66. SEDIMENTOLOGIC HISTORY, LEG 34 DEEP SEA DRILLING PROJECT[1]

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INTRODUCTION

Leg 34 of the Deep Sea Drilling Project offered opportunities to study the geologic history of the Nazca plate which, because of its tectonic setting, unusual sediment cover, and economic implications, has been of increasing interest during the past decade. The plate has at least one extinct spreading center (the Galapagos Rise), is bordered by an extremely fast spreading center (East Pacific Rise), and has an active subduction zone (Peru-Chile Trench) (Herron, 1972). The sediment cover is unusual because of its high iron content which may have future economic importance.

This review gives a synopsis of the lithologic and biostratigraphic data of Sites 319, 320, and 321. Major findings at each site are summarized, major components are described, and biostratigraphy, correlation, and facies distributions are discussed. Comments are made on changes in carbonate compensation depth with time, on the history of South American volcanism, and on the Humboldt (Peru) Current.

Most information given here is based on Leg 34 data. However, several recent significant papers are relevant to the discussions (for example, Berger, 1973; Kulm et al., 1974, Rosato et al., in preparation; Winterer, Ewing, et al., 1974; and Mammerickx et al., 1975). Also, data from DSDP Legs 8 (Tracey, Sutton, et al., 1971) and 16 (van Andel, Heath, et al., 1973) are used where appropriate.

From piston coring programs the near surface sediments of the region are relatively well known and at least one major area of metalliferous sediment has been recognized (the Bauer Deep). A major goal of this study has been to determine the time and space relationships of this and other major facies.

The three sites drilled are Site 319 in the Bauer Deep, and Sites 320 and 321 along the eastern margin of the Nazca plate (Figure 1). Sediments are unusually thin on the Nazca plate; Site 319 was drilled in a small irregular basin that has served as a local sediment pond. Sediment cover is more continuous between Sites 320 and 321, although interrupted by the Mendaña Fracture Zone (Mammerickx et al., 1975).

Sediment distribution on the Nazca plate is affected by several factors which can be grouped into two categories: distance from a spreading center influences the accumulation rate of metalliferous sediment particles; and from the Sclater age/depth relationship (Sclater et al., 1971) the distance from the spreading center controls the bathymetry, and consequently whether it is above or below the carbonate compensation depth, for any given circulation and climatic regime (Berger, 1972).

Proximity to South America strongly affects sediment types through a variety of mechanisms. First, as a geostrophic current the Humboldt (Peru) Current is probably quite old. Productivity associated with this system falls off rapidly with increasing distance from the coast and governs the influx of biogenous opal. Second, proximity to the coast, and particularly the Andes, governs the accumulation rate of volcanic and terrigenous components. This material is dominantly windborne, since the Peru-Chile Trench acts as an effective sediment trap and dispersal barrier for submarine transportation.

SITE SUMMARIES

Site 319

Site 319 is located in 4296 meters in the Bauer Deep, a regional depression between the present East Pacific Rise and the extinct Galapagos Rise. Four sediment units with a combined thickness of 110 meters, overlie the basaltic seismic basement (Figure 2).

The uppermost unit (Unit 1) is a 4-meter thick iron-rich brown clay of late Miocene to Quaternary age. In general, this unit is almost carbonate-free, although carbonate content does increase towards the base. The clay contains abundant phillipsite and ferruginous particles. Unit 2 is an iron-bearing calcareous brown clay and clayey nanno ooze, 24.5 meters thick. It is a transitional unit between the pelagic brown clay of Unit 1 and the nanno ooze of Unit 3 and is late Miocene in age. A general decrease in ferruginous particles and an increase in carbonate occurs with depth in this unit. A nanno ooze, about 47.5 meters thick, comprises Unit 3, which is middle Miocene in age. A small percentage of ferruginous particles colors the otherwise quite pure carbonate ooze. The fourth sediment unit consists of 34 meters of iron-bearing nanno ooze of early and middle Miocene age. Ferruginous particle concentration increases in this basal unit.

Site 320

Three holes were drilled at Site 320, which is located approximately 300 km west of Peru in 4487 meters of water. The sediments were spot cored to a depth of 155 meters, where basalt was encountered, and two sediment units were distinguished (Figure 3). The upper 15.5 meters recovered (Unit 1) consist of greenish-gray to olive-green siliceous fossil-rich clay of Quaternary age.

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Figure 1. *Location map of the Nazca plate showing sites discussed.*

