8. MAGNETOSTRATIGRAPHY AND DIATOM BIOSTRATIGRAPHY OF SITE 584, DEEP SEA DRILLING PROJECT LEG 87, AND IMPLICATIONS FOR THE TECTONIC EVOLUTION OF JAPANESE ISLAND ARCS[1]

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ABSTRACT

Detailed correlation and chronology of Neogene and Quaternary marine sediments are established by the application of a new standard magnetobiostratigraphic timetable. Based on the chronology for the abyssal plain off the Japan Trench, we calculated the rate of accumulation of the sedimentary sequences, and found that the accumulation rate decreases exponentially with increasing distance from land. The rate of accumulation in the forearc is controlled by the submarine topography, particularly the dip of the seafloor. Tertiary sedimentary sequences of the forearc can be divided into the Upper, Middle, and Lower layers, based on the rate of accumulation, on spatial changes in the thickness, and on hiatuses within the drilled sedimentary sequences. They are also recognizable on multichannel seismic profiles. We reconstructed the evolution of the submarine topography and tectonic movement of the pre-Tertiary basement, based on the sedimentation rate and on the spatial distribution of the thickness of sedimentary layers, and obtained an estimate of the dip angle of the seafloor. The reconstruction suggests that the outer margin of the deep-sea terrace (trench upper slope) changed dynamically with the vertical amplitude of more than 1000 m. The chronology of the layers and the tectonic evolution in the forearc are consistent with the evolutionary model of the cyclic plate subduction proposed for the Neogene tectonic evolution of the subaerial geology in the Japanese Island Arcs. Paleomagnetic measurements of the directions of the cross-bedding in the basal sandstone of the Lower Layer in Site 439 do not support the existence of an "Oyashio Paleolandmass" in the forearc, except before the transgressive stage in the late Oligocene.

INTRODUCTION

Detailed correlation and chronology of the Neogene and Quaternary marine sediments of the Japanese Island Arcs have been established by the application of magnetostratigraphy and diatom biostratigraphy. This chapter is a compilation of previous works combined with the diatom biostratigraphy (Akiba, this volume) and magnetostratigraphy (Niitsuma, this volume) of drilled sediments in Site 584, and it establishes a standard magnetobiostratigraphic timetable (Fig. 1).

In this report, the tectonic evolution of the forearc area between the Japan Trench and Japanese Island Arc is considered, based on the new magnetobiostratigraphic timetable, and a new scheme describing the Japanese Neogene stages is proposed. Any understanding of the tectonic evolution of the region is made more by difficult by discontinuities in stratigraphic correlations between southern and central Japan (the area under the influence of the warm Kuroshio) and northern Japan (under the effect of the cold Oyashio).

Layers within forearc basins are traced on the multichannel seismic reflection data and dated by the new timetable for the DSDP drilled sediments. The distribution of the layers in certain time intervals provides information on the tectonic evolution. Current directions of deposition, determined by paleomagnetic technique, should support the regional tectonic picture. We made a paleomagnetic measurement on the cross-bedded sandstone of the lower part of Tertiary sediments at Site 439 in order to check on the "Oyashio paleolandmass" (von Huene et al., 1978).

The new timetable is useful for correlating the sediments of forearc basin and island arcs. The tectonic history in both areas is controlled by the Pacific Plate subduction along the Japan Trench. In this chapter, we try to clarify tectonic evolution along the Japan Trench, using new data on the Neogene sedimentary sequences in the Hokkaido and Tohoku areas of the northern Japanese Island Arc.

Sediment Accumulation Rate as an Indicator of Tectonism

DSDP sites drilled during Legs 56, 57, and 87 are located on various portions of the forearc along the Japan Trench (Figs. 2 and 3; von Huene et al., 1980; Karig et al., this volume). Based on the new timetable (Fig. 1), we can relate horizons to their ages in order to calculate the sediment accumulation rate. For an image of the rate of sediment accumulation, we examined the change in the sediment accumulation rate in Site 436, drilled on the abyssal plain 70 km east of the Japan Trench (von Huene et al., 1980). The rate increases exponentially with age (Fig. 4), as plate motion moved the site toward the Japanese Island Arc. The best-fit exponential relationship on the rate of sedimentation, r, in m/Ma, and the age, T, in Ma, is

$$r = 75 \exp(-0.185T)$$

[1] Kagami, H., Karig, D. E., Coulbourn, W. T., et al., *Init. Repts. DSDP*, 87: Washington (U.S. Govt. Printing Office).

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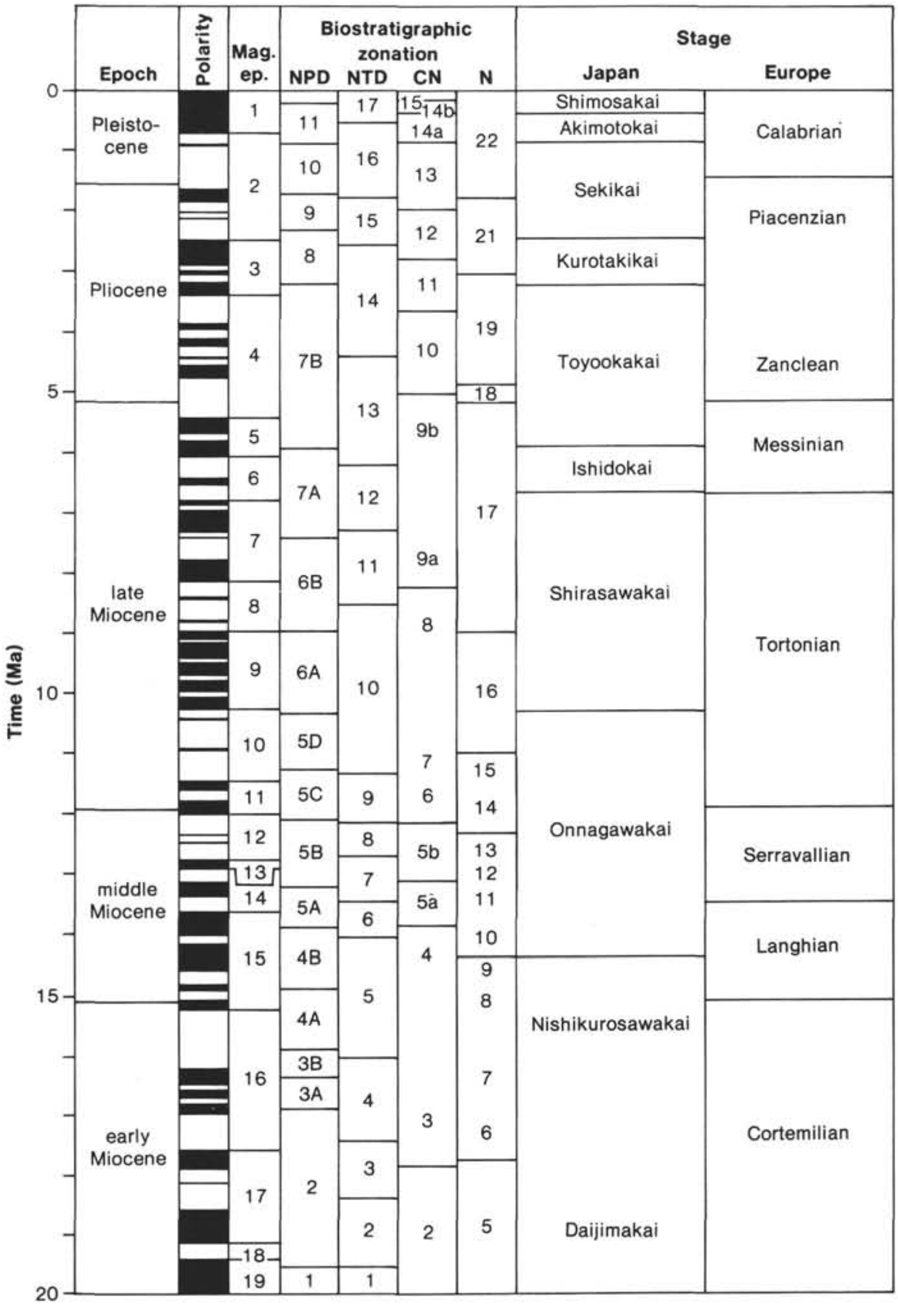


Figure 1. Magnetobiostratigraphic timetable. Diatom biostratigraphy and magnetostratigraphy are based on the Site 584 results (Akiba, this volume; Niitsuma, this volume); Italian stages are based on the magnetostratigraphy of stage stratotypes (Nakagawa et al., 1977; in press) and Ryan and others (1974); Japanese stages are from Niitsuma and Akiba (1983); biostratigraphic compilation is mainly based on Oda and others (1983). Mag. ep.: magnetic polarity epoch; NPD: Neogene North Pacific Diatom Zone (Akiba, this volume), NTD: Neogene Tropical Diatom Zone (Barron, in press), CN: Neogene Coccolith Zone (Okada and Bukry, 1980), N: Neogene Planktonic Foraminiferal Zone (Blow, 1969).

The calculated rate agrees with the actual rate established by a biostratigraphic datum plane at 6 Ma (von Huene et al., 1980). Relative motion of the Pacific Plate and the Eurasian Plate is 11 cm/year = 110 km/Ma (Minster and Jordan, 1978). Using the equation for r, we can compute sediment accumulation rate along the forearc area and calculate the tectonic free rate as 91 m/Ma at trench axis and 110 m/Ma at the deep-sea terrace. These calculated rates can then be used as a standard rate for consideration of tectonic disturbances. If we get a rate different from 110 m/Ma for the deep-sea terrace, we should consider that the rate was controlled by other factors, for example, tectonic subsidence or fluctuating rates of sediment input.

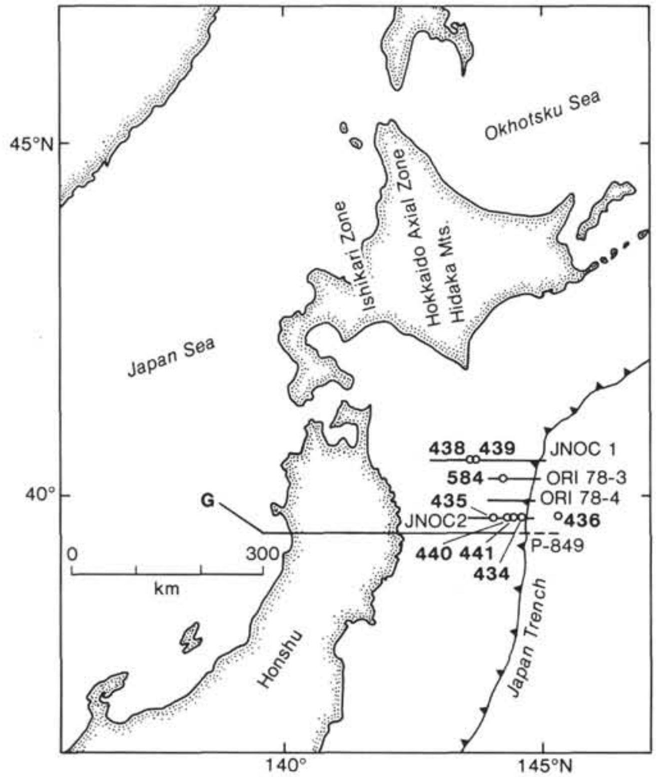


Figure 2. Location of DSDP drilling sites, multichannel seismic reflection profiles in the Japan Trench forearc area (JNOC 1, 2; ORI 78-3, 4; P-849: Nasu et al., 1979; von Huene et al., 1980, 1982; Honza et al., 1978) and geologic cross section (G: Ishiwada et al., 1977).

