequences

studied by us and we instead selected *Globorotalia inflata* (d'Orbigny). *G. inflata* is an extant species known to inhabit the deep-water (more than 100 m of water) environment below the mixed layer (Bé, 1977). This is a species indigenous to the transition zone between the Subtropical and Subpolar provinces, characterized by water temperature ranging from 10 to 18°C. Although there is about 2‰ separation between *G. sacculifer* and *G. inflata* $\delta^{18}\text{O}$ values reflecting the deep-water habitat of the latter species, Duplessy (1978) showed that oxygen isotope records derived from *G. inflata* are remarkably parallel to that of *G. sacculifer*. Thus, the isotope signals of *G. inflata* can be regarded as a reliable carrier of paleotemperature information and its isotopic signals can be used to establish correlatable time markers.

To represent the sea-floor environment, we chose *Amphicoryna scalaris*, a rather common and most consistently present species of the benthic assemblages throughout the studied sequences. As samples at 360 m depth and a section between 440 and 500 m depths yield no specimen of *A. scalaris*, *Cibicides aknerianus* and *Bolivinita quadrilatera*, respectively, were used to represent these intervals.

Foraminiferal species were hand-picked from washed residues over a 150 μm -sieve. Between 3 and 6 specimens of *G. inflata* and from 2 to 3 specimens of *A. scalaris* were used for each measurement. To minimize the effects of changing depth preferences during growth stages on the isotopic composition of the foraminiferal test, rather narrowly defined size fractions (0.4–0.6 μm maximum diameter) of *G. inflata* were selected. The size of *A. scalaris* was also closely controlled to fall within a 1.1–2.4 μm maximum length range. These picked foraminifera were crushed and cleaned in an ultrasonic bath. CO_2 gas

was extracted, without any prior roasting, from the foraminiferal carbonates by reacting with orthophosphoric acid at 60°C and was analyzed in an online VG Micromass 903 Mass Spectrometer at Yamagata University. Isotope ratios were calibrated to the PDB standard through analyses of Solenhofen limestone, NBS #20 (Craig, 1957).

Results of our isotope analyses are shown in Tables 2 and 3 and are graphically plotted against depth below sea floor in Fig. 8.

The $\delta^{18}\text{O}$ record of planktonic foraminifera is characterized by the following distinct intervals with different pattern of isotopic variability (Fig. 8H). The uppermost well sequence above 155 m depth, which is characterized by lower oxygen isotope values, contrasts rather distinctly with an interval from 255 m to 340 m well depth typified by higher $\delta^{18}\text{O}$ values. The remaining two intervals, 160–250 m and 350–500 m well depth, are defined by intermediate values. Within each of these three intervals, isotope values fluctuate in a narrow degree. There is an abrupt upward jump of nearly 2‰ to more negative $\delta^{18}\text{O}$ values from 160 to 155 m well depth and the most negative value reaching -0.62 ‰ occurs at 150 m well depth.

The benthic oxygen-isotope records show a general upward trend towards more negative values, except for a short interval between 280 m and 330 m well depth. In this interval isotopic values are close to those characterizing the uppermost well sequence shallower than 140 m well depth. Many authors (Shackleton, 1974; Woodruff et al., 1980; Graham et al., 1981) advocate several species of the genus *Uvigerina* to incorporate oxygen isotopes in their shells in isotopic equilibrium with ambient seawater. Their carbon isotope is, however, depleted in ^{13}C relative to equilibrium calcite by approximately 1.8‰. Since specimens of *Uvigerina* are

Table 2. Oxygen and carbon isotopic compositions of the planktonic foraminifera *Globorotalia inflata* (d'Orbigny). Values are expressed as a deviation per mil from the PDB standard.

Depth (m)	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$	Depth (m)	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$
105	+0.34	-0.16	260	+1.27	+0.45
110	-0.16	-0.34	265	+1.53	+0.75
115	-0.28	-0.23	270	+0.95	+0.37
120	+0.30	-1.73	275	+1.78	+0.80
125	-0.05	-1.42	280	+1.59	+0.76
130	-0.09	-2.65	290	+1.76	+0.17
135	-0.15	-0.07	300	+1.94	+0.60
140	-0.12	-0.50	310	+1.45	+0.49
145	+0.25	+0.35	320	+1.65	+0.80
150	-0.62 (-2.81)*	-0.03 (-1.43)*	330	+1.71	+1.07
155	-0.55	-3.40	340	+2.23	+0.34
160	+1.11	+0.45	350	+0.97	+0.51
165	+0.19	-0.09	360	+0.78	+0.28
175	+0.83	+0.51	370	+1.28	+0.34
180	+0.87	+0.29	380	+1.07	+0.53
185	+0.51	+0.69	390	+0.85	+0.46
190	+0.82	+0.89	400	+0.79	-0.50
195	-0.11	+0.22	410	+1.97	-0.14
200	+0.79	+0.19	420	+1.27	+0.40
205	+0.01	-0.32	430	+0.36	+0.07
215	+0.15	+0.33	440	+0.01	+0.13
220	+0.87	+0.44	450	+0.88	+0.06
225	+0.78	+0.21	460	+0.42	-1.27
230	+0.34	-0.58	470	+0.62	-0.53
235	+1.15	+0.58	480	+1.42	-0.93
240	+0.75	-0.22	490	+1.25	-0.70
250	+0.27	+0.18	500	+0.95	-0.48
255	+1.49	+0.55			

* One set of specimens yielded very negative oxygen but positive carbon isotope values, necessitating second measurement on a separately picked set of specimens.

not present in a quantity enough for isotopic analyses, we analyzed *Euwigerina peregrina* Cushman var. *dirupta* Todd which is taxonomically closer to the genus *Uvigerina* than *Amphicoryna*. Oxygen isotope measurements at 390 m and 400 m well depth show *Euwigerina* values to be more positive by 0.54‰ and 0.84‰, respectively. On the other hand, carbon isotope values are nearly the same at 400 m depth, but at 390 m *Euwigerina* gives a value 0.76‰ higher.