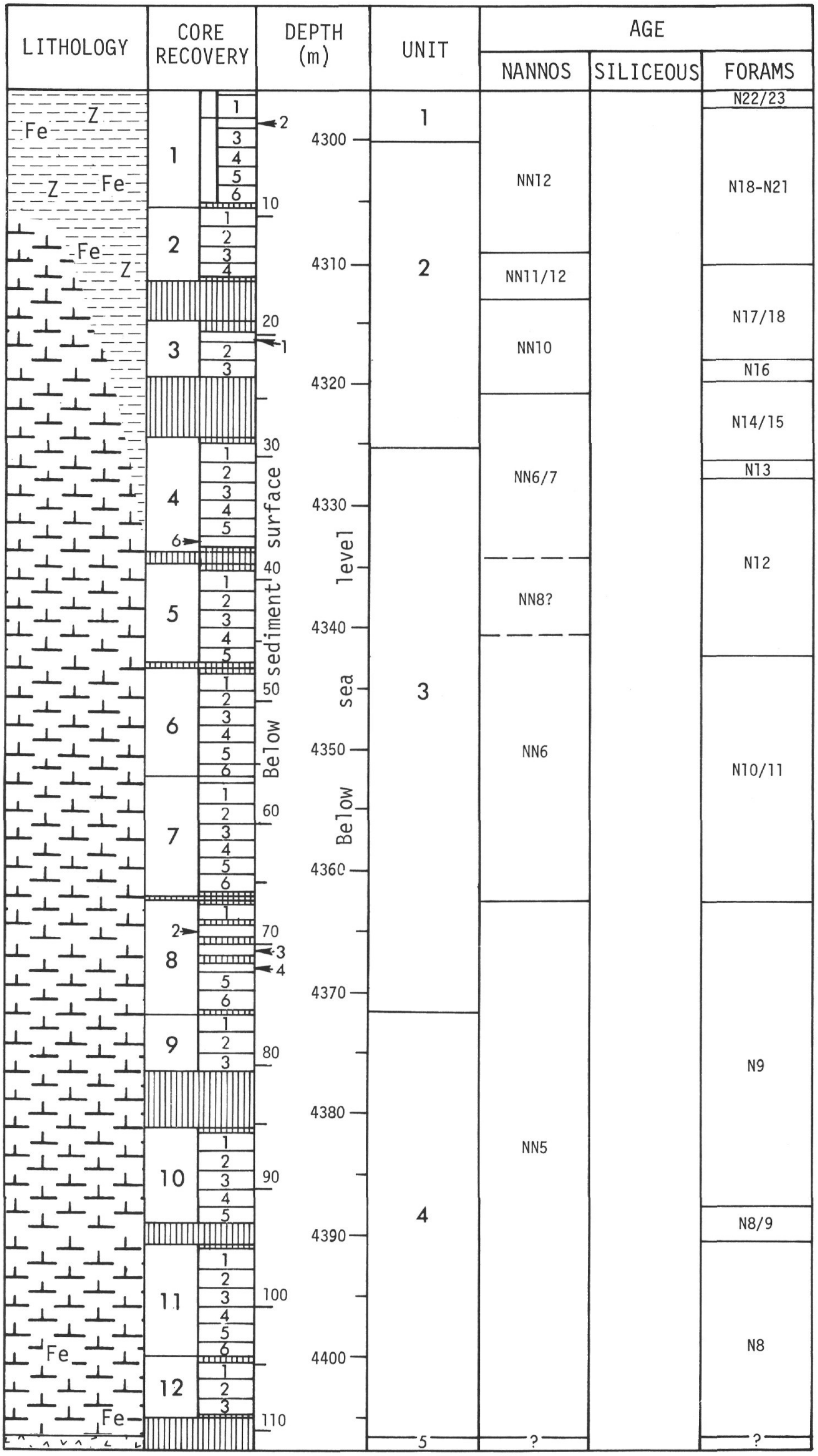

Figure 2. *Stratigraphic column and planktonic zonations, Site 319.*

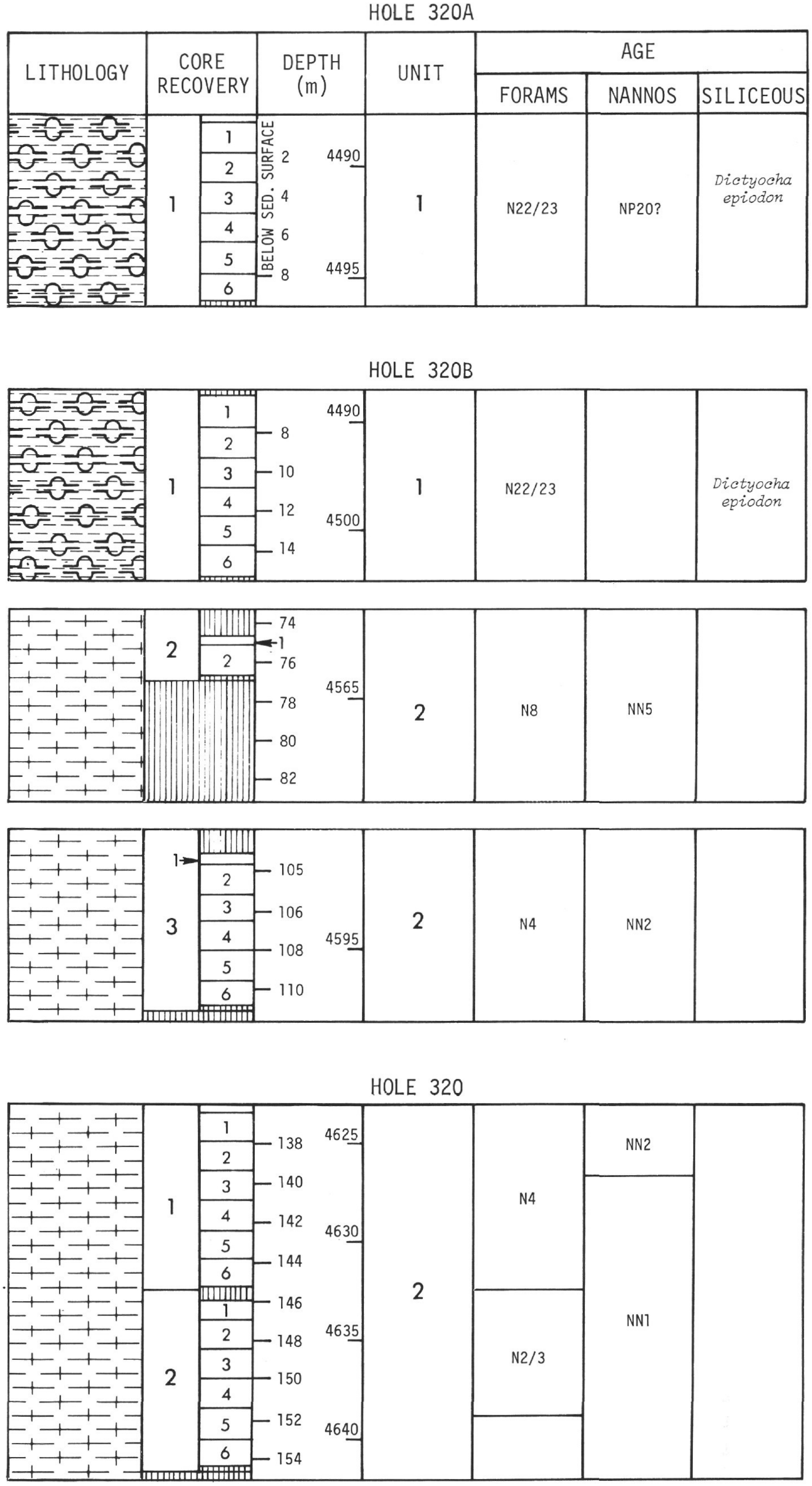

Figure 3. *Stratigraphic column and planktonic zonations, Site 320.*

Volcanic glass is dispersed throughout the unit. The lower unit (Unit 2), cored intermittently from 73.5 meters, is a brown foram nanno ooze of early Miocene and late Oligocene age. Ferruginous components are abundant in this unit.

Site 321

Site 321 is located on the eastern edge of the Nazca plate, south of the Mendaña Fracture Zone, in 4827 meters of water. Sediments at this site were almost continuously cored to a depth of 134.5 meters. Four sediment units were distinguished (Figure 4). Unit 1 is 34.5 meters thick, consists of greenish-gray detrital clay with high concentrations of siliceous fossils, and is Quaternary to Pliocene in age. Volcanic glass is dispersed throughout the unit with higher concentrations towards the base. Unit 2 consists of 14.5 meters of light yellow-brown clay of late Miocene age. Volcanic ash is present in this unit with concentrations up to 55%. Unit 3 consists of 9 meters of zeolitic brown clay for which no age determination was possible. Unit 4 consists primarily of light brown nanno ooze, which is interbedded with darker brown, zeolite-bearing iron-rich nanno ooze. This unit occurs in the interval 58 meters to 124 meters. Fairly high percentages of ferruginous particles (to 35%), zeolites (to 15%), and foraminifera (to 20%) are found at various levels in this unit which is primarily nanno ooze and includes sediments of early Miocene to late Eocene age. The top of the basalt is at 124 meters, and 11.5 meters were penetrated.

SEDIMENT COMPONENTS

Biogenic Components

The biogenic components of sediments recovered during Leg 34 may be divided into three categories. These include: (1) Calcareous—nannofossils (coccoliths and discoasters), planktonic foraminifera, calcareous benthonic foraminifera, echinoderm spines, and ostracodes; (2) Siliceous—radiolaria, silicoflagellates, diatoms, sponge spicules; and (3) Other—agglutinated foraminifera, fish teeth.

Nannofossils were found at all three sites drilled, but were absent from the carbonate-free upper portions of the sediment sections. They form the major portion of the sediments in the Miocene interval of Sites 319 and 320 and in the Paleogene interval at Site 321. Preservation in all these sites is fairly good, with more marked dissolution effects near the top of the nanno-bearing interval at Site 319. Increased dissolution effects were also noted in the Oligocene and Eocene sediments at Site 321.

Planktonic foraminifera form the major portion of the coarse fraction residue in calcareous sediments recovered at all three sites, but never exceed 20%. They are more plentiful at Site 319 than at Sites 320 and 321, being found in all cores recovered at Site 319. Foraminifera at all three sites showed signs of dissolution, particularly at Site 321.

Foraminifera recovered at Site 319 are excellently preserved.

Ostracodes and echinoderm spines form a very small part of the biogenous material recovered and were found in greatest numbers at Site 321. Calcareous benthonic foraminifera occur sparsely in calcareous sediments at all three sites.

Agglutinated benthonic foraminifera were recovered at all three sites, occurring in greatest numbers in the noncalcareous sediments. Generally they are poorly preserved.

Fairly high concentrations of fish debris—primarily fish teeth—were found at Site 319, as a lag after dissolution of the carbonates. This enrichment was not seen in the carbonate-free portion of sediments recovered at Site 321 although some debris was present in the residues. Quantitatively, they form only a small part of the coarse fraction.

Opaline fossils are not abundant in any Site 319 sample, and subsequent studies of several large (ca. 10 cc) samples yielded only a very few fragments of the most robust radiolarians. The lower parts of the eastern margin Sites (320 and 321) were also opal-free, but rich and varied suites were found in the upper levels. The Pleistocene Unit 1 of Site 320 contained 25%-35% opaline fossils, including (in order of decreasing abundance) diatoms, radiolarians, sponge spicules, and silicoflagellates. All were in pristine condition, including the finest diatom processes. The siliceous fossil suites from Unit 1 at Site 321 resemble those from Site 320 in abundance and relative rank. All decrease in abundance downward, with radiolarians persisting as very sparse assemblages of robust elements into Unit 2 (Cores 5 and 6).

Terrigenous Components

Terrigenous sediments (detrital materials eroded from continental or island sources) are abundant in the green siliceous fossil clays at Sites 320 and 321 and are less abundant throughout most of the underlying sediments at those two sites. Terrigenous minerals, as determined from smear slides and X-ray studies (Zemmels and Cook, this volume), include quartz, feldspar, kaolinite, chlorite, mica (illite), and probably some of the montmorillonite family.

At Site 319, in the Bauer Deep, terrigenous minerals occur in small amounts throughout the section, probably the result of wind dispersal from the South American continent. At Site 320, the top unit contains abundant terrigenous minerals including quartz, feldspar, kaolinite, chlorite, and mica which show the strong influence of the South American continent during the Quaternary. At the eastern margin sites (320, 321), terrigenous input was important earlier. Although there is minimal terrigenous input at Site 320 more than about 13 m.y. ago (N6, NN5, early Miocene, Core 2); the abundance of terrigenous minerals in the brown clay (Unit 3) at Site 321 suggests that there may have been some earlier influx south of the Mendaña fracture Zone, possibly as early as the latest Oligocene or early Miocene.