Sediment Accumulation Rates

The relation of sub-bottom depth to age is variable along the Japan forearc (Fig. 5). Pleistocene sediments reach a thickness of 310 m at Site 440, but Sites 434, 438, 441, and 584 are significantly thinner than Site 436 on the abyssal plain. The thickness of the Pleistocene sediments is related to the dip of the submarine topography around the drill sites. Site 440 is located on the inner side of the midslope terrace, and the upper part of the drilled sediments are trough-fill sediments with semi-horizontal depositional surfaces. Site 438 is located on the inner margin of deep-sea terrace on a gently dipping seafloor, about 2°. Sedimentation was continuous from the Pliocene to Pleistocene at both sites, but unconformities occur at the base of the Pleistocene sediments at Sites 584, 441, and 434, located on the upper and lower trench slopes (Fig. 3). The Pleistocene sediments in the forearc area indicate continuous sedimentation.

The upper Miocene to lower Pliocene sediments (6–3 Ma) underlie the Pleistocene sediments and have uniform thickness. These sediments are significantly thicker in the forearc area than the 210 m drilled at Site 436 on the abyssal plain, and the thickness at Site 438 fits well with the value calculated from the exponential distribution equation of the previous section. Thicknesses of about 500 m in the trench slope area at Sites 434, 441, and 584 are larger than the 380 m drilled on the lower deep-sea terrace at Site 438. The uniform distribution of the thickness in the forearc area suggests that the submarine topography was gentle and that the lower deep-sea terrace was relatively steeper than the trench slope in the late Miocene and Pliocene.

Sediments underlying the Pliocene-upper Miocene were drilled at Sites 438, 439, and 584 and dated as late Oligocene to late Miocene (25–10 Ma). Their equivalents were not recovered in the trench lower slope (Sites 441 and 434). Sediment accumulation rate curves for Sites 438 and 584 (Fig. 6) are zoned with diatom fossils and correlated with each other. The rate of accumulation changed drastically at Site 584 and hiatuses (or unconformities) are detected at 590 and 870 m sub-bottom (8.3–10.0 Ma and 13.3–14.5 Ma, respectively). At Site 438, the changes in rate are less abrupt, but the unconformities are also detected at 450 and 685 m, each with respective ages of about 1 Ma later than their counterparts at Site 584. The upper hiatus correlates with the upper boundary of the Oligocene to upper Miocene sediments. Any discussion of the rate of the sediment supply requires correction for bedding tilt and compaction. Bedding tilts for Site 584 are known, because all samples taken for paleomagnetic study were measured for relative orientation and bedding tilt against the core tube (Niitsuma, this volume). The amount of compaction can be corrected by the shipboard measurements on porosity (site chapter, Site 584, this volume). The maximum tilt of bedding is 75° and the correction factor is 0.26, thus the drilled depth interval of the sediment layer is four times larger than its true thickness. The porosities vary from 36 to 76% and the minimum values are found at the upper hiatus (Fig. 6). Even after these corrections for tilt and porosity (adjusted to 65% in Fig. 6) are made, the general trends of the sediment accumulation rate are not affected.

At the time of the upper hiatus (NPD6B, NPD7A), resting spores of *Chaetoceros* spp. were ten times as abundant as elsewhere, and the number of the spores outnumber the total number of diatom fossil specimens two to one. In contrast, the total number of diatom fossils is several times larger than the number of the spores in the other time intervals at both Sites 438 and 584. Because the resting spores of *Chaetoceros* are formed in neritic environments, the dominance of the resting spores in a particular horizon indicates special conditions under which shallow marine biogenic grains were transported without terrigenous matter. The dominance of resting spores is explained by the extremely low accumulation rate of terrigenous grains and selected dissolution of the diatom shells, because spores are resistant to corrosion, or by the increased content of spores relative to terrigenous grains. Intervals of spore dominance are not restricted to horizons with very low accumulation rates, indicating that spore dominance is not only caused by selective dissolution, but also by the increase in relative portion of the spores in the grains transported from nearshore. If we can assume uniform productivity of spores, the terrigenous grain abundance probably decreased because of less rapid erosion of relatively gentler topographic relief of the land. Such a drastic change on the Japanese Island Arcs has been detected, and the duration of the remarkable decreases in the accumulation rate of the late

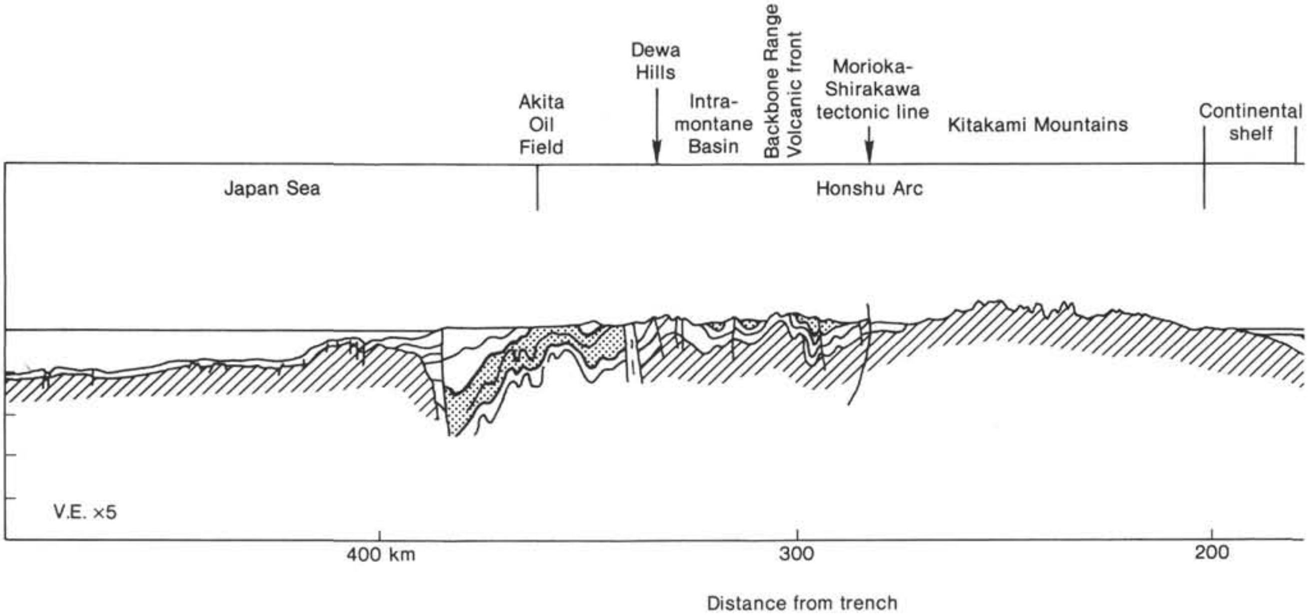


Figure 3. Geologic cross section based on the multichannel seismic reflection data in the Japan Trench forearc area (JNOC 1, 2, ORI 78-3, 4, P-849: Nasu et al., 1979; von Huene et al., 1980; 1982; Honza et al., 1978) and cross section from Ishiwada and others (1977). Numbers represent DSDP sites. Dotted layers represent the Middle Layer and its correlatives. V.E. = vertical exaggeration.

Miocene sediments can be correlated with the hiatuses of the forearc area and explained by the detachment of the descending Pacific Plate (Niitsuma, 1978). The remarkable time interval in the sedimentary sequences is defined by the Japanese stage, "Shirasawakai" (Niitsuma and Akiba, 1984; in press). The reduction of the sediment input is also evident in the changes in accumulation rate at Site 436 (Fig. 4). The correlation of the changes in sedimentation rate on the land and in the forearc area suggests that the tectonic changes in both areas were controlled by the same primary factor, the subduction of the Pacific Plate.

ANALYSIS OF MULTICHANNEL SEISMIC REFLECTION DATA

An interpretive cross section drawn from DSDP sites and multichannel seismic reflection data in the Japan Trench-forearc area (Fig. 3; Nasu et al., 1979; von Huene et al., 1980, 1982; Honza et al., 1978), combined with a geologic cross section across the island arc (Ishiwada et al., 1977) shows a division of the Tertiary and Quaternary sediments into three layers (Fig. 3).

The Upper Layer is trough-fill, identifiable in the deep-sea terraces (JNOC 2, P-849) and on the midslope terrace (JNOC-2, ORI 78-4), and drilled at Site 440 on the inner margin of the midslope terrace. The main part of this Upper Layer is Pleistocene, but its lower boundary may extend to the upper Pliocene. Reflectors representing the trough-fill sediments dip landward, as clearly shown in ORI 78-4 for the midslope terrace (Fig. 7) and in JNOC 2 for the deep-sea terrace (Fig. 8). The feature suggests that the trough filling is not caused by the subsidence of the trough, but by the uplift of the outer ridge of the trough, because the ridge is now under erosion or under almost no deposition. If the axis and inner ridge of the trough remain stationary compared with the outer ridge, the outer ridge will function as a dam, and the subhorizontal or slightly eastward-dipping surface of the trough-fill sediments should tilt toward land by the relative uplift of the outer ridge, as suggested by von Huene and Arthur (1982).

The Middle Layer is the most continuous in the cross section, and uniformly covers the forearc area (Fig. 3). The Middle Layer was drilled at most of the sites in the forearc area, and its main part is Pliocene to upper Miocene.