As ^{12}C -enriched CO_2 dissolved in oceanic waters is removed preferentially by plants through photosynthesis, near-surface waters are enriched in ^{13}C and the degree of enrichment is related to the magnitude of the plant biomass present in the waters (Kroopnick et al., 1970; Broecker and Peng, 1982). The carbon-isotope records of planktonic foraminifera in the well section greater than 160 m well depth is characterized by heavier carbon isotope values and by low vari-

Table 3. Oxygen and carbon isotopic compositions of the benthic foraminifera, *Amphicoryna scalaris* (Batsch) with additional measurements on *Cibicides aknerianus* (d'Orbigny) and *Bolivinita quadrilatera* (Schwager). Values are expressed as a deviation per mil from the PDB standard.

Depth (m)	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$	Depth (m)	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$
105	+1.45	-0.06	270	+2.00	-1.53
110	+1.88	+1.02	275	+2.29	-0.61
115	+1.43	+0.11	280	+1.44	-1.38
120	+1.38	-0.27	290	+1.44	-1.11
125	+1.45	+0.34	300	+1.63	-0.92
130	+2.06	-0.30	310	+1.37	-1.73
135	+1.29	-0.07	320	+1.17	-1.66
140	+1.48	-0.37	330	+1.28	-1.81
145	+1.69	+0.23	340	+2.34	-0.80
150	+1.62	-0.09	350	+1.39	-0.30
155	+2.07	-0.34	370	+2.20	-1.07
160	+2.48	+0.18	380	+2.43	-0.82
165	+2.39	+0.77	390	+1.95	-1.42
175	+2.39	-0.12	400	+1.62	-1.53
180	+1.62	+0.02	410	+2.12	-0.51
185	+2.11	-0.23	420	+1.97	-1.46
190	+2.04	+0.25	430	+2.47	-1.06
200	+2.29	-0.27			
205	+1.83	-0.62	<i>C. aknerianus</i>		
215	+2.03	-0.36	360	+2.11	-0.13
220	+2.56	+0.10	370	+2.92	+0.39
225	+2.05	-0.78			
230	+2.32	-0.37	<i>B. quadrilatera</i>		
235	+2.21	-0.30	420	+2.95	-0.19
240	+2.47	-0.27	440	+2.28	-2.57
250	+2.10	-0.47	450	+3.41	-0.28
255	+2.69	-0.90	460	+3.26	0.00
260	+2.01	-1.30	470	+3.41	-0.75
265	+2.23	-0.82	480	+3.56	-5.97
			490	+3.34	-0.96
			500	+3.52	-2.58

ability. The top section of the well less than 160 m depth, however, displays large shifting values from the minimum of -3.40‰ at 155 m depth and -2.56‰ at 130 m depth, respectively, to the maximum reaching about +0.35‰ at 145 m depth. One possible way of explaining these large shifts is to assume that there is a combined effect of such factors as temporally enhanced oxidation of organic matter and a decreasing rate of the general phytoplankton productivity,

both of which would result from the elevation of Kashima-nada area to shelf water depths as indicated by benthic foraminiferal faunas. The benthic carbon-isotope records show a general trend towards more heavier values with decreasing well depths and no such large shifts as those evidenced by the planktonic foraminifera occur in the uppermost part of the well sequence.

A depth profile of $\delta^{13}\text{C}$ at a GEOSECS station in the North Pacific

exhibits a steep gradient of carbon-isotope changes within the top few hundred meters of the ocean with values varying from about 0‰ at 200–300 m water depth to about +2.2‰ at the surface (Broecker and Peng, 1982). If *A. scalaris* incorporated $^{13}\text{C}/^{12}\text{C}$ ratios in

nearly isotopic equilibrium with that of the environmental water, the observed benthic carbon isotope change provides another supportive evidence for the progressive shallowing of the Kashimada area.

DISCUSSIONS

(1) Chronology of SK-1 Quaternary sediments off Kashima

Based upon planktonic foraminiferal and calcareous nannofossil biostratigraphy, several datum levels which enable assignment of ages are recognized in the Kashima SK-1 Quaternary sequence. These biostratigraphic criteria indicate the presence of a hiatus separating the Quaternary sequence from the underlying Pliocene sediments (Fig. 2).

The Pleistocene record of isotopic variations in planktonic foraminifera is interpreted to be dominated by the changing isotopic composition of the oceans caused by the accumulation and ablation of ice on land (Shackleton, 1967; Shackleton and Opdyke, 1973). Extensive ice development in response to cooling of the Earth would cause large amounts of isotopically light water to be icebound on land, resulting higher ^{18}O concentrations in ocean water. This process makes oxygen isotope changes useful to stratigraphic studies and the Pleistocene record has been shown to be precisely matched and correlated between the Indian, Pacific, and Atlantic Oceans (Thierstein et al., 1977; Hays et al., 1976; Fillon and Williams, 1983).