Volcanogenic Sediments

Volcanogenic sediments occur both as clear silicic glass at Sites 320 and 321 and as montmorillonite (smectite), which occurs throughout the sediment columns at all three sites. Particularly pronounced is the abundance

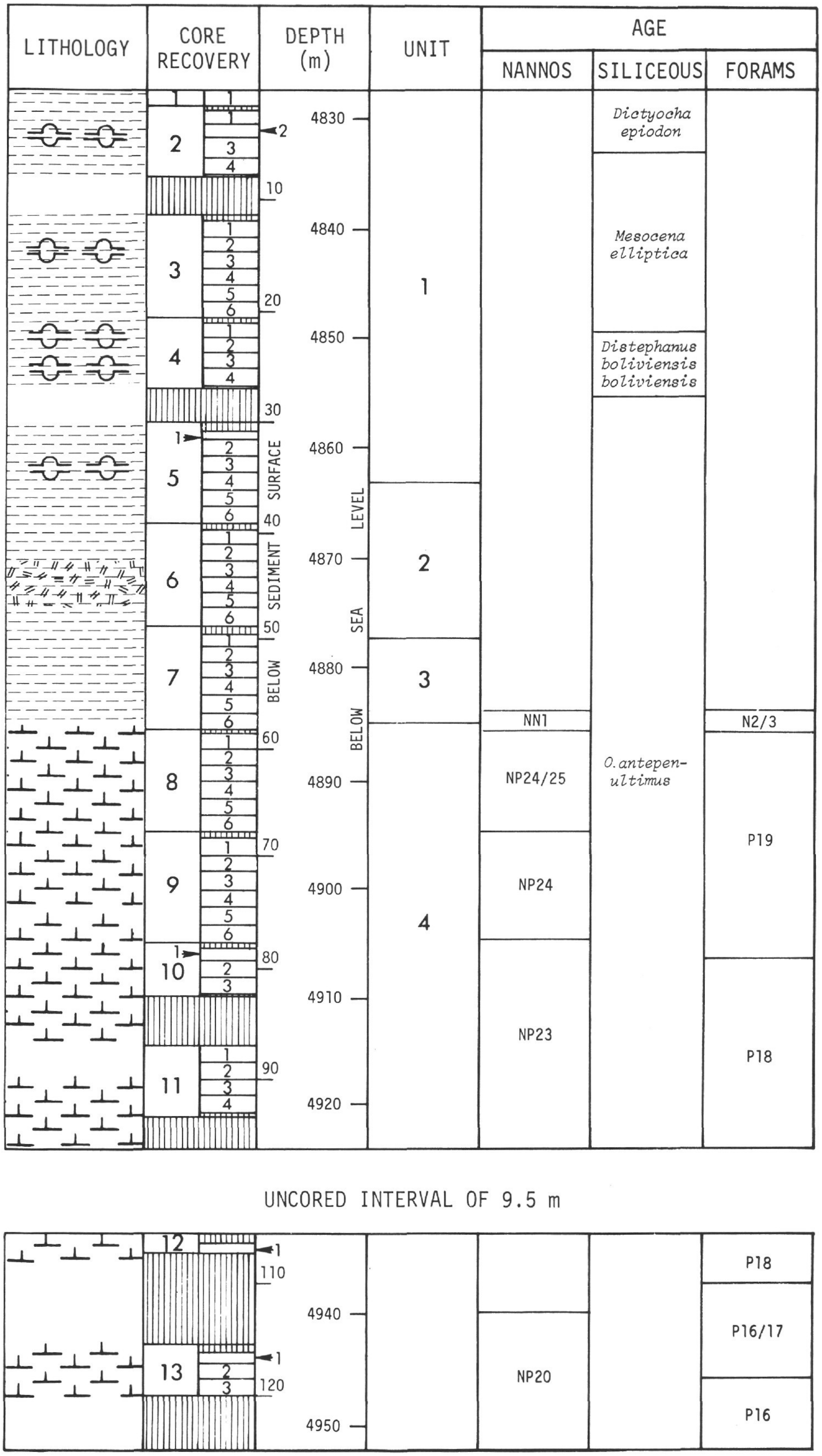

Figure 4. *Stratigraphic column and planktonic zonations, Site 321.*

of clear volcanic glass in the upper unit at Site 320 and the top two units at Site 321. Donelly (this volume) discusses the volcanic glass and associated minerals in more detail. The presence of abundant glass in the upper Miocene to Recent sediments of Site 321 indicates the time (last 10 m.y.) of major silicic volcanism in the Peru area. Apparently, volcanism was more prevalent during the deposition of Unit 2 in the late Miocene and early Pliocene than in the mostly Quaternary Unit 1, an interpretation inconsistent with a worldwide trend toward increased Quaternary volcanism summarized by Kennett and Thunnell (1975).

Montmorillonite is generally thought to indicate altered volcanic sediments; this clay mineral can be detrital or it can form authigenically in marine sediments. Montmorillonite comprises a large percentage of the clays in the upper units of Sites 320 and 321 where it is associated with volcanic glass. It is the prevalent clay mineral at Site 319 and probably was brought to that site by wind and by submarine weathering of basalt with subsequent transport of the resultant fine-grained materials.

Authigenic Sediments

Major authigenic minerals are barite, zeolites, palygorskite, and montmorillonite. These minerals comprise a significant percentage of sediments in some intervals.

Barite is widespread in the sediments (Zemmels and Cook, this volume). Relatively high percentages are particularly notable in the upper two units of Site 319 where brown clay is the dominant lithology. Barite also is common in sediments from Site 320, but is absent from Site 321. The abundance of barite in sediments from the Nazca plate is not unexpected as Arrhenius and Bonatti (1965) reported high concentrations over parts of the East Pacific Rise.

Phillipsite is nearly ubiquitous in the pelagic sediments of all three sites, whereas clinoptilolite was recovered in significant amounts only from the carbonate oozes of Sites 319 and 320 and in smaller amounts from Site 321. Greatest abundance of phillipsite is in the brown clay units of Site 319 (Unit 1) and Site 321 (Unit 3). Clinoptilolite is an important contributor in Units 3 and 4 of Site 319 and Unit 2 of Site 320.

Palygorskite is not a common clay mineral, occurring in significant amounts only in the brown clay unit (Unit 3) of Site 321. The origin of this mineral is not agreed upon, and it apparently can form by authigenesis on the sea floor or can be transported from land. Its close association with the brown clay suggests an authigenic origin at Site 321 where it apparently formed during long contact with seawater belaw the CCD.

CHARACTER AND DISTRIBUTION OF METALLIFEROUS SEDIMENTS

Introduction

Metalliferous particles are apparently ubiquitous components of the calcareous oozes of the Nazca plate, especially in the lower one-third to one-half of the sedimentary column. The particles are similar to those found at the surface of the ocean floor on the East Pacific Rise, in selected cores from other DSDP legs, and from the surface of the Bauer Deep. The three sites of Leg 34 provide new information on the character and distribution of these materials.

Previous Work

Sediments rich in iron, manganese and the so-called transition metals, and low in aluminum, silicon, and titanium have been known from the area of the East Pacific Rise since the cruise of the first (H.M.S.) *Challenger*, nearly 100 years ago. In this century they were noted by Revelle (1944) and were first described in detail by Boström and Peterson (1966), who showed that the materials were amorphous to X-ray and were enriched in Fe, Mn, Cu, Cr, Ni, and Pb, as compared with most deep-sea sediments. The correlation of the metal-rich sediments with areas of high heat flow led Boström and Peterson to postulate a hydrothermal origin for the metal oxides. The same authors later suggested (Boström and Peterson, 1969) that, due to sea-floor spreading, a blanket of these iron-rich sediments might underlie more recent pelagic sediments away from active ridge crests as shown in Figure 5, which is reproduced from von der Borch and Rex (1970). Since then, similar sediments have been described and analyzed from other areas of the East Pacific Rise (Bender et al., 1971; Dasch et al., 1971); from the Mid-Atlantic Ridge (Boström, 1970; Horowitz, 1970; and Cronan, 1972); and from the Indian Ocean (Boström and Fisher, 1971).

More recently, iron/manganese-rich sediments have been described from a number of Pacific legs of the Deep Sea Drilling Project, especially Legs 5, 8, and 16 (von der Borch and Rex, 1970; von der Borch et al., 1971; Cronan, 1973). Cronan's discussion of the basal deposits from several sites of Leg 16 includes a good summary of the previous work.