The Lower Layer on the multichannel seismic profile unconformably covers the pre-Tertiary basement, and its thickness changes by thinning or erosion. von Huene and others (1980; 1982) considered the change of the thickness to be due to thinning around the ancient "Oyashio Paleolandmass." We have another explanation for erosion after the deposition of the layer or simply for nondeposition on the slope. The upper trough-fill is thickest where the Lower Layer is thinnest (Profiles JNOC 1, 2, P-849; Figs. 3 and 8). Evidently, subsidence for the trough fill of the Upper Layer and uplift for erosion or thinning of the Lower Layer occurred in the same portion of the forearc area, a portion that should be very active tectonically. As a result, the total sediment accumulation above the unconformity on the pre-Tertiary basement is of uniform thickness. It seems to be too simple an explanation to estimate the erosion of the terrestrial environments from unconformities or thinning of a sediment layer displayed in the seismic profile. We can find many examples on the seafloor where ancient sediments are exposed. The seismic profile shows distinctly the erosion surface on the slope and depositional surface of the top of the trough-filling sediments. The relation between thickness of the Upper Layer and surface slope in the seismic profiles of this area suggests that erosion occurs on the seafloor where the dip exceeds 2°, which is the

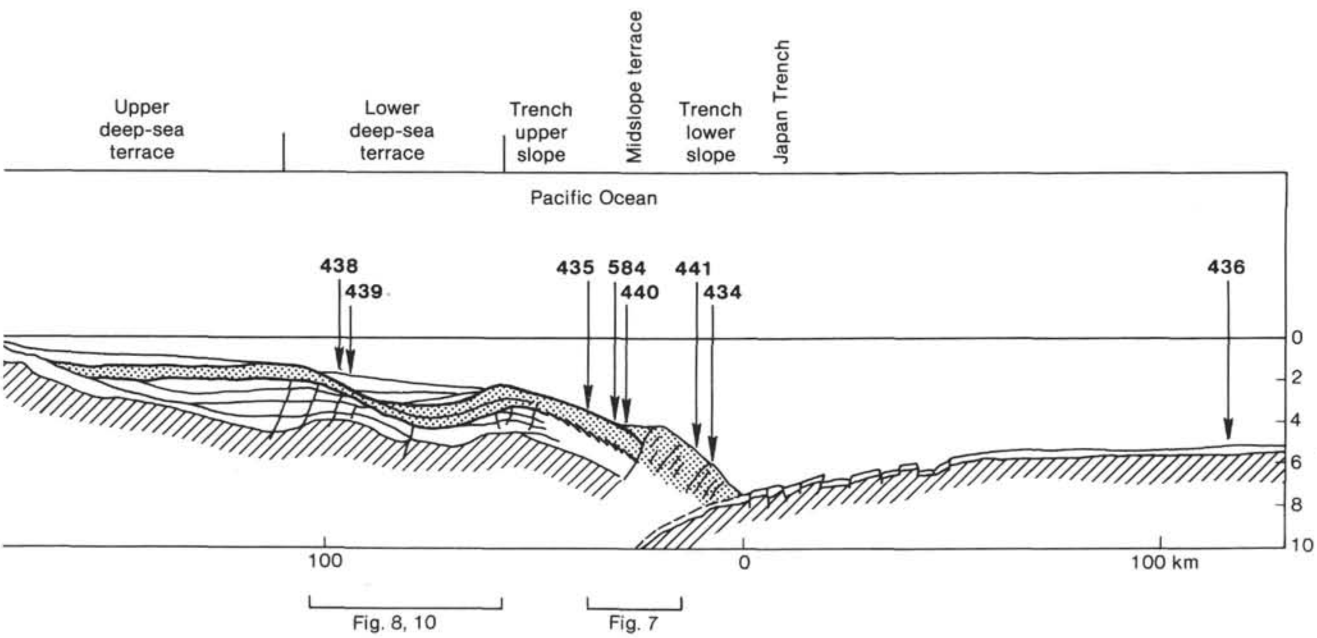


Figure 3. (Continued).

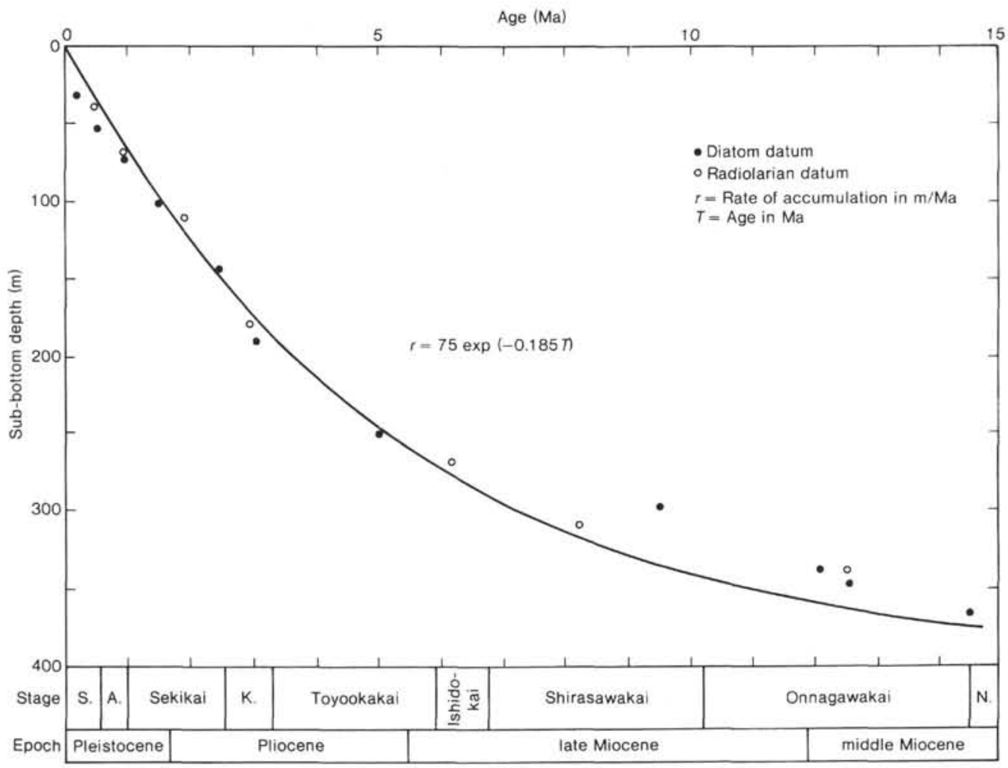


Figure 4. Relation between sub-bottom depth and age in Site 436 on the abyssal plain off the Japan Trench (after von Huene et al., 1980).

surface slope at Site 438. If we accept that surface conditions of deposition or erosion are strongly controlled by the dip angle of the seafloor, then the rate of accumulation has an inverse correlation with the dip angle of the seafloor and can serve as a "paleotiltmeter." The erosion and thinning out of the Lower Layer results from tilting of the seafloor toward the trench, caused by the relative subsidence of the present outer ridge of the trough. If we consider the location of trough-filling Upper Layer and nondepositional Lower Layer as a node, the zone dipped toward the trench after deposition of Lower Layer, it dipped gently toward the trench during deposition of the Middle Layer, and it dipped toward land during deposition of the Upper Layer. Because the midslope ter-

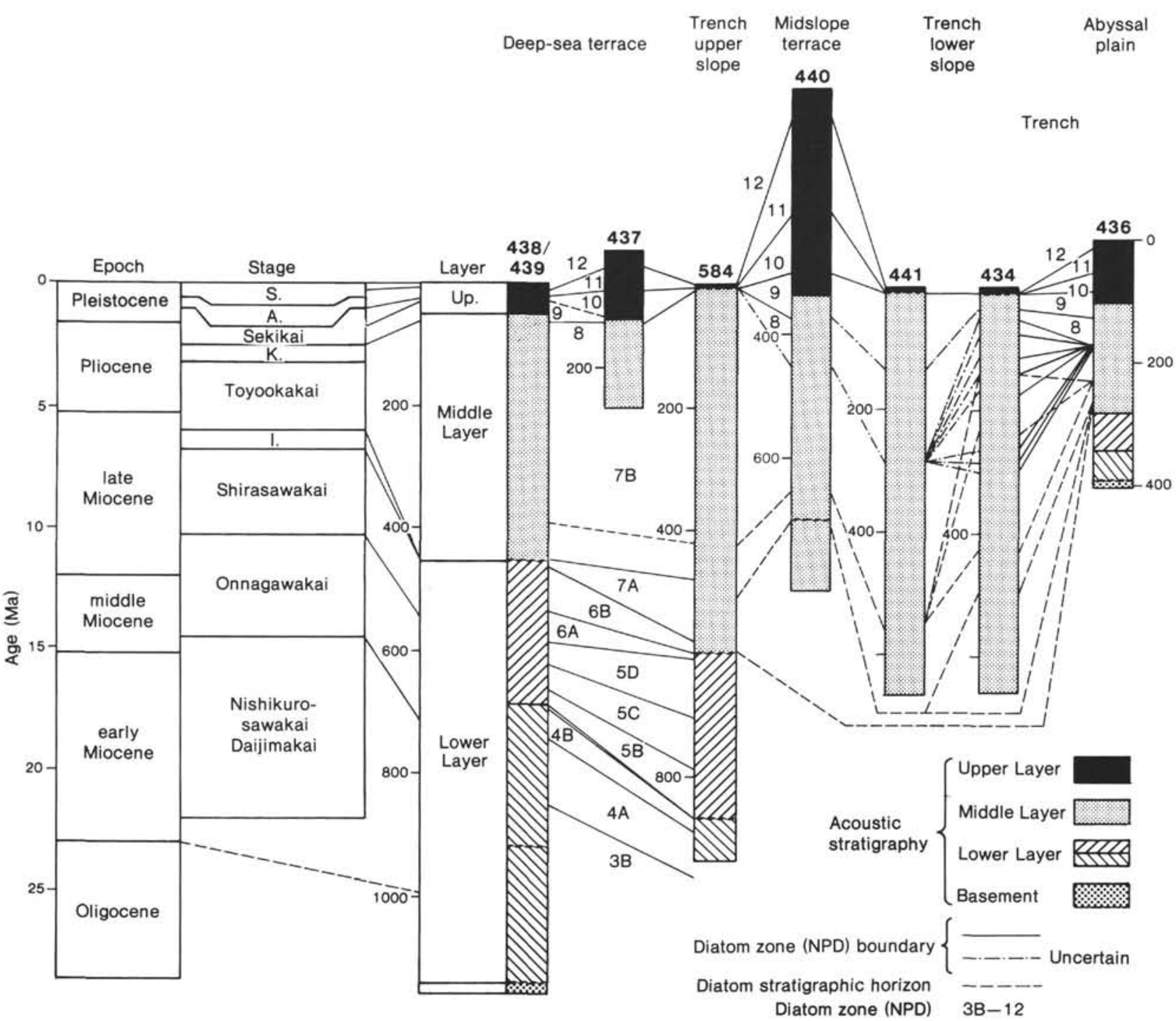


Figure 5. Relation of sub-bottom depth in the sedimentary sequences and ages in the drilled sites of Japan Trench transect, based on diatom biostratigraphic correlation. Crossing of the tie-lines at Site 434 represents the section repeated by the accretionary process. S.: Shimosakai, A.: Akimotokai, K.: Kurotakikai, I.: Ishidokai. Numbers 0–1000 (expressed in hundreds) represent sub-bottom depth (m).

race is located on the boundary of the island-arc basement, this zone should be most sensitive to uplift and subsidence connected with plate subduction.