Shackleton and Opdyke (1976) discriminated 10 distinct intervals characterized by high and low ^{18}O concentrations during a 0.9 Ma period of the late Quaternary. They also established oxygen isotope stages by giving odd-numbers to those time intervals with lower isotopic values and even-numbers

to those showing higher values. The oxygen isotope record of Kashima SK-1 well alone does not reveal any clear cut stage division which would enable correlation with stages defined by Shackleton and Opdyke (1976). With the aid of two dates established by the calcareous nannofossil evidence, however, we attempted to assign isotope stages (Fig. 2). Following Thierstein et al. (1977), the global extinction level of *P. lacunosa* (= *Emiliana annula* plus *E. ovata* in this paper) dated at 0.46 Ma is taken to correspond to the interval from stages 11 to 13 with higher ^{18}O values and the first appearance level of *E. huxleyi* dated at 0.27 Ma to the level immediately before stage 7. An abrupt upward shift from high to low ^{18}O concentrations at 155–160 m well depth, which occurs well after the 0.27 Ma date, is best assignable, because of its magnitude, to the boundary between stages 5 and 6 (0.128 Ma), where one of the greatest magnitude of oxygen isotope changes are known to have occurred in moving from glacial to interglacial modes (Johnson and Andrews, 1986). Going further back in time, the isotopic fluctuations can be identified as far back as the isotope stage 15. If this interpretation is valid, the stratigraphic hiatus between 460–470 m well depth spans a time duration from late Pliocene (ca. 1.9 Ma) to middle Quaternary (ca. 0.6 Ma). The assignment of isotope stage boundaries also enables calculation of gross sedimentation rates by referring to the stage chronology of Shackleton and Opdyke

(1976): 32 cm/1,000 yr for upper bathyal sediments (460–400 m), and 87 cm/1,000 yr for middle bathyal and outer sublittoral to inner sublittoral sediments (390–100 m).

(2) Correlation with onshore Quaternary sediments

The onshore record of middle Quaternary sediments, distributed in the southern Kanto District, consists of several lithologic units including the Kioroshi, Kamiwahashi, Kiyokawa, Yabu, and Jizodo Formations, in downward sequence. The base of these formations is terminated by an unconformable contact. Machida et al. (1980) established a tephrochronology for numerous tephra layers occurring in these formations and showed that the level of these unconformities is correlatable with oxygen isotope stages 6, 8, 10, and 12, all of which correspond to the period of global lower stand of sea level (Fig. 2). The Quaternary isotopic record of Kashima SK-1 well does not show any definite interval which can be correlated with the even-numbered stages. In view of the presence of distinct hiatuses in the Quaternary sequence of the southern Kanto District, we interpret the lack of even-numbered isotope stages to reflect either greatly reduced sedimentation or possibly non-deposition during those time periods. The boundaries between odd- and even-numbered stages are generally not clearly definable. However, small-scale shifts from outer to inner sublittoral zone environment (350, 310, 230, and 220–210 m well depth) as indicated by the study of benthic foraminifera (Fig. 4) all fall at or near the boundaries between these odd- and even-numbered stages or inflection levels of ^{18}O record from lower to high concentrations within the odd-numbered stages. Therefore, it appears that eustatic sea level changes in the Quaternary strongly influenced sediment accumulation in

coastal areas extending from southern Kanto to the environ of Kashima SK-1 well site.

Among various marine terraces developed on the Japanese Islands, one or two well-developed terrace surfaces of intermediate altitude are dated at 0.12–0.13 Ma by the fission-track method (Machida, 1975) and by the U/Th method (Omura, 1980), and are generally called the S surface or intermediate terrace (Ota, 1975). Terraces of the same age are distributed widely in the world, indicating that the sea level at that time was several meters higher than at present (Bloom et al., 1974; Bender et al., 1979; Muhs and Szabo, 1982). The sea level rise responsible for the formation of S surface is called the Shimosueyoshi transgression in Japan. The abrupt and large magnitude of isotopic fluctuations from stages 6 to 5 recognized in SK-1 Quaternary sediments is interpreted to reflect major oceanographic changes brought about concomitantly with the Shimosueyoshi transgression.

(3) Paleoceanography off Kashima

Figure 8 shows our interpretation of the paleoceanographic history of the Kashima-nada area since ca. 0.6 Ma. The foraminiferal P/T ratio and relative frequencies of *F. profunda*, a lower photic layer species of calcareous nanoplankton, suggest a steady decrease of water depth, correspondent to a general retreat of the sea. The ^{13}C concentrations of benthic foraminifera increase upward, approaching to values shown by planktonic foraminifera and may indicate that this upward-decreasing trend of the difference between isotopic compositions of bottom and surface water species also resulted from the shallowing trend of the sea. The deposition of SK-1 Quaternary sediments off Kashima began in the upper bathyal zone as exemplified by the lower half of the well sequence and moved to the sublittoral (shelf) zone

as shown by the upper sequence. The paleotemperature curve of overlying waters shows, supported also by the oxygen isotope fluctuations, two warm periods and one cold period. During the warm period near the well depth of 370–380 m, biogenic carbonates were dominant over the terrigenous materials, whose supply decreased due possibly to a reduced rate of land uplift. The abundance of quartz grains increases in a 30-m interval near the basal part of the Quaternary sequence (Fig. 3). Since an unconformable contact separates the Quaternary sequence from the underlying Pliocene sediments, these quartz grains may be indicative of a new regime of sedimentation over the erosional surface. Volcanic activities on the Japanese island arc during the Quaternary might have intensified during the later half of the deposition time as suggested by the increasing feldspar/quartz ratio. Furthermore, frequent occurrences of quartz grains during that time probably indicate a more extensive land erosion because of the general uplift of land areas. The decrease in ^{18}O concentrations is more profound in surface water than in bottom water. This may indicate increasing mixing with low-salinity coastal waters owing to the shallowing water depth. In comparing down-core fluctuations of water temperatures between those determined by the transfer

functions and those derived from oxygen isotope analysis, Imbrie and Kipp (1971) stated that the secular trend revealed by the paleoecological equations contrast rather sharply with the lack of such a trend exhibited by oxygen isotope ratios. The trend variations observed in oxygen isotope fluctuations for the Quaternary sequence of SK-1 well may be a reflection of local environmental effects caused by a general shallowing of the sea. Although paleotemperature fluctuations estimated for the SK-1 sequence by the paleoecological equations and oxygen isotope analyses agree well in the lower part of the section, they do not generally correspond well in the upper section.