Most of the analyses of DSDP material and the attendant discussion have focused on metal-enriched strata immediately or closely overlying basaltic basement; yet both the summary discussions and individual site reports note concentrations of the "amorphous iron oxides" in other parts of certain cores. At Site 74 Tracey, Sutton, et al., (1971, p. 623 and 640) describe a 1-meter bed "rich in hydrous iron/manganese oxides" at about

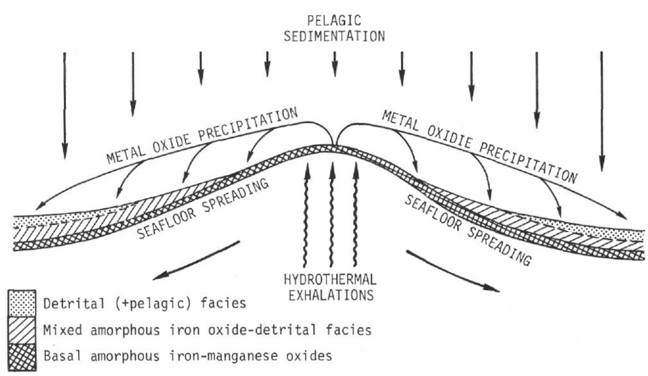

Figure 5. *Schematic representation of inferred sedimentation processes on the East Pacific Rise (Adapted and modified from Bostrom and Peterson, 1969).*

73 meters above basement (29 m subbottom), and this bed is also discussed briefly by von der Borch et al. (op. cit., p. 831). Similarly in Leg 16, Cronan (op. cit.) notes that "grains and aggregates of iron oxides were found throughout most of the sediments cored.....generally in small concentrations"; and the individual site descriptions note concentrations of ferruginous aggregates at the top of Site 160 and at a subbottom depth of 9 meters at Site 160 (van Andel, Heath, et al., 1973, p. 234 and 269).

An inexhaustive spot check of other Initial Reports indicates that pellets or aggregates of iron oxides are fairly common in many Pacific cores, even though they were not sufficiently concentrated to be of special note. For example, in Leg 6 the description of Site 56 notes "limonitic grains" of silt to clay size present as tiny circular rings and "rounder to subangular granular aggregates" (Fischer, Heezen, et al., 1971, p. 58). The report on Leg 9 describes concentrations of "amorphous iron manganese oxides" near the bottom of Site 203, throughout Site 204 but especially between 85 meters and 103 meters, and in the *upper* unit of Site 205. And as we do at Sites 319-321 the authors attribute the brown color of Core 2, Site 203 to these oxides (Burns, Andrews et al., 1973) rather than to pelagic clays. Parenthetically, we note that Sites 203-205 are close to volcanic areas and that the cores contain volcanic debris throughout.

Our spot check suggests, therefore, that grains or aggregates or iron/manganese-rich material may be much more common in DSDP cores than has been appreciated, especially where they are present in only minor amounts. It is clear also that they are not confined to the sediments just above the basaltic basement, although most of the higher concentrations are found in the lower parts of the sedimentary column.

Metalliferous Sediments of the Bauer Deep

In addition to areas along and adjacent to spreading centers, metalliferous sediments have been found on the sea-floor surface in the Bauer Deep, a structural basin about halfway between the East Pacific and Galapagos rises. These sediments have been the subject of a number of studies, largely by personnel from Oregon State University and the Hawaii Institute of Geophysics, in connection with the Nazca plate Project of the International Decade of Ocean Exploration. Results of these studies are summarized in the introductory part of the Site Report for 319 (this volume). As noted there, the metal-rich sediments of the Bauer Deep resemble those found elsewhere on the East-Pacific Rise, except that those of the Bauer Deep are higher in Si and Ni, and have lower Fe/Al and Mn/Al ratios than those close to the Rise. However, Heath et al. (unpublished report) note that in the Bauer Deep the Fe/Al and Mn/Al ratios, although lower than deposits typical of ridge crest are still considerably higher than is typical for sediments this far from the crest. Dymond et al. (1973) ascribe the chemical differences largely to the higher content of iron-rich montmorillonite in the Bauer Deep samples. They consider that the similarities far outweigh the differences, that the differences are due to transport and/or local diagenetic conditions, and that the deposits of both areas have a common origin. Of possible origins that have been suggested, they (p. 3368) consider that the chemical evidence strongly favors a refined version of the original Boström-Peterson hypothesis, i.e., volcanic or hydrothermal emanations mixing with seawater and subsequent precipitation of the metal constituents at low temperature and in equilibrium with seawater.

Petrographic Description

Prior descriptions of similar materials have followed no consistent terminology, largely because the particles have a wide range in size, color, and opacity, and because most chemical and X-ray analyses did not distinguish clearly any separate compounds or mineral species. They are described variously as "grains," "pellets," "spherules," "flakes," "aggregates," and "micronodules," but with no real consistency among different authors. In earlier DSDP volumes, Cronan (1973, p. 601) describes them as grains and aggregates of iron oxides, spherical to subspherical in shape, reddish to yellow-brown, translucent to opaque, and ranging in size from a few microns to tens of microns. von der Borch and Rex (op. cit., p. 543) describe them as translucent amorphous spherules, 0.5 to 24 microns in diameter, and light to dark yellowish-brown in color, and they note further that the darker colors may be due to admixtures of manganese oxides. (Although they refer also to manganese nodules and micronodules in other parts of the sedimentary column of Sites 37 and 39, they clearly do not equate their "micronodules" with the iron oxide spherules.) And in the Initial Report for Leg 8, von der Borch et al. (op. cit., p. 831) call the metalliferous components "amorphous iron oxides" and describe them as "discrete yellow-brown translucent spherules and *aggregates* (italics are ours) which range in diameter from 0.5 to 25 microns." A scanning electron micrograph shows one sperule with a surface texture of rod-like forms, others with a more crystalline appearance. These spherules are about 10 microns in diameter, but their ragged outline resembles what we refer to as "aggregates."

In mild contrast to the above, Dasch et al. (1971, p. 176) describe the metalliferous components of sediments from 9°S, 102°W as consisting principally of yellow microcrystalline silicate aggregates (iron-montmorillonite or "smectite" by X-ray analysis) and "typical ferruginous micronodules," with minor amounts of orange-red palagonite. They state further that: "these yellow aggregates do not grade into the orange-red, virtually isotropic palagonite grains, or into the micronodules." The micronodules contain some todorokite, although much of the material is apparently only crudely crystalline.

Although in our petrographic examination of smear slides (cf. especially Site 319) we have noted three general varieties of particles that seem to correspond roughly with those of Dasch, we were not able to draw sharp distinctions between the types and our red-brown grains are not palagonite. Rather, our descriptions are similar to Cronan's (1973, 1974, p. 507). Because of all the variations in terminology we have not adopted any definitive names; we have called all the metalliferous particles (including the probably smectite flakes) "red-brown to yellow-brown, semi-opaque oxides" and abbreviate this informal term for convenience to "RSO"

Recapitulating from the more detailed description, in Site 319, our three types of RSOs are:

1) Yellow flakes and spherules: 1-10 microns, translucent and mostly isotropic. A few flakes (5%-10%?) seem to be microcrystalline. At least the lighter colored flakes are probably Dasch's "smectite."

2) Red to brown semi-opaques: 8-25 microns, color range yellow-brown to red-brown, mostly isotropic but some showing microcrystalline birefringence. They are apparently gradational with the yellow flakes of type (1) and the aggregates of type (3). They are not palagonite.

3) Aggregates: dark red and brown to black semi-opaque to opaque and 20 to more than 100 microns. These are probably the aggregates of Cronan and von der Borch and the micronodules of Dasch.

Chemistry and Mineralogy

The bulk chemistry of metalliferous particles from various parts of Pacific Ocean sediments has been pretty well determined within reasonable limits by a number of previous workers and is well summarized by Dymond et al. (1973) and Cronan (1974). Analyses of Leg 34 RSOs are given in separate papers by Boström et al. (this volume) and Dymond et al. (this volume). Comparison with previous analyses shows no significant differences between our RSOs and other metalliferous sediments.

Much less in focus is our knowledge of the mineralogy of chemical partitioning between the types of particles. The particles are difficult to characterize petrographically and most early workers found them largely amorphous to X-rays. Only more recently Dasch et al. (1971) have identified some iron-montmorillonite (smectite) in the smaller yellow flakes, and todorokite and possibly other oxides of Fe and Mn in some of the larger more opaque particles. In what appears to be a major advance Dymond et al. (1973) have indicated that ultra-slow-scan X-ray diffraction shows quite a bit of mineralogical detail in the "amorphous" sediments.