We analyzed multichannel seismic reflection Profile JNOC 2 to clarify the tectonic movement of the forearc area. The first step of the analysis was to divide the seismic profile into 13 layers and pre-Tertiary basement. The second step was to convert the original time section to the depth section (Fig. 9 after Saki et al., 1980). The depth section of the 13 layers is shown in the front panel of Figure 10. The third step was to estimate the submarine topography at the time of the deposition of each layer, referring the thickness of the layer as used as paleotiltmeter, assuming that the gradient of the free depositional surface is 0.34°, the maximum gradient for deposition is 2.24°, and the gradient of the erosional surface is more than 3.45° (upper part of Fig. 10). The fourth step was to calculate the depth of the basal unconformity of the Tertiary sediments from the seafloor (lower part of Fig. 10).

The submarine topography has changed dynamically, subsiding more than 1000 m since the middle Miocene (Fig. 10), and allowing deposition of the trough-fill and the formation of the deep-sea terrace. The present form of the submarine topography in the forearc area persisted since the Pleistocene; a different submarine topography had developed before the Pliocene. Figure 10 also shows the relative uplift of the outer ridge of the trough and the upper part of the trench upper slope since the middle Miocene. Reconstruction based on the sedimentary layers excludes the existence of an "Oyashio Paleolandmass," because it requires deposition on unrealistically steep slopes around the paleolandmass. The paleontologic estimate of the depth of the depositional environments for Sites 438 and 439 (von Huene, 1980) is consistent with our reconstruction.

Current Direction in Sandstone of the Lower Layer

Paleomagnetic samples were from a cross-laminated sandstone in the interval between 925 and 993 m of Site

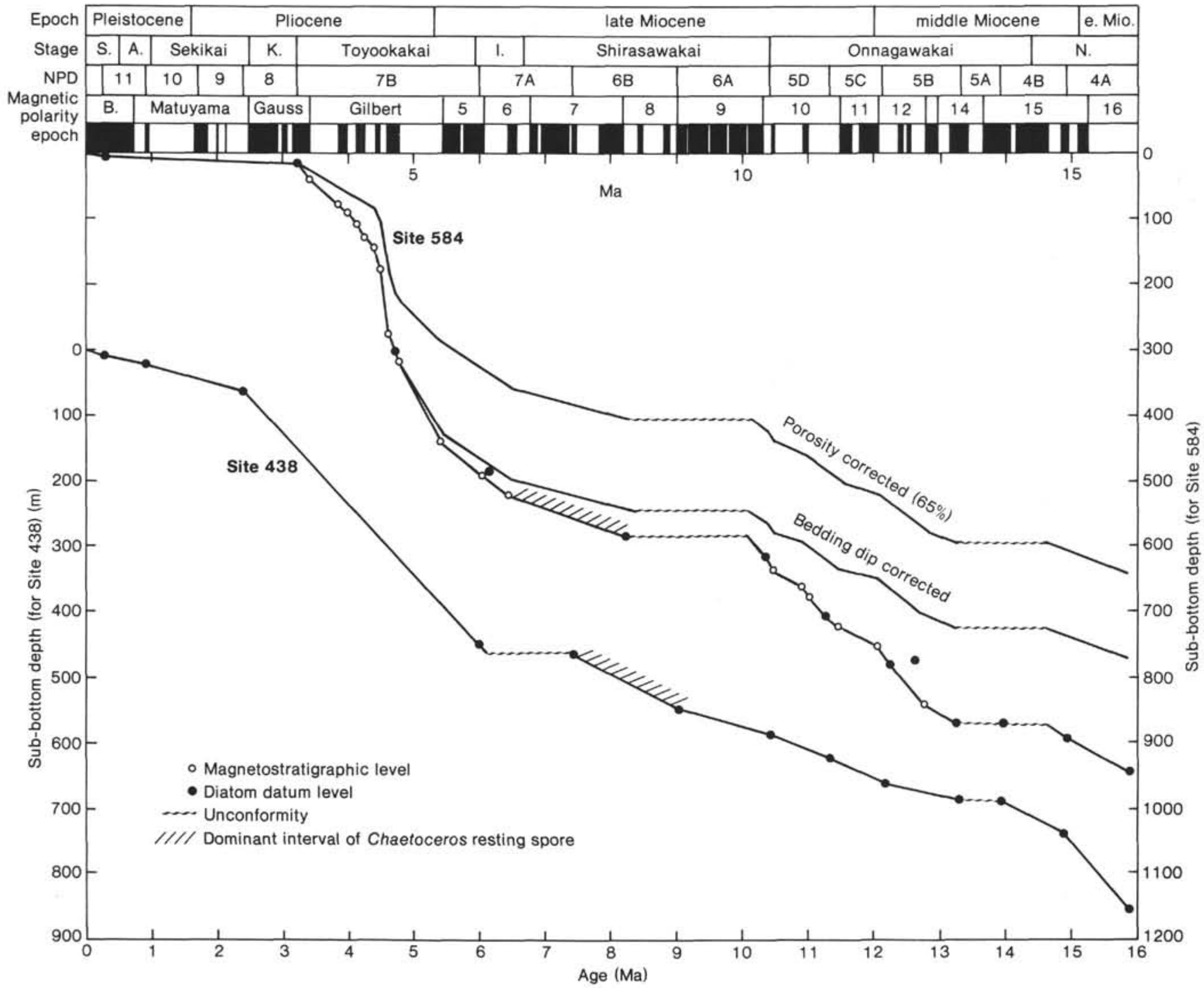


Figure 6. Relation of sub-bottom depth to age at Sites 438 and 584. Relation of sub-bottom depth and age after correction for tilt and compaction, in which porosity is adjusted to 65%, is also shown for Site 584. e. Mio.: early Miocene, S.: Shimosakai, A.: Akimotokai, K.: Kurotakikai, I.: Ishidokai, N.: Nishikurosawakai, B.: Brunhes.

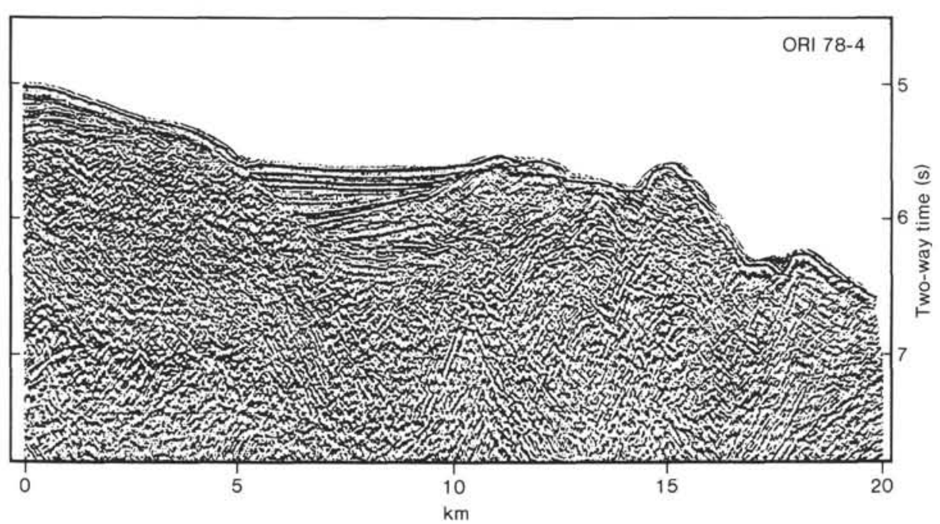


Figure 7. Multichannel seismic reflection Profile ORI 78-4 (Nasu et al., 1979) showing the reflectors with landward dip under the midslope terrace.

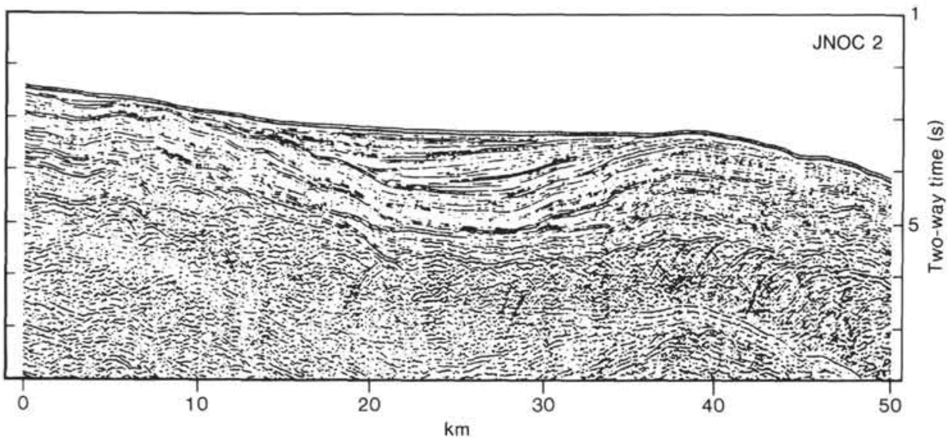


Figure 8. Multichannel seismic reflection Profile JNOC 2 (von Huene et al., 1980) showing the reflectors with landward dip under the deep-sea terrace.

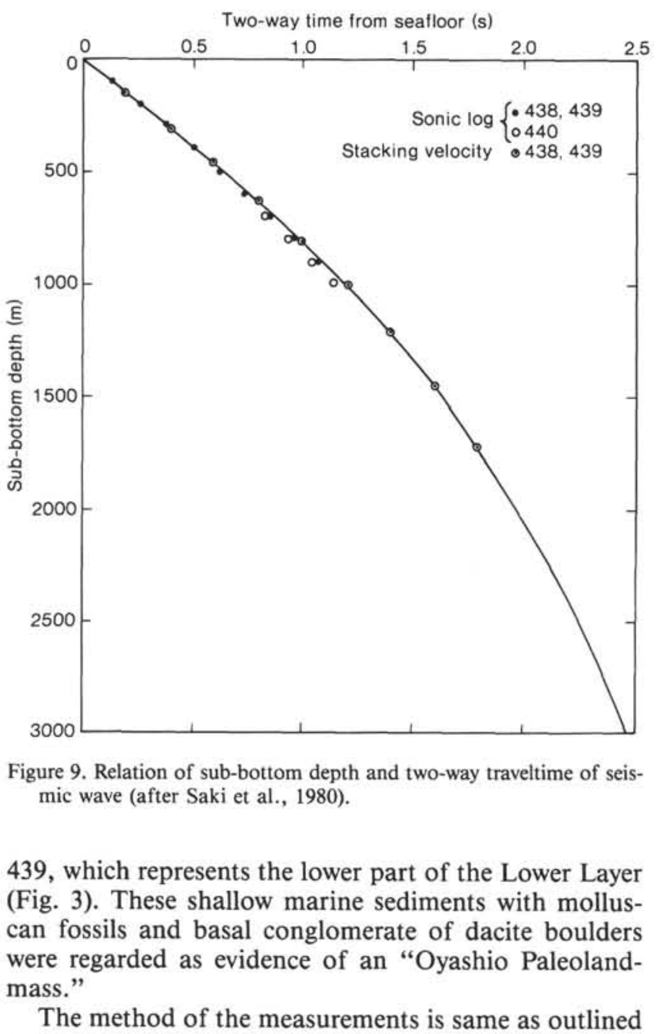


Figure 9. Relation of sub-bottom depth and two-way traveltime of seismic wave (after Saki et al., 1980).