This may also indicate environmental changes toward the shelf zone. Another interesting feature of paleoceanographic changes is the countervailing effects of the Kuroshio (third factor) and the Tsugaru Warm Current (first factor) since about 0.3 Ma (the time level indicated by the lower filled-in arrow in Fig. 8F). The uppermost well sequence of Kashima SK-1, above the 100 m well depth, yields only very scarce calcareous nannoplankton, possibly because of the elevation of this part of ocean basin to the inner sublittoral zone (less than 50 m depth). This uppermost well sequence was precluded from our analysis because of the lack of preserved fossil record.

APPENDIX — Faunal reference list of selected benthic foraminiferal species

A preliminary report on the Pleistocene benthic foraminifera from Kashima SK-1 well was published by Takayanagi and Hasegawa (1986), together with scanning electron photomicrographs of ecologically important taxa. As the taxonomy of both benthic and planktonic foraminifera will be treated more fully elsewhere, this list provides a taxonomic reference to those species pertinent to the discussion presented in

this paper.

- Ammonia japonica* (Hada) Pl. 17, figs. 2a-c
Rotalia japonica Hada, 1931, p. 137, text-figs. 93a-c.
Ammonia japonica (Hada). Ujiié, 1963, p. 236, pl. 2, figs. 3, 4.
Ammonia takanabensis (Ishizaki) . . Pl. 17, figs. 3a-c
Streblus takanabensis Ishizaki, 1948, p. 57, pl. 1, figs. 5a-c.
Rotalia takanabensis (Ishizaki). Asano, 1951c, pt. 14, p. 16, figs. 124–126.

- Ammonia takanabensis* (Ishizaki). Hung, 1964, p. 56, pl. 1, figs. 2a-c.
- Amphicoryna scalaris* (Batsch) Pl. 15, fig. 20
- Nautilus (Orthoceras) scalaris* Batsch, 1791, pl. 2, figs. 4a, b (*fide* Ellis and Messina, 1940 *et seq.*).
- Nodosaria scalaris* (Batsch). Parker, Jones and Brady, 1865, p. 227; 1871, p. 157, pl. 9, fig. 42.
- Amphicoryna scalaris* (Batsch). Barker, 1960, p. 134, pl. 63, figs. 28-31.
- Lagenonodosaria scalaris* (Batsch). Asano, 1938d, p. 210, pl. 25, fig. 28; pl. 27, figs. 11-13.
- Amphicoryna scalaris* (Batsch) forma *sagamiensis* (Asano) Pl. 15, fig. 21
- Lagenonodosaria scalaris sagamiensis* Asano, 1936b, p. 613, pl. 30, figs. 6, 7.
- Bolivinita quadrilatera* (Schwager) Pl. 16, fig. 5
- Textularia quadrilatera* Schwager, 1866, p. 253, pl. 7, fig. 103.
- Bolivinita quadrilatera* (Schwager). Cushman, 1927a, p. 90.
- Bolivinita quadrilatera cuneata* Asano, 1938b, p. 74, pl. 16 (5), figs. 19a, b.
- Buccella* sp. A Pl. 17, fig. 8
- Bulimina subulata* Cushman and Parker Pl. 16, fig. 3
- Bulimina elongata* d'Orbigny. Brady, 1884, p. 401, pl. 51, figs. 1, 2 (not of d'Orbigny).
- Bulimina elongata* d'Orbigny var. *subulata* Cushman and Parker, 1937, p. 51, pl. 7, figs. 6, 7.
- Bulimina elongata subulata* Cushman and Parker. Asano, 1950, pt. 2, p. 3, figs. 10, 11.
- Buliminella elegantissima* (d'Orbigny) Pl. 16, fig. 4
- Bulimina elegantissima* d'Orbigny, 1839c, p. 51, pl. 7, figs. 13, 15 (*fide* Ellis and Messina, 1940 *et seq.*).
- Buliminella elegantissima* (d'Orbigny). Cushman, 1911, p. 89.
- Cassidulina carinata* Silvestri Pl. 16, fig. 7
- Cassidulina leavigata* d'Orbigny var. *carinata* Silvestri, 1896, p. 104, pl. 2, figs. 10a-c (*fide* Ellis and Messina, 1940 *et seq.*).