Of the various substances they identify, some (e.g., phillipsite, phosphatic debris, biotite, etc.) are "normal" components of deep-sea sediments. The compounds that seem to be constituents of the metalliferous particles are: iron-rich montmorillonite ("smectite"), moderately well crystallized goethite, and an assemblage of manganese (and ferromanganese?) hydroxyoxides including todorokite and psilomelane. But even these do not account for all the metal content, for the authors note that the percentages of the minerals given in their Table 7 are too high because the actual samples have considerable material that is amorphous, even to the slow-scan X-rays.

We have not attempted to duplicate these X-ray patterns in our Leg 34 samples, but the petrographyand chemical analyses of these cores suggest that they have similar mineralogy. We do suggest that our RSO particles which show "pin-point birefringence" are indeed microcrystalline and are the iron montmorillonite (yellow flakes) and goethite (red and yellow-brown grains) of Dymond et al. (1973).

Distribution on Nazca Plate

Although only three sites were drilled, the results suggest that metalliferous particles are a significant component of the lower one-quarter to one-half of the sediments that blanket the Nazca plate, but that their abundances in the upper parts of the column are locally variable.

At Site 319 metalliferous particles are present from top to bottom but bimodally concentrated in the top 28 and bottom 34 meters. As discussed in the site summary and as shown by the accumulation rates, the increased concentrations in the upper 28 meters can be accounted for by a drastic drop in the total sedimentation rate some 11 m.y. ago plus dissolution of carbonate from the upper few meters after the basin went below the CCD. Thus no special new source such as off-crest volcanism or a sudden influx of exogenous material is required to explain the high surficial concentration of metals in the Bauer Deep. The rather abrupt changes from high concentrations (about 10%) in Unit 4 to much lower (1%-2%) in Unit 3 is less easy to explain. It might reflect the transfer of spreading activity from the Galapagos Rise to the East Pacific Rise, but this is just speculation. Whatever the cause, the persistence of high concentrations and accumulation rates throughout Unit 4 followed by a sudden drop to low values does not fit the simple model of gradual decrease with increasing distance from a spreading center.

At Site 321, metalliferous particles are confined to the oozes that comprise the bottom half of the section, and concentrations are relatively high throughout the unit. There is a suggestion of higher concentration both in the basal beds and again near the top of the unit, where the RSO content falls abruptly to zero in the overlying non-calcareous zeolitic clay (Unit 3). This abrupt cessation is even more problematical than the 10-fold decrease in Hole 319, for the zeolitic clays with their low sedimentation rate should have higher concentrations than the oozes if there was anything like a constant supply of the metal oxides. Apparently the source of metalliferous particles was cut off at about the same time as Site 321 sank below the CCD, but the cause is not clear.

Site 320, Unit 1, a greenish-gray siliceous ooze, resembles the top unit of Site 321; Unit 2, which comprises at least half the section is a metalliferous nanno-ooze like Unit 4 at Site 321. As the middle part of the section was not cored, the position and character of the upper contact of the ooze is not known. The "RSO" content is uniformly high throughout the ooze, averaging somewhere between 5% and 10% with occasional beds running 15% or higher. As at the other sites there is no "floor" of the RSOs in the bottom few meters.

The results of Sites 319-321 therefore suggest that metalliferous particles are an important constituent of at least the lower half of the sediments of the Nazca plate, and that, in contrast to some other areas they are mostly associated with the calcareous oozes or their residue (Figure 6). The upper limits of high metal concentration are rather sharp and at different time horizons in the three sites.

Origin or Source of the Metal Oxides

Several origins, sources, and mechanisms of concentration have been postulated for metalliferous

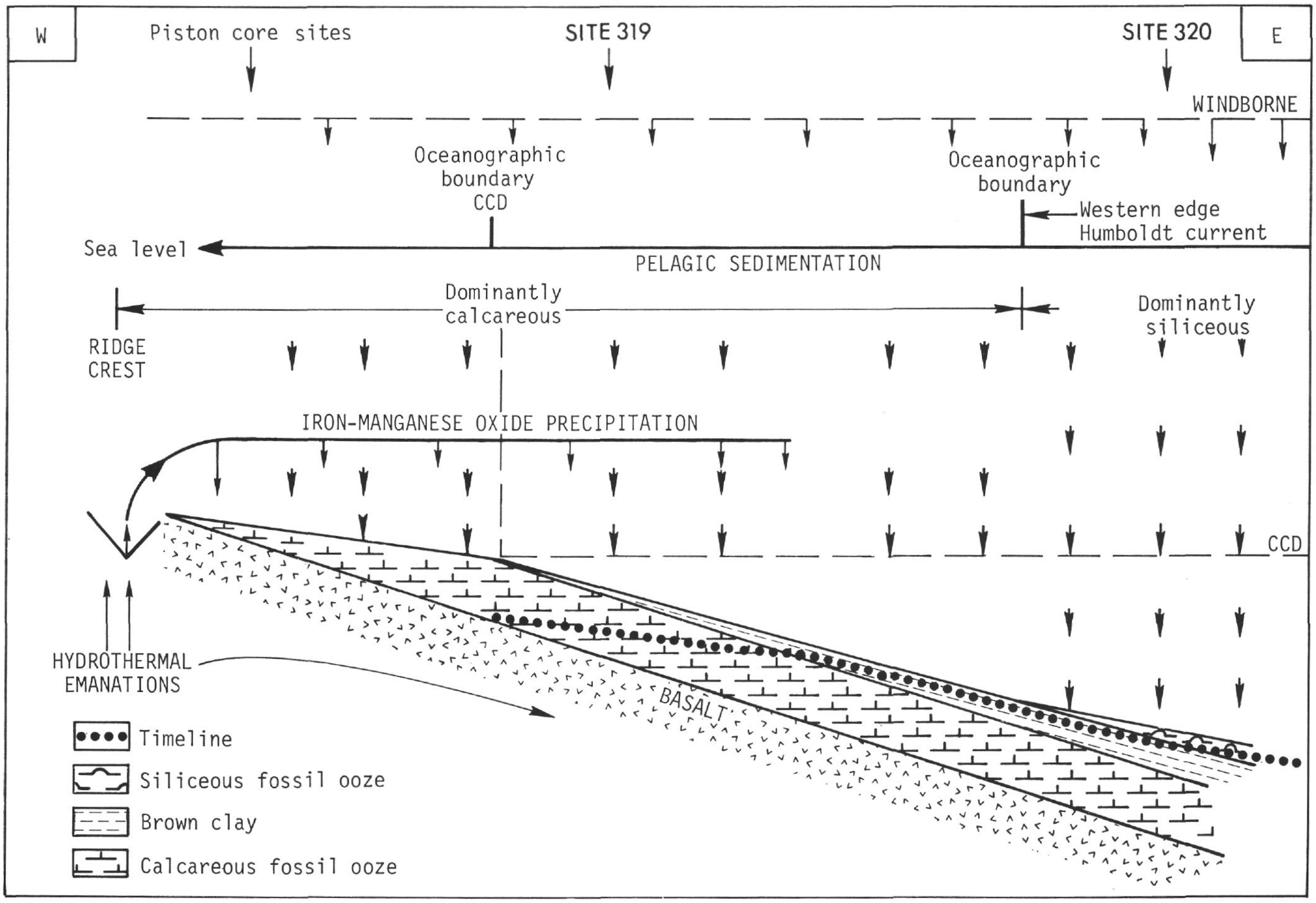

Figure 6. *Nazca plate sedimentation model.*

sediments, but most workers have concluded that the bulk of evidence favors some variation or elaboration of the original Boström-Peterson suggestion, i.e., the particles are low temperature precipitates that result from the mixing of hydrothermal exhalations and seawater. As noted by Dymond et al. (1973, p. 3368) and Cronan (1974, p. 509-511), this is the only hypothesis to date that can account for both the chemistry and distribution of the deposits.

The evidence from Leg 34 is consistent with this general mechanism. As noted above, however, the vertical distribution of the particles at Sites 319 and 321 is not consistent with the model that concentration is a simple function of distance from a spreading center. Rather the sudden diminishing of RSOs in 319 and their sudden complete cessation in 321 require some complexing factors such as change in ocean currents or sudden transfer of spreading activity to new centers.

Finally, our petrographic data coupled with the X-ray data of Dymond et al. (1973) suggest that the original precipitates were mostly colloidal or amorphous mixtures but that some crystallized enough to show up petrographically and to give patterns when exposed to slow-scan X-ray. Moreover, even in the colloidal or amorphous phase there was a tendency toward size separation of some of the constituents. The aluminum, silicon, and some iron tended to collect in smaller grains, some of which became montmorillonite; the oxides of iron, manganese and possibly some of the other metals tended to form larger particles, some of which crystallized as goethite and todorokite. Further work will be needed to determine the extent of the chemical size sorting and whether the particles really form a continuous solid-solution-like series.