439, which represents the lower part of the Lower Layer (Fig. 3). These shallow marine sediments with molluscan fossils and basal conglomerate of dacite boulders were regarded as evidence of an "Oyashio Paleolandmass."

The method of the measurements is same as outlined by Niitsuma (this volume), and magnetic cleaning was carried out with alternating field (AF) demagnetization of 15 mT (Table 1, Fig. 11). The magnetic intensity is 9.5×10^{-4} to 3.3×10^{-3} A/m after 15-mT AF demagnetization. Inclinations of all samples are positive, and the mean and standard deviation are $53.1 \pm 6.3°$, except for Sample 439-14-2, 48–50 cm. An inclination of 76.3° of that sample is explained by a geomagnetic polarity transition. Bedding planes of the sediment dip 11 to 24° and the paleomagnetic orientation of the dip azimuth is $113.2 \pm 24.0°$ with respect to magnetic north, directions that are consistent with the eastward-dipping reflectors displayed in multichannel seismic reflection Profile JNOC 1 (Fig. 3).

The dip azimuths of the cross laminations with respect to bedding planes are scattered, but mainly eastward. The scattered dip directions indicate unstable current directions during deposition of the sandstone on a shallow, eastward-dipping seafloor. If an "Oyashio Paleolandmass" existed to the east of Site 439 (von Huene et al., 1980; 1982), the direction of the cross-bedding should be westward from the transgressive stage of the late Oligocene to late Miocene, not eastward! So both the cross-bedding orientations and seismic stratigraphy are at variance with the assumption of an "Oyashio Paleolandmass."

TECTONIC EVOLUTION OF FOREARC AREA

The pre-Tertiary basement was covered with upper Oligocene shallow marine sandstone and conglomerate, a sedimentation cycle that continued into the late Miocene, forming the Lower Layer of cross section (Fig. 3). The seafloor gradually deepened (von Huene et al., 1980; 1982) and, where the dip steepened toward the trench, a part of the sedimentary overburden was eroded. The outer boundary of the pre-Tertiary basement subsided. In the last phase of the cycle, the steepest dips were in the inner part of the boundary. Input of terrigenous sediment decreased, and most of the forearc was nondepositional (except for accumulation of resting spores of marine benthic diatoms transported from shallow water). This stage is the boundary of the Lower and Middle layers in the cross section.

In response to regional tectonics, the terrigenous input increased, and sediments corresponding to the Middle Layer (Fig. 3) uniformly covered the forearc area. Subsequently, relief of submarine topography increased,

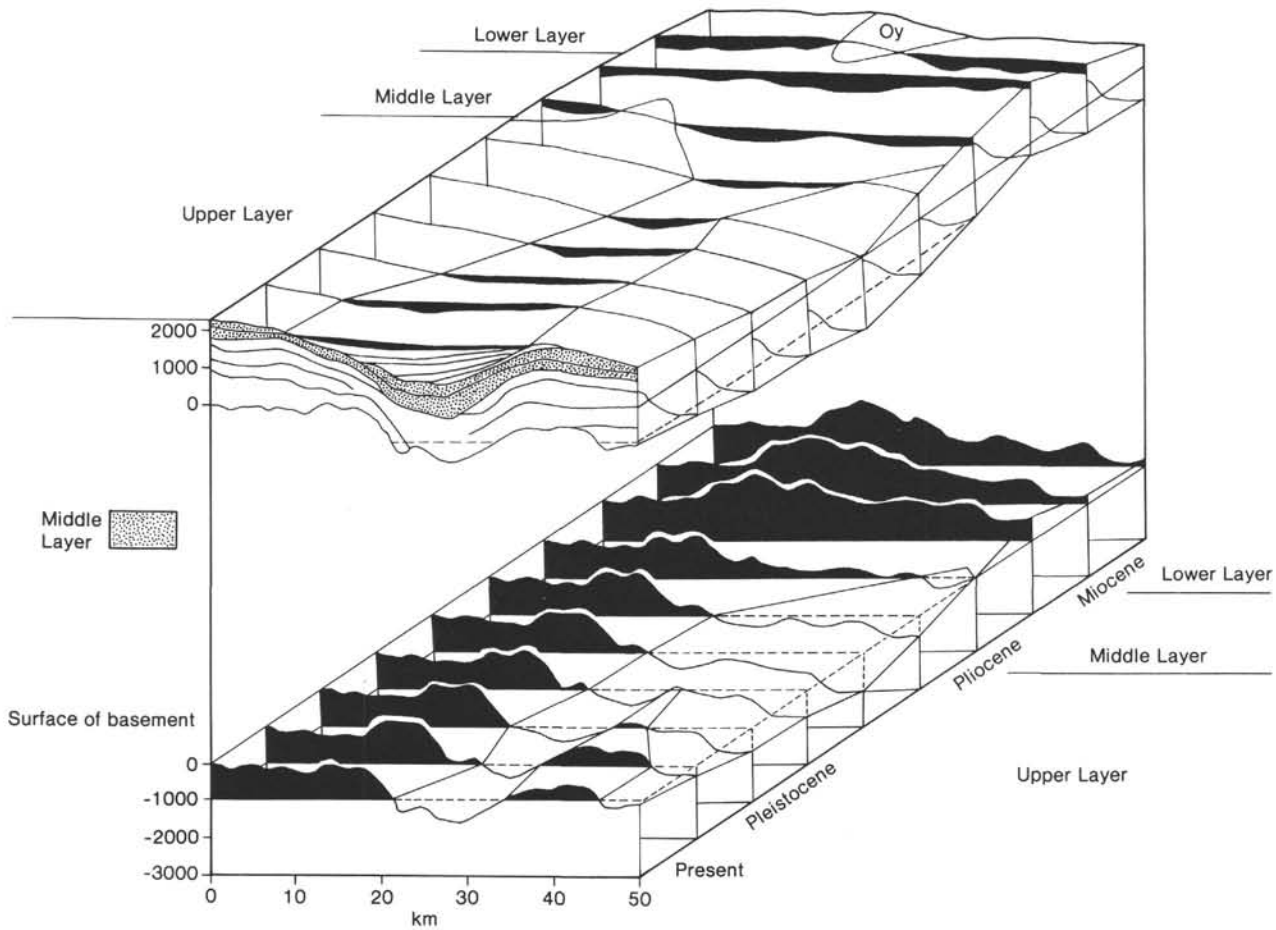


Figure 10. Changes in the submarine topography in the lower deep-sea terrace of the Japan Trench since the middle Miocene and tectonic movement of the pre-Tertiary basement, based on the thickness and form of each sedimentary layer. Each panel corresponds to the paleobathymetric section and the depth of the pre-Tertiary basement at the time of the boundary of each sedimentary layer, which is darkened. Division into 13 sedimentary layers is based on the multichannel seismic Profile JNOC 2 (Fig. 8). Conversion from time-section to depth-section is made by the relation shown in Figure 9. The position of the west end of the basement is adjusted to 0 m. Oy: proposed portion of "Oyashio Paleolandmass" by von Huene and others (1982), which was not paleoland area but slope in middle to late Miocene. Darkened areas in lower block represent basement, which is higher than the − 1000 m level.

Table 1. Paleomagnetic analysis of the early Miocene cross-bedded sandstone in Hole 439, located on the deep-sea terrace of the Japan Trench.

Core-Section (interval in cm)	Sub-bottom depth (m)	Dip of bedding plane		Magnetic inclination (error angle)	Magnetic intensity (A/m)
		Angle	Azimuth[a]		
13-1, 71-73	926.22	18	74.0	36.8 (3.9)	3.34×10^{-3}
14-2, 48-50	933.99	21	259.8	76.3 (6.5)	9.52×10^{-4}
15-3, 123-125	939.24	13	114.7	50.4 (3.3)	1.89×10^{-3}
15-4, 91-93	940.42	15	107.8	52.8 (5.8)	1.20×10^{-3}
21-1, 93-95	992.94	24	148.8	63.1 (1.4)	3.32×10^{-3}
Average ± standard deviation			111.3 ± 26.6	50.8 ± 9.4 (except 14-2)	

[a] Magnetic oriented.

and sediments were dammed in subsiding troughs. The trough-fill corresponds to the Upper Layer of the cross section.

The most significant change in the Neogene history of tectonism occurred in the late Miocene, when relative subsidence turned to uplift at the outer boundary of the basement. This tectonic change coincides with the amount of change in the terrigenous input. The tectonic changes in the late Miocene explain aspects of the Neogene geology on the Japanese Island Arcs. Perhaps these changes were caused by the detachment of the subducting Pacific Plate after the opening of the Japan Sea and Kurile Basin (Niitsuma, 1978; Niitsuma and Akiba, 1984).