- Cassidulina carinata* Silvestri. Matoba, 1967, p. 252, pl. 28, figs. 11, 12.
- Cassidulina norvangi* Thalmann var. . . Pl. 16, fig. 8
- Cassidulina islandica* Norvang forma *minuta* Nørvang, 1945, p. 43, text-figs. 8a-c (*fide* Ellis and Messina, 1940 *et seq.*).
- Cassidulina islandica* Nørvang var. *norvangi* Thalmann. Thalmann *in* Phleger, 1952, p. 83, footnote 1.
- Cassidulina norvangi* Thalmann. Nomura, 1983a, pl. 23, figs. 10-12; pl. 24, figs. 1-3; 1983b, p. 53, pl. 4, figs. 12a-c, 13.
- Cibicides aknerianus* (d'Orbigny) . . Pl. 17, figs. 6a-c
- Rotalina akneriana* d'Orbigny, 1846, p. 156, pl. 8, figs. 13-15.
- Truncatulina akneriana* (d'Orbigny). Cushman, 1921, p. 316, pl. 63, figs. 3a-c.
- Cibicides aknerianus* (d'Orbigny). Asano, 1951b, pt. 13, p. 17, figs. 30-32.
- Cibicides aknerianus* (d'Orbigny) forma *subdepressa* (Asano) Pl. 17, figs. 7a-c
- Planulina subdepressa* Asano, 1951b, pt. 13, p. 15, figs. 16-18.
- Elphidium excavatum* (Terquem) s.l. . Pl. 16, fig. 13
- Polystomella excavata* Terquem, 1875, p. 25, figs. 2a-f (*fide* Ellis and Messina, 1940 *et seq.*).
- Polystomella striatopunctata* (Fichtel and Moll). Heron-Allen and Earland, 1909, p. 695, pl. 21, figs. 2a-c.
- Polystomella striatopunctata* (Fichtel and Moll) var. *selseyensis* Heron-Allen and Earland, 1911, p. 448 (list).
- Elphidium excavatum* (Terquem). Cushman, 1930 (part), p. 21, pl. 8, figs. 1-3.
- Elphidium incertum* (Williamson) var. *clavatum* Cushman, 1930, p. 20, pl. 7, figs. 10a, b.
- Elphidium subgranulosum* Asano, 1938a, p. 586, pl. 14 (3), figs. 4a, b.
- Elphidium selseyense* (Heron-Allen and Earland). Cushman, 1939b, p. 59, pl. 16, figs. 26-28 (after Heron-Allen and Earland, 1909).
- Elphidium clavatum* Cushman. Loeblich and Tappan, 1953, p. 98, pl. 19, figs. 8-10.
- Elphidium excavatum* (Terquem) forma *clavata* Cushman. Feyling-Hansen, 1972, p. 339, pl. 1, figs. 1-9; pl. 2, figs. 1-9.
- Elphidium excavatum* (Terquem) forma *excavata* (Terquem). Miller et al., 1982, p. 128, pl. 1, figs. 9-12; pl. 2, figs. 1, 2; pl. 3, figs. 1, 2; pl. 4, figs. 13-16; pl. 5, figs. 15, 16; pl. 6, figs. 6-8, 14.
- Elphidium excavatum* (Terquem) forma *selseyensis* (Heron-Allen and Earland). Miller et al., 1982, p. 132, pl. 1, figs. 13-16; pl. 5, figs. 10-13; pl. 6, figs. 9-13.
- Euvigerina* cf. *yabei* (Asano) Pl. 16, fig. 6
- Cf. *Uvigerina yabei* Asano, 1938c, p. 79, pl. 17 (6), figs. 1, 2.
- Uvigerina* cf. *yabei* Asano. Aoki, 1965, p. 58, pl. 7, figs. 20, 21, 27.
- Globigerina bulloides* d'Orbigny . . . Pl. 15, figs. 1-3
- Globigerina bulloides* d'Orbigny, 1826, p. 277, no. 1; 1839b, p. 132, pl. 2, figs. 1-3 (not fig. 28).
- Globigerina quinqueloba* Natland . . Pl. 15, figs. 4-6
- Globigerina quinqueloba* Natland, 1938, p. 149, pl. 6, figs. 7a-c.
- Globigerinoides ruber* (d'Orbigny) . . Pl. 15, figs. 7, 8
- Globigerina rubra* d'Orbigny, 1839a, p. 82, pl. 4, figs. 12-14.
- Globigerinoides rubra* [sic] (d'Orbigny). Cushman, 1927b, p. 87 (not pl. 19, fig. 6).
- Globigerinoides ruber* (d'Orbigny). Parker, 1962, p. 230, pl. 3, figs. 11-14; pl. 4, figs. 1-10.
- Globocassidulina bisecta* Nomura . . Pl. 16, figs. 9a, b
- Globocassidulina bisecta* Nomura, 1983a, p. 73,

