67. LITHOLOGIC EVIDENCE FOR CONVERGENCE OF THE NAZCA PLATE WITH THE SOUTH AMERICAN CONTINENT

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INTRODUCTION

Geophysical data (Minster et al., 1974) indicate that the Nazca plate is presently converging with South America at a rate of 10 cm/yr. The sediments and underlying crystalline rocks apparently are being transported across the plate and subducted beneath the continent or scraped off the descending slab and accreted to the continental slope. Recent studies confirm that some of the Nazca plate sediments are being accreted to the continental slope (Kulm et al., 1974; Rosato, 1974) and indicate that the tholeiitic basalt crust is being ruptured to form long axial ridges in the trench axis (Kulm et al., 1973; Prince, 1974; Prince and Kulm, in press).

If the Nazca plate is indeed converging with the continent at a fast rate, there should also be some record of this convergence in the sedimentary deposits on the plate, especially along its eastern boundary where pelagic sedimentation interfaces with hemipelagic sedimentation of the coastal regions. Turbidity current deposits, with the exception of uplifted turbidite basins seaward of the Peru Trench (Prince et al., 1974), are absent on the Nazca plate (Rosato el al., in press; Rosato, 1974; Chapters 4 and 5, this volume); and hemipelagic sedimentation from the continent dominates the region near the continental margin. We should see a significant reduction in terrigenous components downhole grading into essentially pelagic sedimentation in the lower part of the core section if the Nazca plate is converging with the continent. The pelagic and hemipelagic deposits at Site 321 do show this trend in sedimentation which suggests convergence for the past 5-10 m.y.

In order to recognize lithologies of oceanic origin in the continental margin, it is essential that we establish the nature and composition of the sedimentary portion of crust on the descending oceanic plate. Deep-sea drilling on Leg 34, along the eastern edge of the plate, provides this information in sufficient detail so that comparisons can be made between those materials recovered in the drill holes and those suspected exotic oceanic materials recovered by coring in the Peru Trench and on the adjacent continental margin.

The objectives of this study are to: (1) utilize the nature and composition of the materials obtained by Leg 34 to confirm the oceanic character of materials recovered in previous studies in the vicinity of the convergent zone; and (2) test the existence of the fast convergence rate using downhole variations in late Cenozoic sedimentary components such as clay minerals, opal, quartz, and organic carbon content.

PREVIOUS STUDIES

A recent investigation by Rosato (1974) of the clay mineralogy and organic carbon content of the Peruvian continental margin and adjacent Nazca plate sediments shows that the surface sediments can be resolved into three factors (oceanic, continental A, and continental B; see Table 1) using Q-mode factor analysis. The hemipelagic and pelagic sediments of the Nazca plate (oceanic factor) are characterized predominantly by the clay minerals smectite (Figure 1) and illite (Figure 2) (referred to as montmorillonite and mica by DSDP) with minor amounts of kaolinite and chorite and a low organic carbonate content. Mixed-layer clays are also absent in the plate sediments. Upper continental margin sediments are characterized by the continental A factor (mixed-layer clays, illite, chlorite, and kaolinite) or by the continental B factor (abundant illite and absence of smectite and mixed-layer clays).

SEDIMENTARY FACIES

The sedimentary facies recovered at Site 321 are described in Chapter 5, Site 321, this volume. The early Cenozoic iron-rich, calcareous nannofossil ooze of Unit 4 (124-58 m) was deposited near a spreading center, presumably the fossil Galapagos Rise and passed through the calcium carbonate compensation depth (CCD) in late Oligocene time as the plate moved eastward toward South America (Chapter 5, Site 321, this volume). The Miocene brown clays (Units 2 and 3, 58-34.5 m) represent pelagic deposition below the CCD with the occasional ash falls in Unit 2 being carried from the Andean Mountains by easterly winds. The present lower trophospheric winds (below 10 km) in this region flow in a counterclockwise pattern around the subtropical high pressure cell (Rosato et al., 1975; Lamb, 1965; Rumney, 1968) and transport eolian material from the continent to the plate. A similar wind system may have been present during the late Cenozoic when the continental ash layers were deposited with the clays of Unit 2. The relative abundance of diatoms in the Pleistocene sediments of Unit 1 suggests that either Site 321 was approaching the upwelling zone off South America or upwelling began at this time. Kulm et al. (1974) found a cool water planktonic foraminiferal assemblage in Pliocene and early Quaternary carbonates recovered from the lower continental slope off Peru which indicates an upwelling system was probably present in late Cenozoic time.