Extension of the Forearc Area

Using seismic reflection profiles, we can trace the forearc area along the Japan Trench to the south and the outer boundary of the island arc basement to the east (Honza et al., 1978). In the Joban area, Paleogene and Neogene sediments are widely exposed (Fig. 12). The sedimentary sequence is divided into the Shiramizu, Yunagaya, and Taga groups (Mitsui, 1971; Kato, 1980; Fig. 13). The Shiramizu Group is the lowest and is composed mainly of terrestrial coal measures. The Goyasu Formation is the lower part of the overlying Yunagaya Group and consists of shallow marine sandstone intercalating conglomerates of dacite and dacitic ignimbrite boulders in the transgressive stage of the late Oligocene to early Miocene. Because the change in sedimentary environments and the dacitic conglomerate are both similar to those in Site 439, the late Oligocene to early Miocene

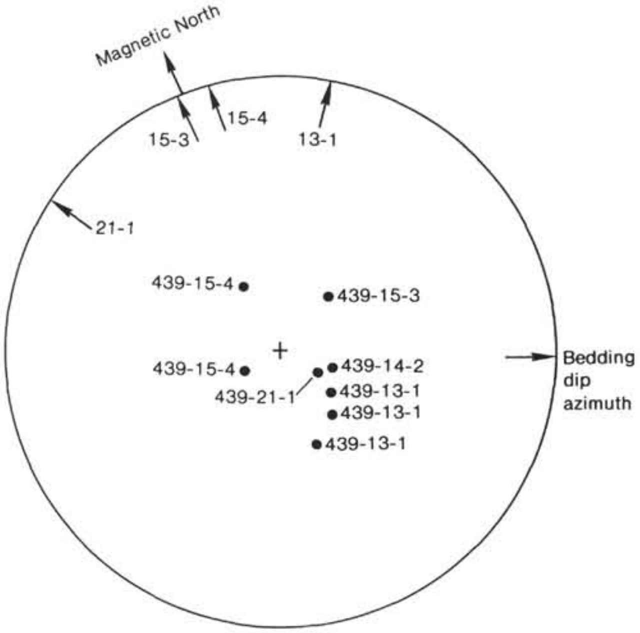


Figure 11. Upper hemisphere, stereo net plot of poles of the cross-bedding plane in Hole 439 plotted against dip azimuth of bedding plane after bedding tilt correction. Numbers represent samples from Hole 439. Magnetic declinations and mean declination of each sample are also shown.

transgression and the dacitic activity were not a limited, local phenomenon.

The Japan Trench joins the Kurile Trench several tens of kilometers north of the drilled sites. There are two possible northern extensions of the forearc; one to the west of the Hokkaido axial zone and the second along the Kurile Trench. A remarkably thick marine sequence outcrops along the westside of the Hokkaido axial zone (Fig. 14). Correlation of these sequences based on their diatom biostratigraphy shows a regional unconformity at NPD8-NPD10 (Fig. 15) and an age that correlates with unconformity between the Upper and Middle layers in the forearc (Fig. 3). Above the unconformity, Pleistocene sediments corresponding to the Upper Layer are of shallow marine or terrestrial origin and the rate of sediment accumulation is less than 100 m/Ma for the most part, except to the northeast of Tomakomai, which is the southern end of the Ishikari Zone. The upper Miocene to Pliocene sediments, corresponding to the Middle Layer, are distributed continuously across the belt and the sediment accumulation rate is 110–350 m/Ma (Fig. 15). These sediments are a diatomaceous mudstone facies. Under the diatomaceous mudstone is a hiatus represented by an abundance of resting spores of *Chaetoceros* spp. (⊕ in Fig. 15) that extends to the Biratori area (see 3, Figs. 14, 15) at the southern end of the belt along the west flank of the Hokkaido axial zone. These sedimentary sequences and indicated timing of tectonic uplift are similar to those in the forearc area. Spore-dominated sediments are found also in the Atsunai area (4, Figs. 14, 15) east of the southern end of Hokkaido axial zone along the Kurile Trench. The sedimentary succession and tectonic changes there since the late Miocene are similar to those both in the forearc area and to the west of the axial zone. These similarities indicate that, since the late Miocene, the northern extension of the forearc branched to the north along the Hokkaido axial zone and to the east along the Kurile Trench.

Several thrusts cut the Tobetsu Formation of the Ishikari Belt (Fig. 16; Mitani, 1978). These offsets in the Pliocene of the Middle Layer indicate east-west compressional stress after the Pliocene. Tectonic movement is directly related to the collision of the Honshu and Kurile arcs and to the building of the Hidaka Mountains in the Hokkaido axial zone. Pleistocene mountain building raised the marine sediments above sea level. Uplift of the marine sediments occurred in the Kurotakikai and the early part of the Sekikai of the Japanese Neogene stages. The Kurotakikai corresponds to the uplift of the Kanto Mountains in central Japan caused by a collision at the junction of the Honshu and Izu arcs. Evidently collision and uplift occurred at both the north and south ends of the Honshu Arc, and those events controlled the deposition of the sedimentary sequences in the forearc basin.

NORTHERN EXTENSION OF THE OUTER BOUNDARY OF ISLAND ARC BASEMENT

The southern extension of the outer boundary of island arc basement has been determined by the seismic profiler, as mentioned in the previous section. The age of the basement is probably Cretaceous and it may extend to the north in the Hokkaido axial zone (Fig. 12). The central part of the axial zone is divided into the West and the Main Hidaka Metamorphic belts. The West Belt is an ophiolite and is covered with Cretaceous forearc sediments (Komatsu et al., 1983; Kiminami and Kontani, 1983). The Main Belt is composed of rock sequences representative of the upper mantle to lower crust of a continent or island arc (Komatsu et al., 1983). The Hidaka Belt is strongly uplifted in the Hidaka Mountains, where these rock sequences are exposed. The Hidaka Main Thrust, a mylonite zone of several tens of meters to 1.5 km in width, separates the section of the ocean crust in the West Belt and the continental crust in the Main Belt. The thrust is a suture between ocean and continental crust. The polarity of the forearc basins in the Cretaceous suggests that the suture zone was a convergent boundary (Okada, 1974) where Paleogene continental crust accreted (Komatsu et al., 1983). In the view of the structure of the basement rocks, the northern extension of the outer boundary of island arc basement can be traced into the suture, because basement is considered to be the accretionary complex of Cretaceous time.

SUMMARY AND CONCLUSIONS

Detailed correlation and chronology of Neogene and Quaternary marine sediments are established by the application of a new standard magnetobiostratigraphic timetable. Based on that chronology for the abyssal plain off the Japan Trench and a calculated rate of accumula-

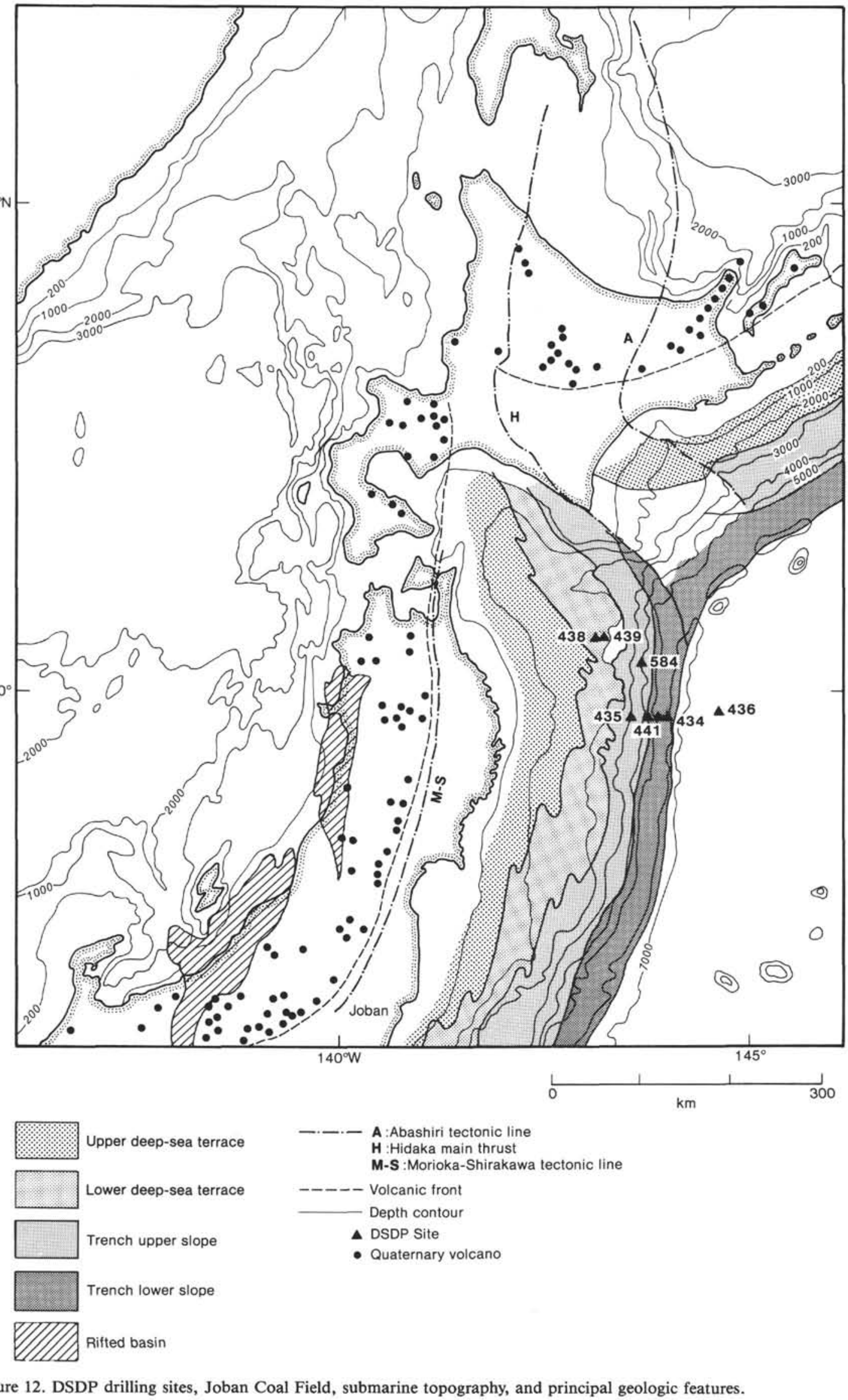


Figure 12. DSDP drilling sites, Joban Coal Field, submarine topography, and principal geologic features.