- pl. 2, figs. 2, 3.
Globorotalia inflata (d'Orbigny)
Globigerina inflata d'Orbigny, 1939b, p. 134, pl. 12, figs. 7-9.
Globorotalia inflata (d'Orbigny). Parker, 1962, p. 236, pl. 5, figs. 6-9.
- Globorotalia tosaensis* Takayanagi and Saito
Globorotalia tosaensis Takayanagi and Saito, 1962, p. 81, pl. 28, figs. 11, 12.
- Globorotalia truncatulinoides* (d'Orbigny)
Rotalina truncatulinoides d'Orbigny, 1839b, p. 132, pl. 1, figs. 25-27.
Globorotalia truncatulinoides (d'Orbigny). Cushman, 1927c, p. 176.
- Haynesina germanica* (Ehrenberg) s.l.
..... Pl. 16, figs. 10a, b
Nonionina germanica Ehrenberg, 1840, p. 23; Ehrenberg, 1841, pl. 2, figs. 1a-g (*fide* Ellis and Messina, 1940 *et seq.*).
Haynesina germanica (Ehrenberg) s.s., emend. Banner and Culver, 1978, p. 191, pl. 4, figs. 1-6; pl. 5, figs. 1-8; pl. 6, figs. 1-7; pl. 7, figs. 1-6; pl. 8, figs. 1-10; pl. 9, figs. 1-11, 15, 18.
Haynesina germanica (Ehrenberg) *evansi* Banner and Culver, 1978, p. 195, pl. 9, figs. 17, 18.
- Hoeglundina elegans* (d'Orbigny)..... Pl. 17, fig. 1
"Nautili *Ammoniformes* five *trochiformes*". Soldani, 1780, App. p. 99, pl. 2, figs. 13, q, Q, R.
Rotalia (Turbinulina) elegans d'Orbigny, 1826, p. 276.
Pulvinulina elegans (d'Orbigny). Parker, Jones and Brady, 1871, p. 174, pl. 12, fig. 142 (after Soldani, 1780).
Epistomina elegans (d'Orbigny). Cushman, 1915, p. 63, pl. 26, figs. 3a-c.
Hoeglundina elegans (d'Orbigny). Brotzen, 1948, p. 92, pl. 17, figs. 7-8.
- Murrayinella takayanagii* (Matoba) Pl. 17, figs. 5a-c
Pararotalia minuta (Takayanagi) and var. Matoba, 1967, p. 256, pl. 27, figs. 5, 6 (not *Rotalia ? minuta* of Takayanagi, 1955).
Pararotalia ? takayanagii Matoba, 1970, p. 63, pl. 6, figs. 9, 10.
- Neogloboquadrina asanoi* (Maiya, Saito and Sato)
Globoquadrina asanoi Maiya, Saito and Sato, 1976, p. 409, pl. 3, figs. 1-3.
Neogloboquadrina asanoi (Maiya, Saito and Sato). Thompson, 1980, pl. 3, figs. 10-12.
- Neogloboquadrina eggeri* (Rhumbler)
..... Pl. 15, figs. 9-11
Globigerina eggeri Rhumbler, 1901, p. 12, text-fig. 20 (after Brady, 1884, pl. 79, figs. 17a-c).
Neogloboquadrina eggeri (Rhumbler). Saito, Thompson and Breger, 1981, p. 111, pl. 36, figs. 3, 4.
- Neogloboquadrina incompta* (Cifelli)
..... Pl. 15, figs. 12-14
Globigerina incompta Cifelli, 1961, p. 83, pl. 4, figs. 1-7.
- Neogloboquadrina pachyderma incompta* (Cifelli). Rögl and Bolli, 1973, p. 571, pl. 107, pl. 10 ?
Neogloboquadrina incompta (Cifelli). Saito, Thompson and Breger, 1981, p. 108, pl. 34, figs. 2a-d.
- Neogloboquadrina pachyderma* (Ehrenberg)
..... Pl. 15, figs. 15, 16
Aristerospira pachyderma Ehrenberg, 1861, p. 276; 1872, pl. 1, figs. 4.
Neogloboquadrina pachyderma pachyderma (Ehrenberg). Rögl and Bolli, 1973, p. 571, pl. 11, figs. 2-6; pl. 16, figs. 16-18.
- Nonionella stella* Cushman and Moyer Pl. 16, fig. 6
Nonionella miocenica Cushman var. *stella* Cushman and Moyer, 1930, p. 56, pl. 7, figs. 17a-c.
Nonionella stella Cushman and Moyer. Uchio, 1960, p. 61, pl. 4, figs. 15, 16.
- Porosorotalia makiyamai* (Chiji) .. Pl. 17, figs. 9a, b
Buccella makiyamae [sic] Chiji, 1961, p. 234, figs. 2a-c; pl. 1, figs. 13, 14.
Porosorotalia makiyamae [sic] (Chiji). Matoba, 1967, p. 256, pl. 27, figs. 12, 13.
Buccella ? makiyamae [sic] Chiji. Matoba, 1970, p. 49, pl. 7, figs. 13a-c.
Buccella makiyamai Chiji. Hasegawa, 1979, p. 144, pl. 7, figs. 3a-c.
- Pseudononion japonicum* Asano .. Pl. 17, figs. 14, 15
Pseudononion japonicum Asano, 1936a, p. 347, text-figs. A-C.
Pseudononion tredecum Asano, 1936c, p. 622, pl. 33, figs. 7a-c.
Pseudononion kanbaraense Matsunaga, 1963, p. 110, pl. 38, figs. 8a-c.
Pseudononion oinomikadoi Matsunaga, 1963, p. 110, pl. 39, figs. 1a-c.
- Pseudoparrella naraensis* Kuwano Pl. 16, fig. 12
Pseudoparrella naraensis Kuwano, 1950, p. 317, figs. 6a-c.
Epistominella naraensis (Kuwano). Asano, 1951a, p. 6, figs. 34-36.
- Pseudoparrella tamana* Kuwano Pl. 16, fig. 11
Pseudoparrella tamana Kuwano, 1950, p. 317, figs. 5a-c.
Epistominella tamana (Kuwano). Asano, 1951a, p. 7, figs. 40-42.
- Pseudorotalia gaimardii* (d'Orbigny) *compressiuscula* (Brady) Pl. 17, fig. 4
Rotalia papillosa Brady var. *compressiuscula* Brady, 1884, p. 708, pl. 107, figs. 1a-c; pl. 108, figs. 1a-c.
Streblus gaimardii (d'Orbigny) var. *compressiuscula* (Brady). Barker, 1960, p. 220, 222, pl. 107, figs. 1a-c; pl. 108, figs. 1a-c.
Pseudorotalia gaimardii (d'Orbigny). Matoba, 1967, p. 257, pl. 27, figs. 4a-c.
Pseudorotalia gaimardii compressiuscula