Several aspects of the sedimentary facies point to movement of the Nazca plate toward South America. However, the rate of transport cannot be estimated from the gross characteristics of facies alone.

ANALYSIS OF SITE 321 LITHOLOGIES

Clay Mineralogy

The clay mineral data used in this study were obtained from DSDP analyses (Zemmels and Cook, this vol-

TABLE 1
Percent Clay Minerals and Organic Carbon in End Members of Surface Sediments of the Nazca Plate and South American Margin off Peru (Rosato, 1974)

Factor	Name	Sample	Smec.	Clay Minerals (%) M.L.	Illite	Kaol.	Chlo.	Organic Carbon (%)
1	Oceanic	R77-1[a]	50.8	0.0	26.0	10.6	12.6	0.88
2	Continental A	23-1[b]	0.0	40.8	26.4	14.8	18.0	4.15
3	Continental B	V33-1[c]	0.0	0.0	61.5	12.2	26.3	5.96

Note: Smec. = Smectite; M.L. = Mixed Layer; Kaol. = Kaolinite; Chlo. = Chlorite.
[a]17°59.8'S, 79°09'W.
[b]15°11.9'S, 76°14.7'W.
[c]10°40'S, 78°10'W.

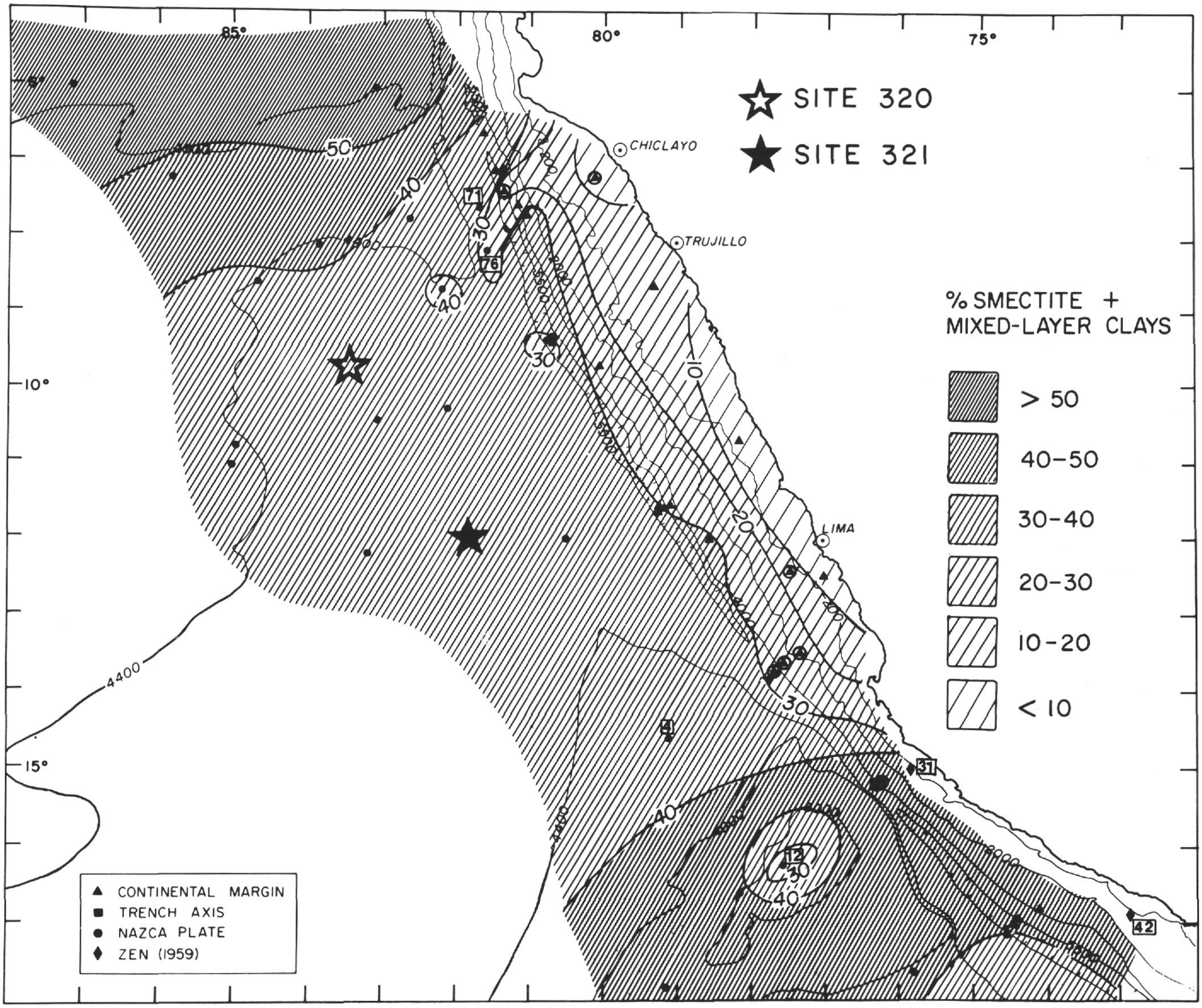

Figure 1. *Surface distribution of smectite and mixed-layered clay. Circled symbols indicate sediments with mixed-layered clays (after Rosato, 1974). Note locations of Sites 320 and 321.*

ume). DSDP sample preparation and X-ray techniques are similar to those used by Rosato (1974). Although the clay mineral analyses may give slightly different values because they were done in two different laboratories, we feel that the clay data for surface samples (Rosato, 1974) are comparable to the clay subsurface data obtained at