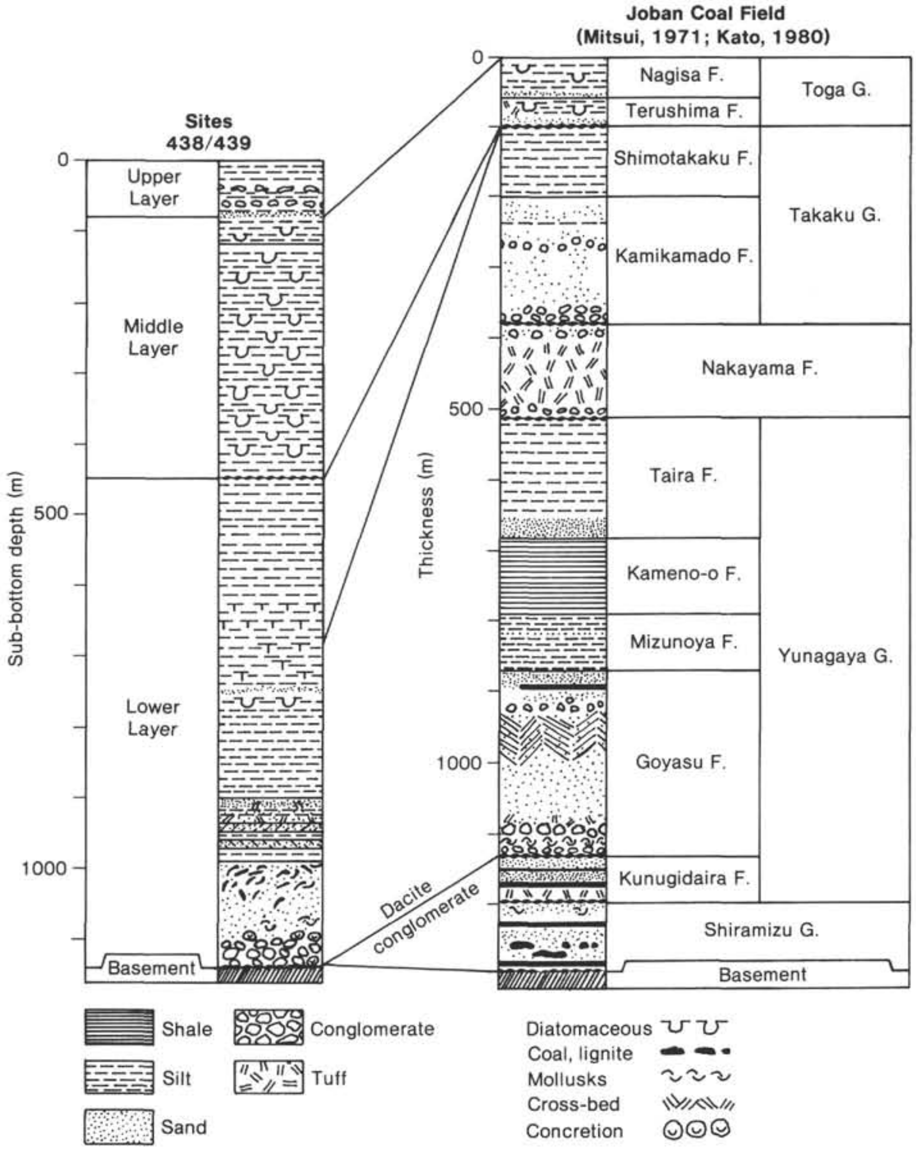


Figure 13. Paleogene and Neogene sedimentary sequences in the Joban Area and Sites 438 and 439 of the forearc of the Japan Trench. F.: Formation; G.: Group.

tion of the sedimentary sequences, we found a general relation of exponentially decreasing accumulation rate with increasing distance from land.

Submarine topography, particularly the dip of the seafloor, controls the rate of accumulation in the forearc: hiatuses occur on slopes greater than 2.24°, and the dip angle and rate of accumulation are negatively correlated for slopes less than 2.24°.

We divided the Tertiary sedimentary sequences of the forearc into Upper, Middle, and Lower layers, based on the rate of accumulation, on spatial changes in the thickness, on hiatuses within the drilled sedimentary sequences, and on multichannel seismic profiles. The Upper Layer is characterized by the trough-fill in the midslope terrace and the deep-sea terrace. The Middle Layer has uniform distribution in the forearc and a rate of sedimentation consistent with the relation between rate of accumulation and distance from land. The Lower Layer is limited in the inner belts of the forearc, along the margin with the mid-slope terrace, and its thickness decreases under the central part of the lower deep-sea terrace.

We reconstructed the evolution of the submarine topography and tectonic movement of the pre-Tertiary basement, based on the sediment accumulation rate and on the spatial distribution of the thickness of sedimentary layers for an estimate of dip angle of the seafloor. The reconstruction suggests that the outer margin of the deep-sea terrace (trench upper slope) changed dynamically with the vertical amplitude of more than 1000 m. The spatial distribution of the three layers can be explained by vertical movements of the outer margin of the deep-sea terrace: local subsidence and slope formation along the central part of the present deep-sea terrace controls deposition of the Lower Layer; a neutral position and formation of a smooth submarine topography for sedimentation of the Middle Layer; and uplift and formation of a trough-ponding sediment of the Upper Layer under the present deep-sea terrace. Chronology of the layers

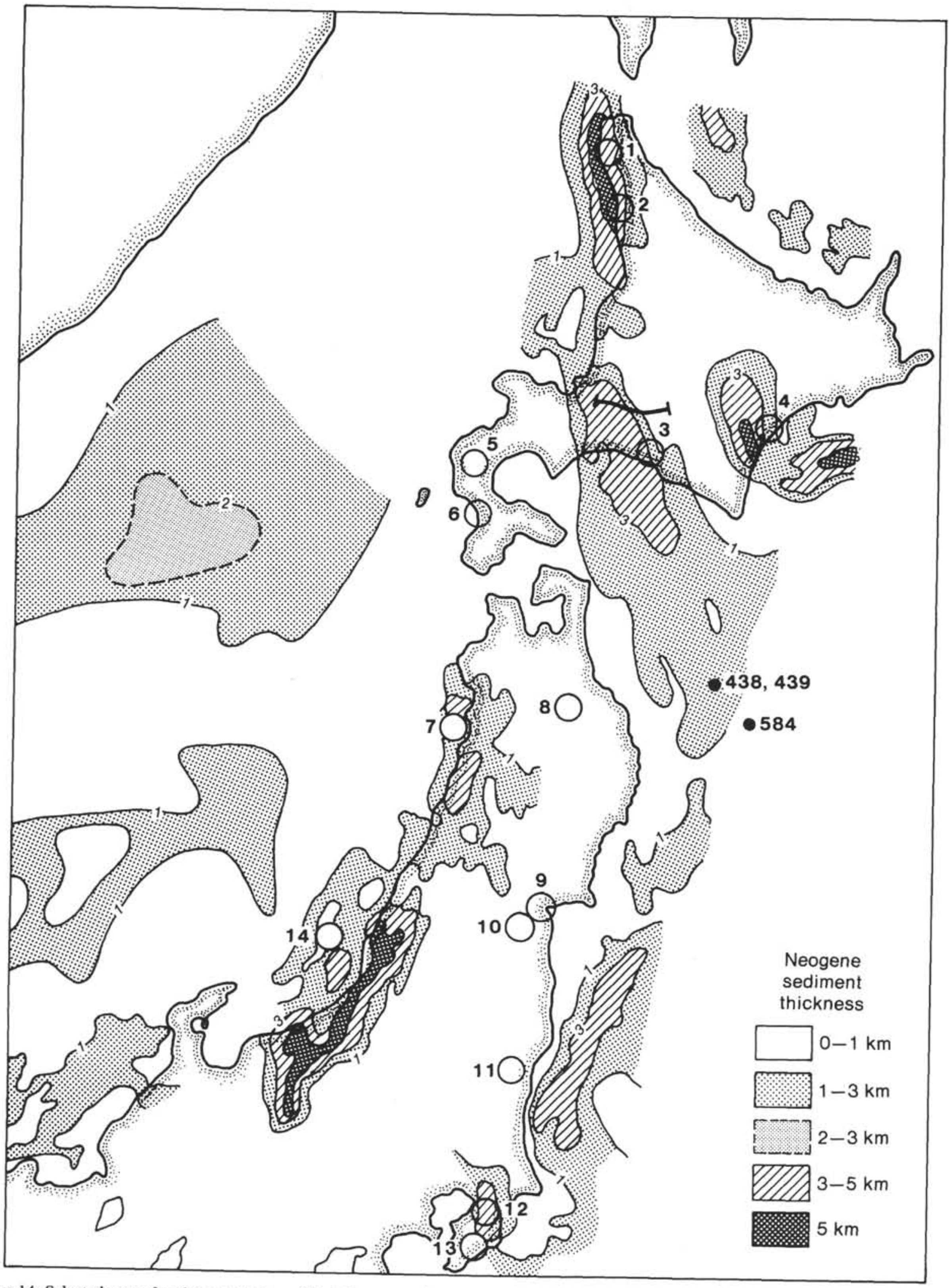
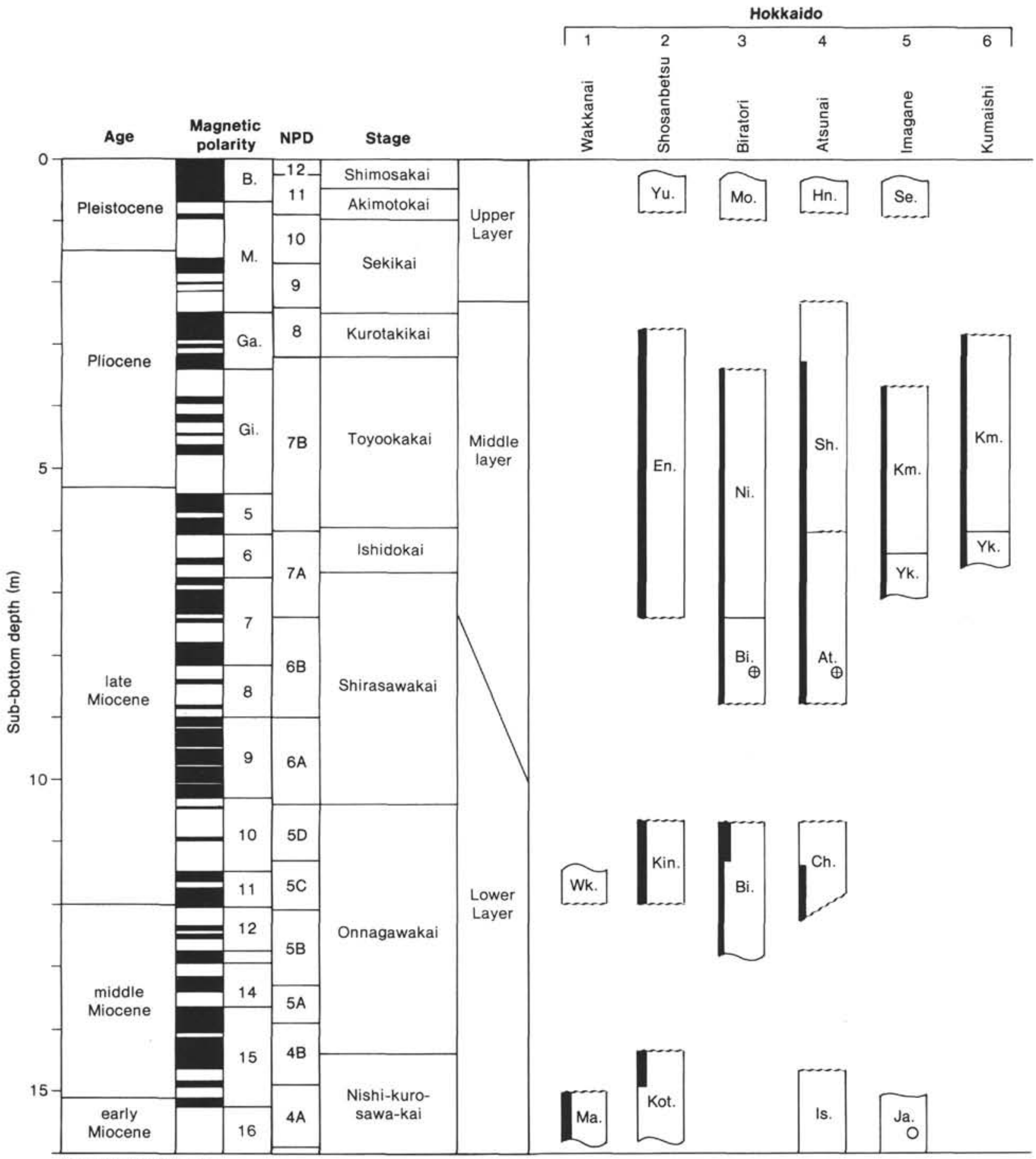