Sedimentation Model

A model for the type of sedimentation identified on the Nazca Plate is provided in fig. 3b of Frakes and Kemp (1972). The Nazca plate is a little more complex than the simplified version of Frakes and Kemp, but the principles are the same. Their layer F_1 can be taken to be the calcareous ooze of all Nazca plate sites, cropping out near the East Pacific Rise and sampled by piston cores AMPH 30P and DWBP 134 (see Figure 1).

Layer F_2 is generally the overlying clays and the main oceanographic boundary is the carbonate compensation depth. The system is a little more complex because of the presence of another sediment layer and another oceanographic boundary in the eastern region of the Nazca plate, which is the western edge of the influence of the Humboldt Current. The extra sediment element introduced consists of abundant siliceous microfossils.

Even this modified scheme is an oversimplification as volcanic ash from the Andes could be used to identify another sediment layer if its distribution were better known. This factor also introduces a nonoceanographic boundary, the western edge of abundant windborne ash, into the system.

LITHOSTRATIGRAPHY

It is clear from the discussions of paleontology (Quilty, Blechechmidt, this volume) and biostratigraphy (next section of this chapter) that the section at Site 319 includes some slumped material and that the site is a local sediment accumulation pond in an area of discontinuous sedimentation (Chapter 3, this volume). In addition, a fracture zone separates Sites 320 and 321, so that sedimentation is discontinuous in this region also. Because of these discontinuities, it is inappropriate to discuss lithostratigraphic "formations" on the Nazca plate. Nonetheless, there are common elements in the sedimentary histories at the three sites which should be noted.

First, sedimentation at all three sites began above the CCD, since basal sediments are carbonate-dominated at all three sites. Accumulation of carbonate sediments continued at each site for a period of time ranging about 12 m.y. at Site 319 to about 13 m.y. at Site 321. Each site is now beneath the CCD, and is accumulating carbonate-free sediments which include metalliferous clays at Site 319, and opal-rich detrital clays at Sites 320 and 321 (Figure 6).

Second, it may be possible to reconstruct the most likely sedimentary section at Site 320, which was only spot-cored, given the section and biostratigraphic information available there and at Site 321, and seismic reflection data for both sites. The lowermost sediment at Site 320 is iron-bearing calcareous ooze (320B, Cores 1 and 2), about 27 m.y. old which is believed to have accumulated without substantial change or interruption until some time younger than about 13 m.y. (320, Core 2). The only lithologic unit cored above this one is the opaline fossil detrital clay of 320, Core 1 and 320A Core 1. At nearby Site 321, two lithologic units are developed between these: a zeolitic clay, and a volcanic ash-bearing clay. As indicated on Figure 7, we feel that there is a volcanic ash unit at Site 320, but that the zeolitic clay is a local facies at 321 which is not developed at 320.

No fossils were found in the zeolitic clay at Site 321, but paleontologic data from sediments above and below indicate that this unit accumulated at about 0.6 m/m.y., an extremely slow rate, from about 25 to 10 m.y. ago. The base of this unit is coincident with a fairly strong seismic reflector. Carbonate ooze as young as about 13 m.y. is known from Site 320, and there may be younger carbonate sediment in the uncored section. At Site 321, the volcanic ash-bearing sediments are as old as about 10 m.y. Because Sites 320 and 321 are almost the same distance from the most likely (Andean) sources, it may be assumed that a volcanic ash-bearing clay was deposited at Site 320 as well. Also, because Site 321 is considerably deeper than Site 320, we suggest that the zeolitic clay at that site represents accumulation after the site passed through the CCD but before the introduction of significant detrital material.Then, Site 320 did not pass through the CCD until about the time that detrital sedimentation had begun. Corroborating this interpretation, the only seismic reflector at Site 320 is an extremely weak one at about 60 meters, which, extrapolating the ooze sedimentation rate (5-6 m/m.y.), yields an estimate in the range of 10 m.y. for the 60-meter reflector.

BIOSTRATIGRAPHY

Basis for Correlation

Three major fossil groups have been used to construct Figure 8. Most of the correlation is based on planktonic foraminifera (Quilty, this volume), but the distribution of this group is such that it cannot be used alone. To assist, calcareous nannoplankton (Blechschmidt, this volume) and siliceous microplankton (Sachs, this volume; Bukry, this volume) have been used. Calcareous nannoplankton have CCD problems like those of the planktonic foraminifera. At each DSDP site, sedimentation commenced with ferruginous calcareous oozes, but as time progressed the area subsided below the CCD and calcareous sediments were replaced by clays and, in places, siliceous oozes. Where the latter contain siliceous microfossils, these have proved useful for correlation.

The upper part of Figure 8 is a correlation section for the three sites and two piston cores, DWBP 134 and AMPH 30P which are discussed in more detail elsewhere (Quilty, this volume). The lower part of the figure places all sections in their true spatial relationship, projected approximately parallel to the magnetic striping direction along 12°S. Figure 9 has been produced to show the depth/time relationship of the Leg 34 sediment sections to that in Site 157 of Leg 16.

Sedimentation Rates

The three sites of Leg 34 are widely scattered and on their own give little but purely local information, In this section, data from these three sites are compared with similar data from Nazca plate Site 157 (van Andel, Heath, et al., 1973), and Pacific plate Sites 74 and 75 (Tracey, Sutton, et al., 1971). All sites have sections of similar age and thickness and, all except Site 157, are presently below the CCD. Basic sedimentation rate curves for all six sites are shown on Figure 10.

At each site, except Site 157 where the entire section consists of calcareous ooze, the section consists of a siliceous ooze or clay overlying a calcareous ooze section. The thickness of noncalcareous sediment is greater the farther the present mudline is below the present CCD.

Sediments at Site 157 are well above the present CCD and include 431 meters of continuously deposited upper Miocene to Recent calcareous ooze (cherty towards the base) deposited at an average rate of some 60 m/m.y. When the section is divided into shorter time intervals this rate varies somewhat, but inconsistently. Because of the high sedimentation rate, only the upper part of this section is shown in Figure 10.

Sediments at Site 74 are composed of about 23 meters of radiolarian ooze (which apparently represents continuous sedimentation at an average rate of 1 m/m.y. since the early Miocene) overlying Eocene to lower Miocene calcareous oozes, with Fe and Mn oxides,