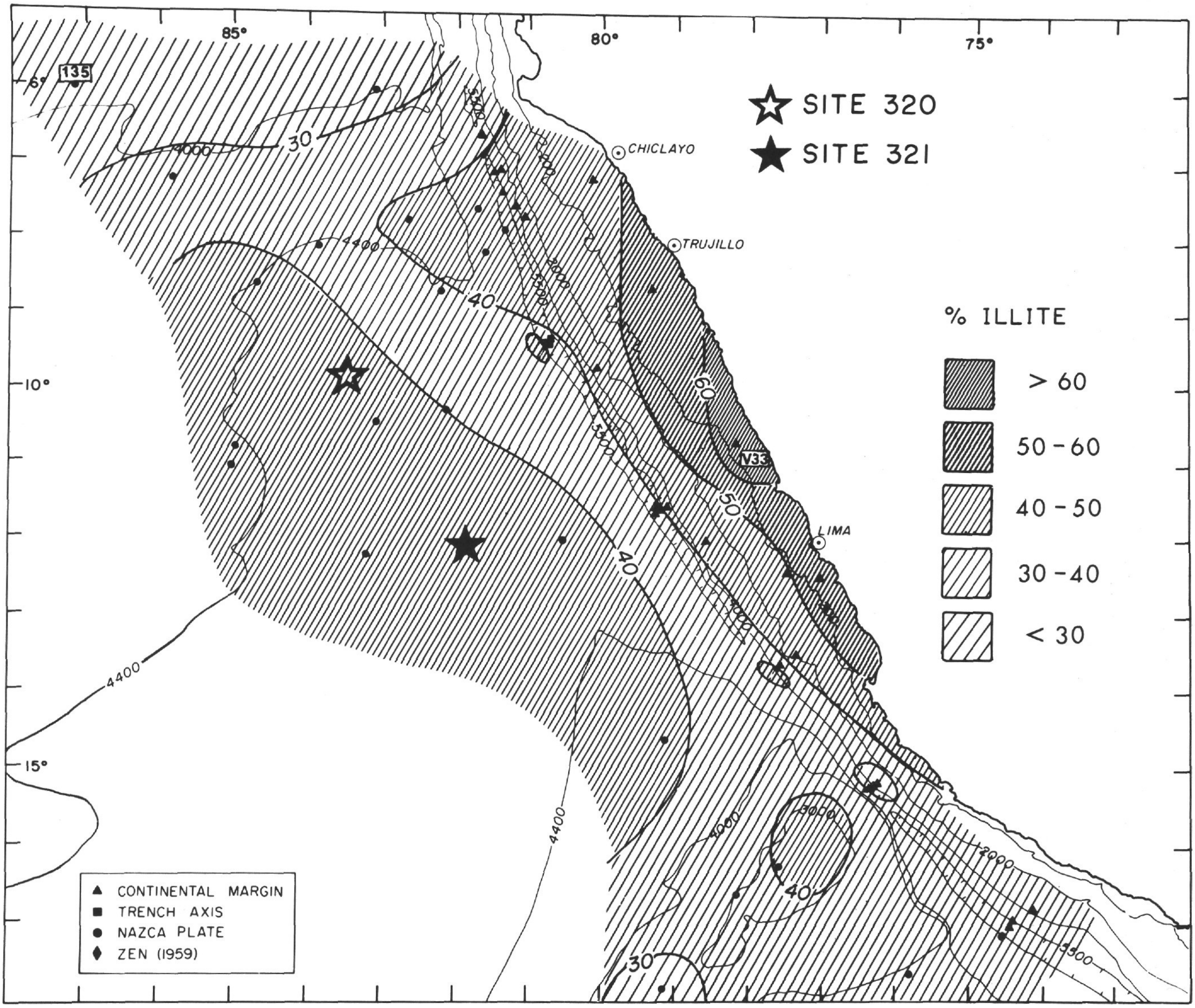

Figure 2. *Surface distribution of illite (after Rosato, 1974). Note locations of Sites 320 and 321.*

Site 321, because the clay mineral species are the same and their relative abundances (smectite > mica > kaolinite ≅ chlorite and mixed-layer clays absent) are in reasonably close agreement.

Looking upsection at Site 321, the smectite content decreases markedly from the late Miocene to the Pleistocene (Figure 3). Smectite concentrations are variable in the yellow-brown clays of Unit 2 (49-34.5 m), but are similar to values in the lower part of silty clays of Unit 1 above. Other studies (Heath et al., 1974; Rosato, 1974) show that smectite dominates the clays on the Nazca plate (Figure 1), especially those near the equator and in partially altered subsurface ash layers. This latter observation may account for the fluctuations in the smectite content in the ash-rich portion of the brown clays in Unit 2. The brown clays of this unit and zeolitic brown clays of Unit 3 (58-49 m) are typical of pelagic deposits far removed from terrigenous sources.

Illite increased markedly in the Pleistocene at Site 321 (Figure 3). According to Rosato (1974), the concentration of illite (Figure 2) decreases rapidly seaward as fluviatile terrigenous sediments settle out of the water column, but is is slightly greater on topographic highs and at some distance from shore on the Nazca plate due to atmospheric transport. The surface distribution of illite implies both an eolian and fluvial input. The stratigraphic distribution of illite at Site 321 shows relatively low concentrations from 10 to 2 m.y. During this period abundant Andean volcanic ash was transported from the continent to the site. Illite concentrations doubled between 2 and 1 m.y. ago, presumably as a result of increased continental input due to plate convergence. Alternatively, eolian transport also may have increased during the Pleistocene as a result of intensified atmospheric circulation.

Kaolinite and chlorite are minor components in the clay mineral assemblage at Site 321 and remain essentially unchanged during late Cenozoic time (Figure 3).

Organic Carbon

The organic carbon content of sediment samples was determined by the Leco induction furnace method