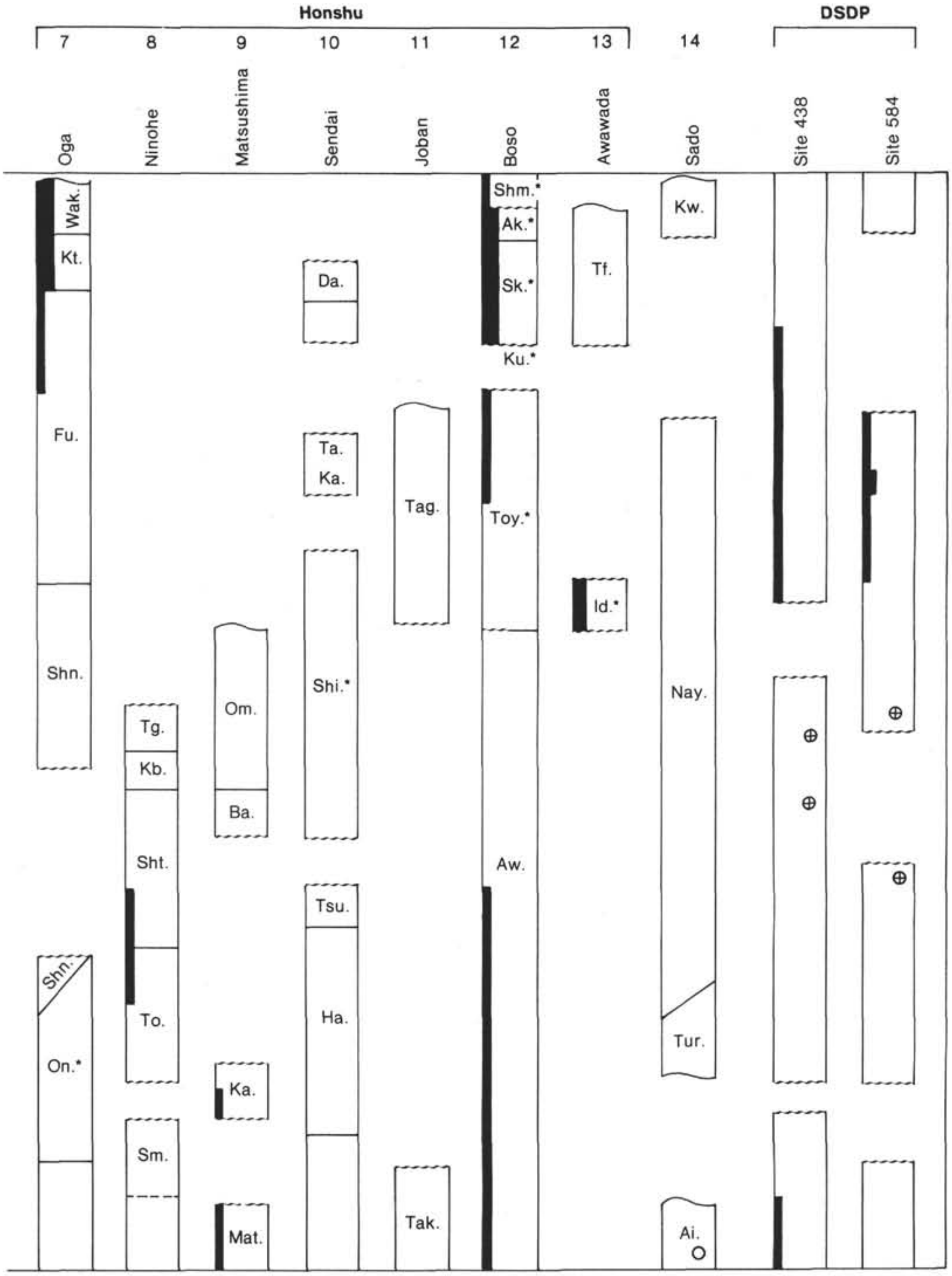
Figure 14. Selected areas for the correlation of the Neogene sedimentary sequence (shown in Figure 15) and distribution of Neogene marine basins (after Ishiwada and Ogawa, 1976). Thick wavy line denotes cross section location (Fig. 16).



F:Formation G:Group

1 Wk.:Wakkanai F., Ma.:Masuporo F.
2 Yu.:Yuchi F., En.:Enbetsu F., Kin.:Kinkomanai F., Kot.:Kotanbetsu F.
3 Mo.:Moebetsu F., Ni.:Nina F., Bi.:Biratori F.
4 Hn.:Honbetsu F., Sh.:Shiranuka F., At.:Atsunai F., Ch.: Chokubetsu F., Is.:Ishiizawa F.
5 Se.: Setana F., Km.: Kuromatsunai F., Yk.: Yakumo F., Ja.: Jara diatomite
6 Km.:Kuromatsunai, Yk.:Yakumo F.

Figure 15. Stratigraphic correlation of Neogene sediments of northern Japan. Location of stratigraphic columns is shown in Figure 14. B.: Brunhes; M.: Matuyama; Ga.: Gauss; Gi.: Gilbert; *: stratotype of the Japanese Neogene stages; : dominant horizon of the resulting spore of *Chaetoceros;* ○: fresh water diatom flora. Rate of sediment accumulation is less than 100 m/Ma: , 100 ~ 500 m/Ma: , more than 500 m/Ma:



7 Wak.:Wakimoto F., Kt.:Kitaura F., Fu.:Funakawa F., Shn.:Shinzan diatomite, On.:Onnagawa F., Nk.:Nishikurosawa F. (Kitazato, 1975)
8 Tg.:Togawa F., Kb.:Kubo F., Sht.:Shitazaki F., To.:Tomesaki F., Sm.:Suenomatsuyama F., Kd.:Kadonosawa F.
9 Om.:Omatsuzawa F., Ba.:Bangamori F., Ka.:Kashimadai F., Mat.:Matsushimawan G.
10 Da.:Dainenji F., Mu.:Mukaiyama F., Ta.:Tatsunokuchi F., Ka.:Kameoka F., Shi.:Shirasawa G., Tsu.:Tsunaki F., Ha.:Hatatate F., Mo.:Moniwa F. (Manabe, 1980)
11 Tag.:Taga G., Tak.:Takaku G.
12 Shm.:Shimosa G., Ak.:Akimoto Subgroup, Sk.:Seki Subgroup, Ku.:Kurotaki Unconformity, Toy.:Toyooka Subgroup, Aw.:Awa Subgroup
13 Tf.:Toyofusa G., Id.:Ishido G.
14 Kw.:Kawachi F., Nay.:Nakayama F., Tur.:Tsurushi F., Ai.:Aikawa F.

Figure 15. (Continued).

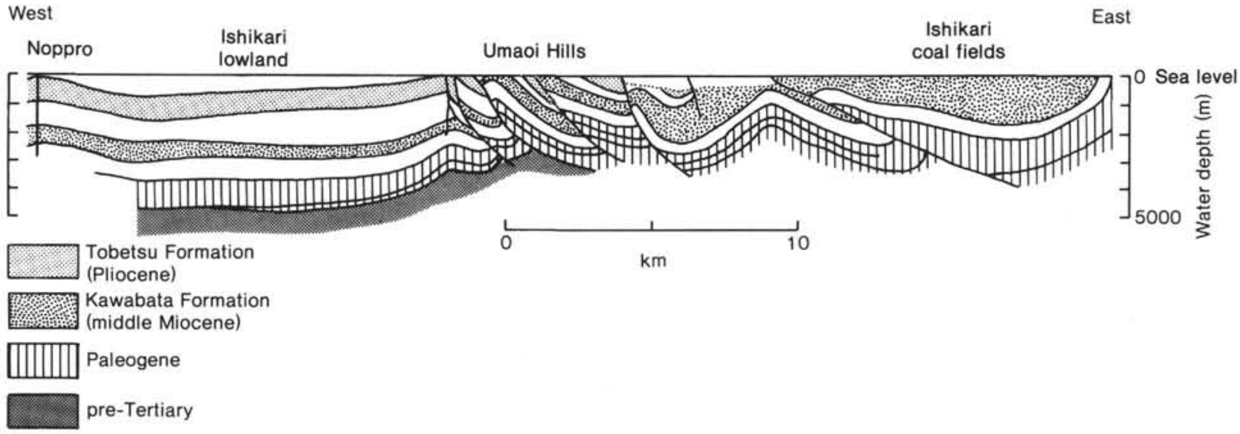


Figure 16. Cross section of the Ishikari Basin, central Hokkaido, showing the post-Pliocene folding and westward thrusting (Mitani, 1978). The location of the cross section is shown in Figure 14 as ⊢—⊣.

and the tectonic evolution in the forearc are consistent with an evolutionary model of the cyclic plate subduction, which was proposed based on the Neogene tectonic evolution of the landbase geology in the Japanese Island Arcs.

Two major tectonic movements affected sedimentation in the forearc area and are distinguished on the basis of their effect on the three layers; Pacific Plate detachment in the Shirasawakai after the opening of the Japan Sea and Kurile Basin in the Onnagawakai at the time of deposition of the Lower Layer to the Middle Layer and collision of the Kurile and Honshu arcs at the Hidaka Mountains in the Sekikai at the time of deposition of the Middle Layer and Upper Layer.

Paleomagnetic measurements of the directions of the cross-bedding in the basal sandstone of the Lower Layer in Site 439 do not support the existence of an "Oyashio Paleolandmass" in the forearc, except possibly before the transgressive stage in the late Oligocene. The record of marine transgression and dacitic volcanic activity found in Site 439 are also found in the Joban Coal Field.

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