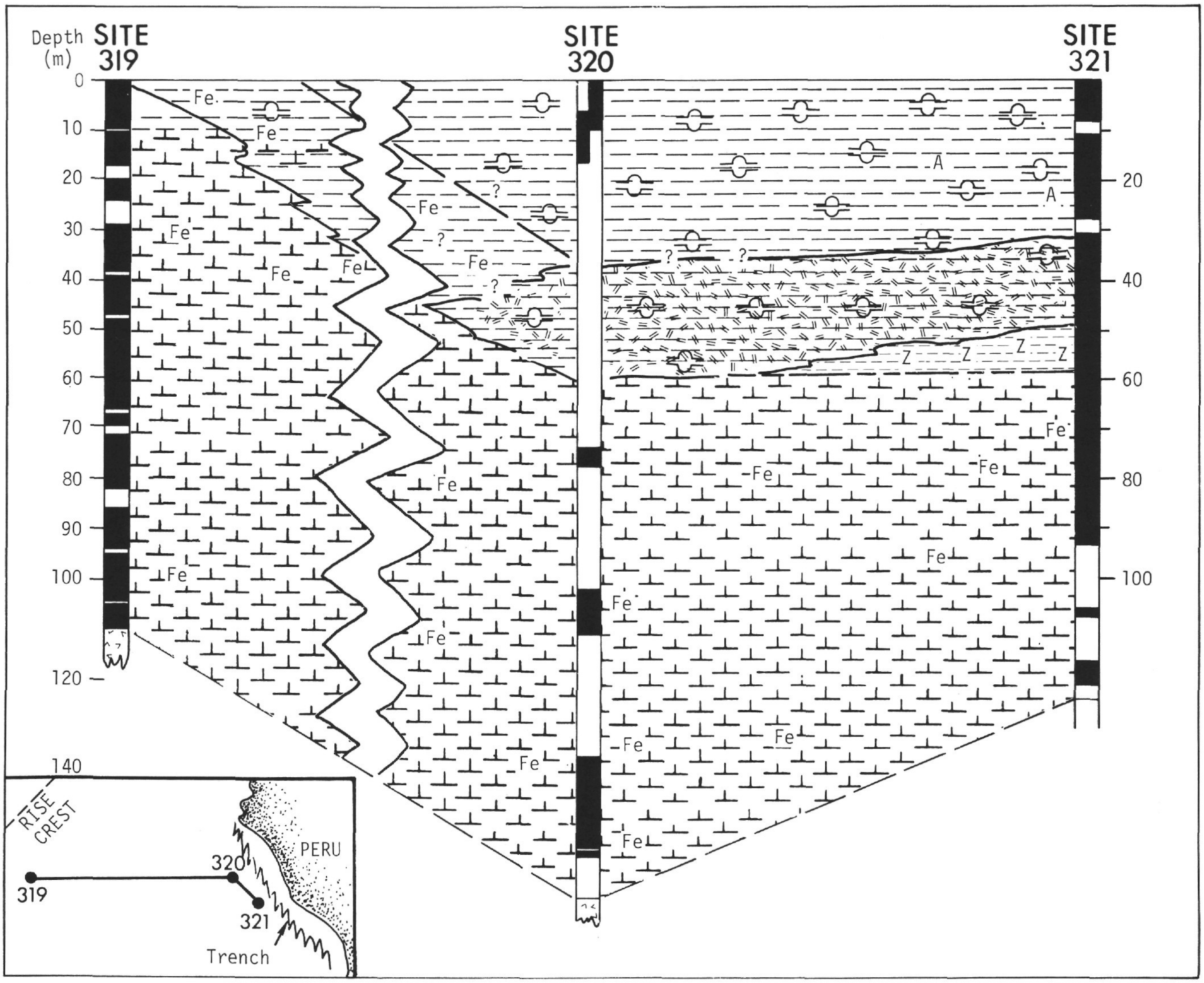

Figure 7. *Lithostratigraphy-depth relationships of sites drilled on Leg 34.*

representing accumulation at about 4-5 m/m.y. In Figure 9, sediments older than late Eocene in age have not been plotted.

At Site 75 drilling encountered 79.5 meters of lower Oligocene to Miocene nannofossil ooze overlain unconformably by about two meters of zeolitic brown clay. The calcareous section accumulated in the Oligocene and early Miocene at about 5 m/m.y. Rates for the younger clays are not well known but probably are much slower. Information on Sites 319-321 are included in the appropriate site reports (Chapters 3-5, this volume).

The following features of sedimentation rates are noteworthy:

1) There is generally a marked difference in sedimentation rates between the more quickly accumulated calcareous section (5-60 m/m.y.) and the much more slowly accumulated clays and siliceous oozes which overlie it (1-20 m/m.y.). This is due, in part, to dissolution effects. Sediments on the sea floor at Site 319 are not far below the CCD at the present time and most of the brown clay may have accumulated in the calcareous ooze above the CCD, with later dissolution destroying the carbonate, leaving the brown clay. This is suggested by the presence of calcareous benthonic skeletons (benthonic foraminifera, and echinoid spines) in the core catcher of Core 1 at Site 319. If Site 319 had not passed through the CCD, its expected sedimentation rate history would have resembled that observed at Site 157. Sedimentation at Site 319 is not typical for the region, because the calcareous sediments show evidence of reworking. Also, Site 319 lies in a small, local basin surrounded by higher sea floor, and much of the sediment in the small basin must have come from the surrounding higher areas. Thus, sedimentation rates probably are inflated.

2) The apparent sedimentation rates of coeval sediments at Sites 74, 75, and 321 are almost identical at 5-6 m/m.y. The interval involved includes the late Eocene, Oligocene, and perhaps the early Miocene. At Site 321, original rates, may have been higher, but have been lowered to the present figure by dissolution effects