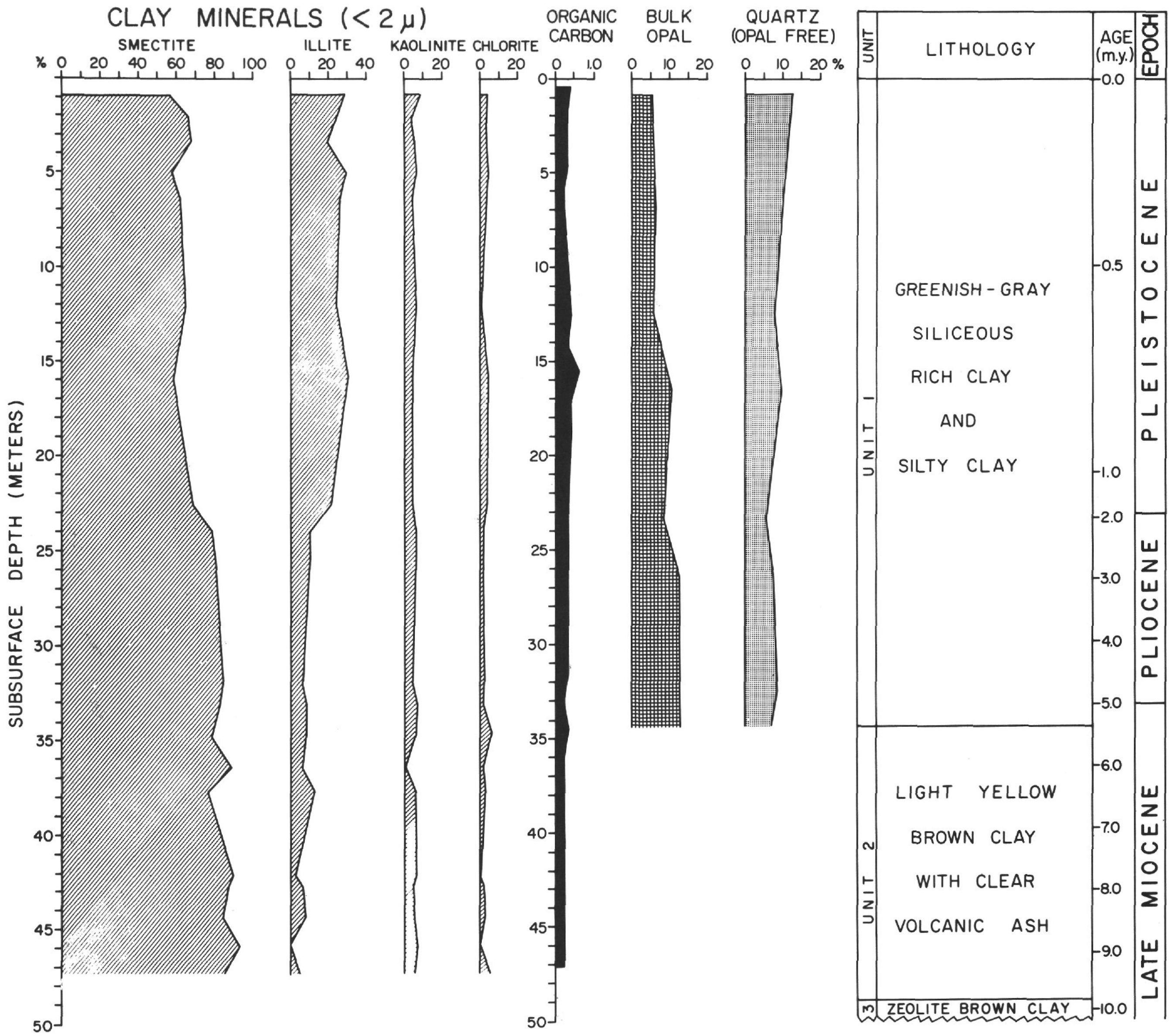

Figure 3. *Percent clay mineral composition, organic carbon, opal (calcium carbonate free), and quartz (opal and carbonate free) in late Cenozoic sediments of Units 1 and 2 at Site 321.*

(Cameron, Carbon-Carbonate Results, this volume), which is the same method used by Rosato (1974) for Nazca plate and continental margin sediments. At Site 321 the organic carbon content is quite low and essentially constant, ranging from 1.2% to 0.4% of the total sediment. Although the upper Miocene sediments have the lowest values, trends are probably not significant because the variations are close to the analytical precision. Organic carbon values in the surface sediments range up to 0.5% for the Peru and Chile basins along the eastern edge of the plate (Rosato et al., 1975). These values are similar to those obtained at Site 321. The highest organic carbon values in the area (up to 6.9%) are found beneath the upwelling region along the coast and along the equator (Rosato, 1974; Rosato et al., 1975; Figure 3).