(Brady). Hasegawa, 1979, p. 153, pl. 7, figs. 5a-c.

- Pulleniatina obliquiloculata* (Parker and Jones)
Pl. 15, figs. 17-19
Pullenia obliquiloculata Parker and Jones, 1865,
 p. 183.
Pullenia sphaeroides (d'Orbigny) var. *obliqui-*
loculata Parker and Jones, 1865, p. 365, pl. 19,
 figs. 4a, b.

- Pulleniatina obliquiloculata* [sic] (Parker and Jones). Chushman, 1927b, p. 90, pl. 19, fig. 5.
Quinqueloculina vulgaris d'Orbigny Pl. 16, figs. 1, 2
 "Fruentaria Seminula" Soldani, 1795, p. 228,
 pl. 152, fig. E (*vide* Parker, Jones and Brady,
 1871).
Quinqueloculina vulgaris d'Orbigny, 1826, p.
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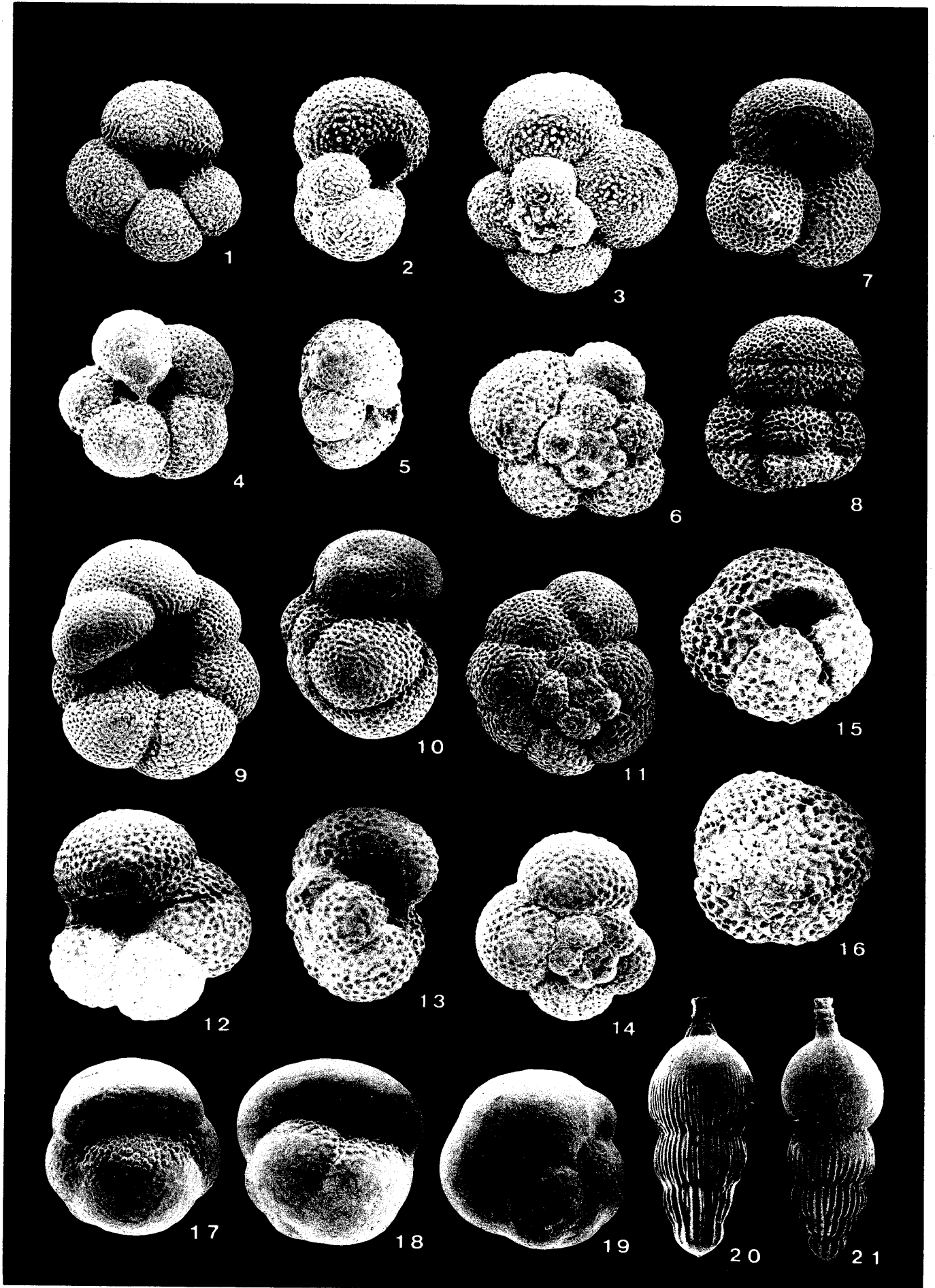
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Plate 15

- Figs. 1-3. *Globigerina bulloides* d'Orbigny
1-umbilical side view, 2-edge view, 3-spiral side view, 193 m, $\times 116$.
- Figs. 4-6. *Globigerina quinqueloba* Natland
4-umbilical side view, 5-edge view, 6-spiral side view, 205 m, $\times 173$.
- Figs. 7, 8. *Globigerinoides ruber* (d'Orbigny)
7-umbilical side view, 8-spiral side view, 180 m, $\times 147$.
- Figs. 9-11. *Neogloboquadrina eggeri* (Rhumbler)
9-umbilical side view, 10-edge view, 11-spiral side view, 180 m, $\times 88$.
- Figs. 12-14. *Neogloboquadrina incompta* (Cifelli)
12-umbilical side view, 13-edge view, 14-spiral side view, 200 m, $\times 175$.
- Figs. 15, 16. *Neogloboquadrina pachyderma* (Ehrenberg)
15-umbilical side view, 16-spiral side view, 235 m, $\times 175$.
- Figs. 17-19. *Pulleniatina obliquiloculata* (Parker and Jones)
17-umbilical side view, 18-edge view, 19-spiral side view, 180 m, $\times 88$.
- Fig. 20. *Amphicoryna scalaris* (Batsch)
Side view, 185 m, $\times 34$.
- Fig. 21. *Amphicoryna scalaris* (Batsch) forma *sagamiensis* (Asano)
Side view, 185 m, $\times 34$.