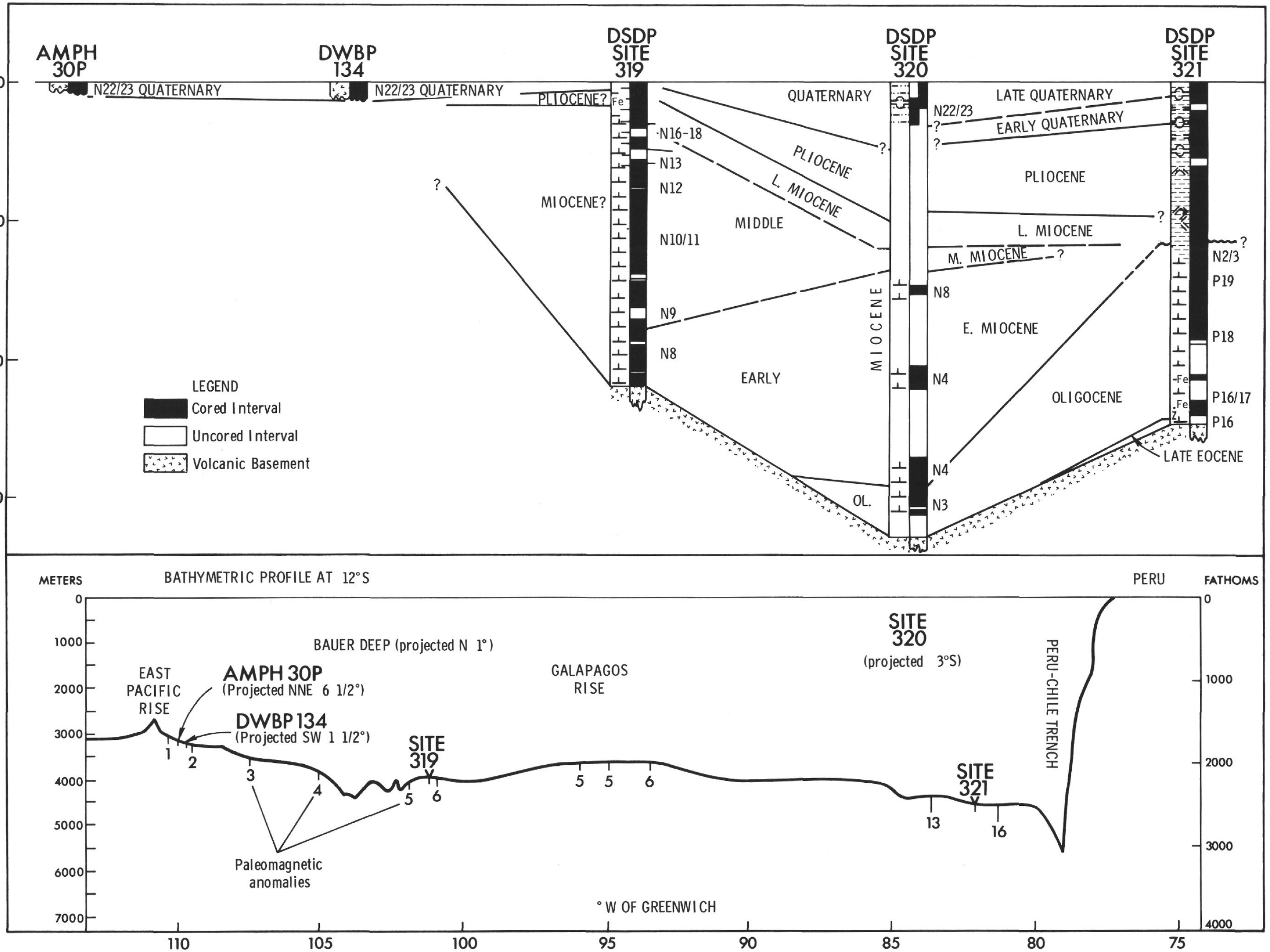

Figure 8. *Age relationships and bathymetric profile across the Nazca plate.*

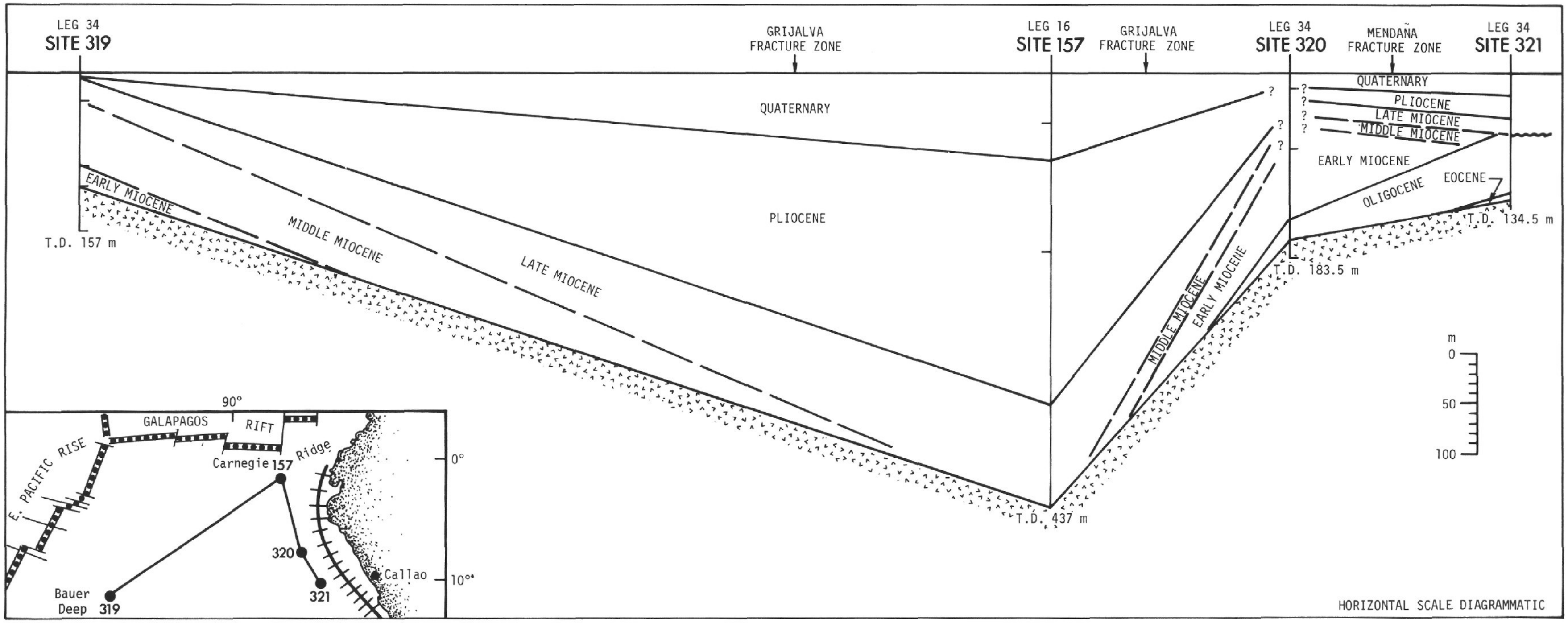

Figure 9. *Time correlation of DSDP Nazca plate sites.*

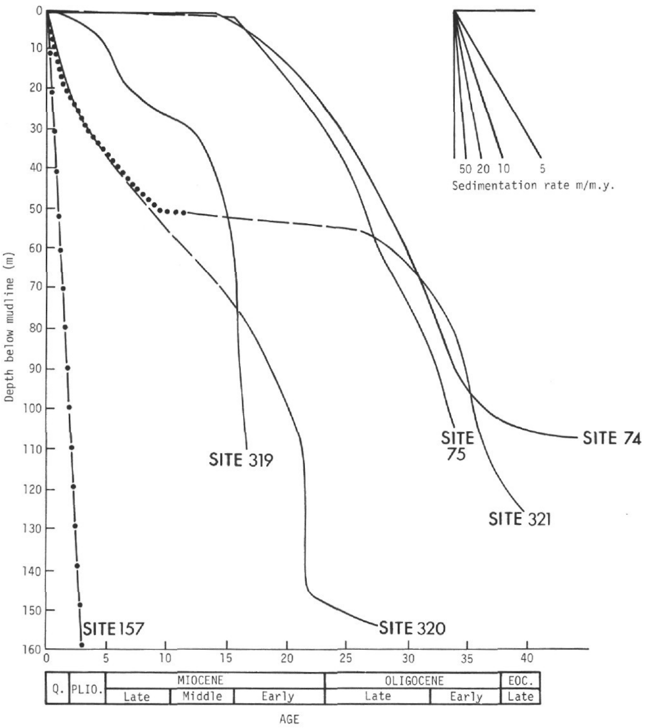

Figure 10. *Sedimentation rates – Nazca plate plus East Pacific Sites 74 and 75.*

which are obvious from examination of the microfaunas. A figure of 5-10 m/m.y. seems reasonable for the upper Eocene to lower Miocene interval. Sediments from Site 320 show a similar, though slightly higher, accumulation rate for the upper Oligocene and lower Miocene section.

3) The apparent sedimentation rates in the lower and middle Miocene at Site 319 and in the upper Miocene to Recent at Site 157 are much higher than in any other carbonate sections under consideration. Rates range from 30-60 m/m.y. The magnitude of the change and the differences in water depth (157:2591 m; 319:4296 m) at the two sites suggest that it is not merely a CCD phenomenon but probably represents a change in the rate of production of organisms. The age at which this change occurs is not clear but approximates the middle-late Miocene, probably about 11-14 m.y. ago.

4) Apparent sedimentation rates for the Pliocene to Recent at Sites 320 and 321 are much higher than for coeval noncalcareous sediments elsewhere in the area under consideration. This is probably a reflection not only of higher organic productivity due to land proximity and to the presence of the nutrient-rich Humboldt Current, but also the greater influx of terrigenous and volcanic components.

DISCUSSION

The essentially continuous sections cored on Leg 34 on the western (319) and eastern (321) margins of the Nazca plate have provided a basis for studying temporal distributions and variations in metalliferous sediments. As pointed out by Dymond et al. (this volume), the basal metalliferous sediments throughout the plate resemble those presently accumulating at the East Pacific Rise, tending to confirm the hydrothermal origin for these sediments suggested by Boström and Peterson (1966, 1969). On the other hand, the near-surface sediments of the Bauer Deep (Site 319) have been affected by other processes, possibly hydrogenous precipitation (Dymond et al., this volume). However, distributional data, particularly from Site 321, indicate that accumulation patterns are not simple functions of distance from a spreading center, but that local conditions may intervene. Pending resolution of these matters, calculation of budgets and amounts of metalliferous sediments seems premature.

The data available do allow some reasonable interpretations of the geological history of the sites. From considering a small change in accumulation rates of metalliferous particles at Site 319 about 8 m.y. ago, Dymond and others suggest that this may have been near the time of development of the East Pacific Rise. Although speculative, this suggestion is supported by independent geological evidence (Rea, in preparation).

On the eastern margin, there is also sufficient data available to infer a complete sedimentary section at Site 320 (spot-cored), and to interpret the geological history of the area. At about 38 m.y., iron-bearing nannofossil ooze began to accumulate at Site 321. At about 27 m.y., sedimentation began at Site 320. In the intervening time, approximately 11 m.y., Site 321 may be expected to have subsided about 350 meters, from the Sclater age-depth relationship (Sclater et al., 1971). In this case, at about 2.5 m.y., Site 321 was in deeper water than Site 320, and subsided through the CCD. This event may have been caused by climatic change, but it is important that Site 320 accumulated carbonate ooze, until at least 13 m.y. since its depth was less. Having dropped below the CCD, slow accumulation of zeolitic clay began at 321. As discussed above (Lithostratigraphy), it is most likely that the zeolitic clay facies never accumulated at Site 320, but that sedimentation there graded from carbonate ooze into volcanic ash-bearing detrital clay.

At Site 321, the oldest volcanic ash-bearing sediment is about 10 m.y. old (late Miocene). Since sediment as young as 13 m.y. at Site 320 may be carbonate ooze without ash, and since these sites are a comparable distance from probably Andean sources, 10-13 m.y. probably brackets the onset of explosive volcanism in the Andes. Alternatively, it could be argued that both sites were too far from the volcanoes to receive ash at earlier dates and the lower limit of ash dates the time when the sea floor came close enough to receive ash from the continents. If we accept a constant convergence rate of the Nazca plate and the South American continent of 10 cm/yr (Minster et al., 1974), then the change in distance during 10 m.y. is about 1000 km which could easily be too far for glass shards to be transported. Although 1000 km is approximately the limit of dispersal for recognizable North Pacific ash beds (Hays and Ninkovich, 1970), shard concentrations could probably be recognized at significantly greater distances. The absence of shards at lower levels indicates either silica mobilization (probable for the zeolitic clay of Site 321, Core 7), or deposition before the onset of explosive volcanism (nanno oozes at Sites 320 and 321), or a combination.

Drilling on Leg 34 encountered sediments which offer some insight into the late Eocene to Recent history of the region close to what is now the Peru-Chile Trench. Sediments as old as late Miocene at Site 321 contain abundant siliceous microfossils, the oldest recorded from the Nazca plate. Discussion elsewhere in this chapter suggests that this may also be the case at Site 320. At Site 157, siliceous microfossils are present and they may be the source for chert in otherwise calcareous sediments. At Site 319, siliceous microfossils are extremely rare in sediment of the same age. At this time, Sites 320 and 321 were probably about 1000 km offshore, as discussed above. If development of this fairly coolwater silica-bearing facies requires southern influence, this may indicate that at this time there was not yet strong flow through the Drake Passage, but that "Antarctic" water was diverted North as a wider Eastern Boundary Current than exists today.

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