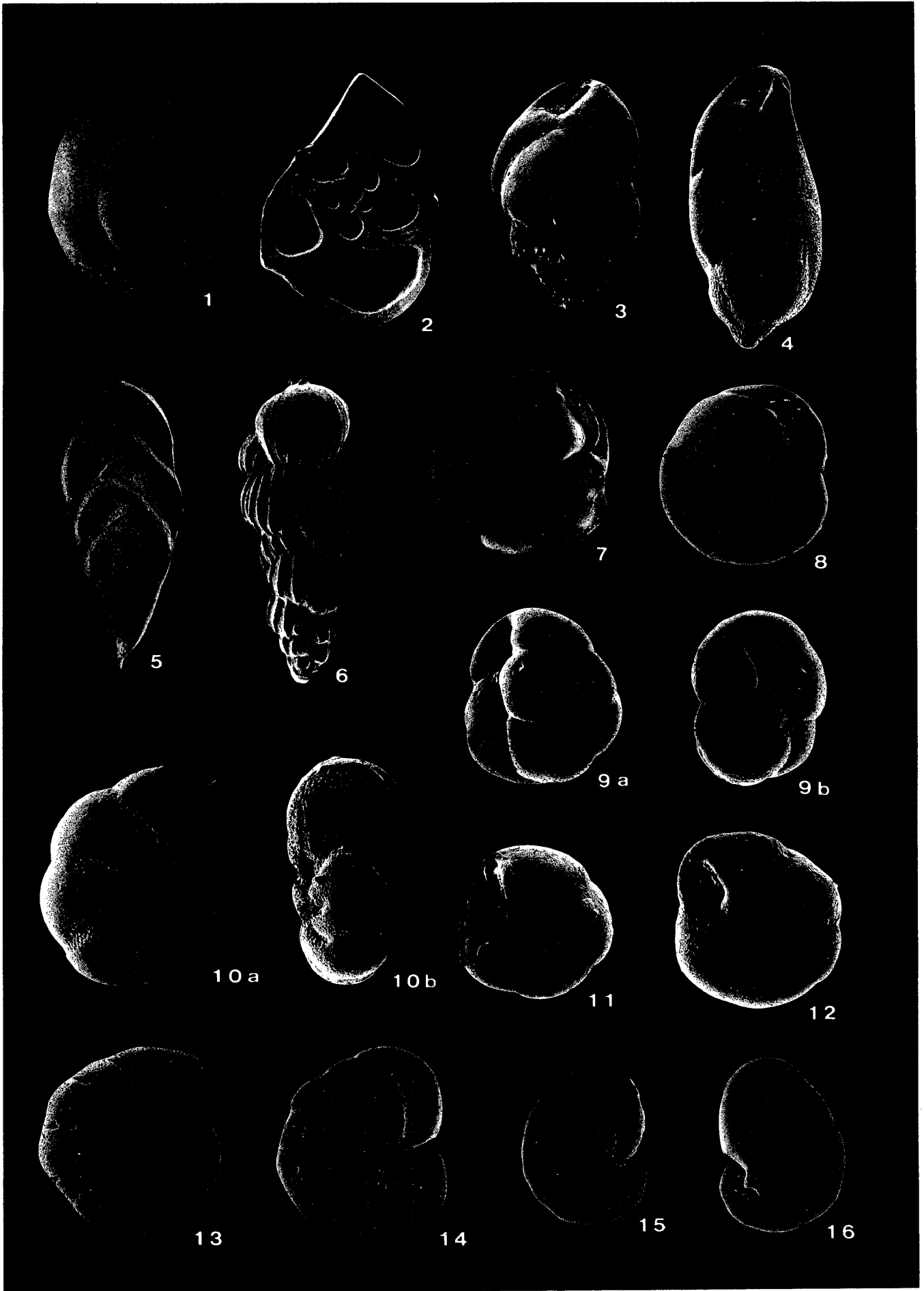


Plate 16

- Figs. 1, 2. *Quinqueloculina vulgaris* d'Orbigny
1-side view, $\times 45$, 2-transverse section, 165 m, $\times 34$.
- Fig. 3. *Bulimina subulata* Cushman and Parker
Side view, 470 m, $\times 96$.
- Fig. 4. *Buliminella elegantissima* (d'Orbigny)
Side view, 230 m, $\times 144$.
- Fig. 5. *Bolivinita quadrilatera* (Schwager)
Side view, 420 m, $\times 34$.
- Fig. 6. *Euuvigerina* cf. *yabei* (Asano)
Side view, 290 m, $\times 72$.
- Fig. 7. *Cassidulina carinata* Silvestri
Side view, 270 m, $\times 144$.
- Fig. 8. *Cassidulina norvangi* Thalmann
Side view, 230 m, $\times 144$.
- Figs. 9a, b. *Globocassidulina bisecta* Nomura
9a-side view, 9b-edge view, 420 m, $\times 144$.
- Figs. 10a, b. *Haynesina germanica* (Ehrenberg) s. l.
10a-side view, 10b-edge view, 10 m, $\times 144$.
- Fig. 11. *Pseudoparrella tamana* Kuwano
Umbilical side view, 410 m, $\times 144$.
- Fig. 12. *Pseudoparrella naraensis* Kuwano
Umbilical side view, 150 m, $\times 216$.
- Fig. 13. *Elphidium excavatum* (Terquem) forma *selseyensis* (Heron-Allen and Earland)
Side view, 290 m, $\times 72$.
- Figs. 14, 15. *Pseudononion japonicum* Asano
Side views, 125 m, $\times 48$.
- Fig. 16. *Nonionella stella* Cushman and Moyer
Umbilical side view, 165 m, $\times 48$.

Plate 17

- Fig. 1. *Hoeglundina elegans* (d'Orbigny)
Umbilical side view, 380 m, $\times 45$.
- Figs. 2a-c. *Ammonia japonica* (Hada)
2a-umbilical side view, 2b-edge view, 2c-spiral side view, 140 m, $\times 64$.
- Figs. 3a-c. *Ammonia takanabensis* (Ishizaki)
3a-umbilical side view, 3b-edge view, 3c-spiral side view, 140 m, $\times 64$.
- Fig. 4. *Pseudorotalia gaimardii* (d'Orbigny)
Umbilical side view, 105 m, $\times 45$.
- Figs. 5a-c. *Murrayinella takayanagii* (Matoba)
5a-umbilical side view, 5b-edge view, 5c-spiral side view, 155 m, $\times 288$.
- Figs. 6a-c. *Cibicides aknerianus* (d'Orbigny)
6a-umbilical side view, 6b-spiral side view, 6c-edge view, 220 m, $\times 45$.
- Figs. 7a-c. *Cibicides aknerianus* (d'Orbigny) forma *subdepressa* (Asano)
7a-umbilical side view, 7b-spiral side view, 7c-edge view, 390 m, $\times 45$.
- Fig. 8. *Buccella* sp. A
Umbilical side view, 135 m, $\times 96$.
- Fig. 9. *Buccella tenerrima* (Bandy)
Umbilical side view, 290 m, $\times 128$.
- Figs. 10a, b. *Porosorotalia makiyamai* (Chiji)
9a-umbilical side view, 9b-edge view, 140 m, $\times 96$.