These high organic carbon values in the surface sediments (Rosato, 1974) and recent oceanographic studies of upwelling in the area (Smith et al., 1971) suggest that the main part of the upwelling region is situated over the continental margin. A large portion of the organic carbon is probably derived through biological productivity. Although the bulk of the upwelling region lies over the margin, the radiolarian assemblages in the surface sediments (Molina-Cruz, 1975) and the relative abundance of diatoms about 1.0 to 0.5 m.y. ago at Site 321 indicate that the site is receiving fauna and flora typical of the upwelled waters at a distance of about 200 km beyond the main upwelling region. The Pleistocene eustatic lowering of sea level to minus 125 meters would shift the upwelling zone approximately 100 km seaward of its present position, but this still would not bring Site 321 within the confines of the main part of the upwelling region. Apparently some of the fauna and flora in the surface waters either diffuse seaward from the main upwelling zone or are transported farther seaward by surface currents. Based upon this study, it is clear that more work is required to understand the complicated sedimentation patterns associated with upwelling regions.

Opal

Opal determinations (Table 2, Figure 3) were made at Oregon State University using the techniques described (Calvert, 1966; Goldberg, 1958). The bulk opal content (carbonate-free basis) at Site 321 is about 12% in Pliocene sediments (5.0-3.0 m.y.) when sedimentation rates were low (0.33 cm/1000 yr). Opal decreased to about 10% from 3.0 to 0.8 m.y. with a further decrease to 5% from 0.8 m.y. to the present. The opal content is lowest in the Pleistocene deposits despite the excellent preservation of siliceous fauna and flora and the appearance of diatoms about 1.0-0.5 m.y. ago (Chapter 5, Site 321, this volume). Dissolution may be an important contribution to the low opal content, but it appears that the siliceous components are being diluted by the higher input of terrigenous silts and clays during the past 1 m.y., with perhaps the highest input suggested by the marked decrease in opal during the past 0.6 m.y. The latter interval includes several eustatic glacial lowerings of sea level with a consequent increase in sediment load carried by rivers because of the increased gradients. Using the surface and subsurface distribution of clay minerals, Rosato (1974) detected a seaward shift in the shoreline which was correlated with the eustatic lowering of sea level.

Opal concentrations (Molina-Cruz, 1975) in surface sediments of the northeastern part of the Nazca plate gradually increase seaward of the Peruvian margin north of 15°S latitude and also increase northward on the plate toward the equator (Figure 4). Near-surface opal contents at Site 321 are close to those found in the surface sediments nearby. The effects of the glacial periods are believed to be minimal at the location (12°S) of Site 321 and the present-day climatic conditions apparently are typical of the past 5 m.y. It appears that during the Pliocene and Pleistocene, Site 321 was west of its present position. Brown clays of Units 2 and 3 are typical of pelagic sedimentation several hundred kilometers from the continent; there is no doubt that Site 321 was farther to the west prior to the Pliocene.

Quartz

The quartz contents (Table 2, Figure 5) of Site 321 sediments have been determined simultaneously with opal by X-ray diffraction. Values have been converted to opal-free concentrations for comparison with surface concentrations determined by Molina-Cruz (1975) for the northeastern part of the Nazca plate (Figure 5). The surface and downcore analyses have been made in the same laboratory, so the results are comparable. The surface data show a tongue of high quartz concentrations extending from the continent northwesterly toward the equator. The quartz probably represents both eolian and fluvial sources with the more distant sediments probably composed mainly of eolian quartz.

TABLE 2
Weight Percent Opal and Quartz (Carbonate-free) in the Pliocene-Pleistocene Sediments at Site 321

Sample (Interval in cm)	Bulk Opal (%)	Bulk Quartz (%)	Quartz (Opal Free) (%)
1-1, 85-87	5.19	12.01	12.67
2-4, 82-84	6.21	9.29	9.90
3-1, 136-138	5.43	7.41	7.83
3-4, 96-98	10.45	8.59	9.59
4-2, 125-127	8.02	4.95	5.38
4-4, 119-121	12.59	6.25	7.15
5-2, 100-102	12.66	6.42	7.35
5-3, 133-135	12.64	5.65	5.47

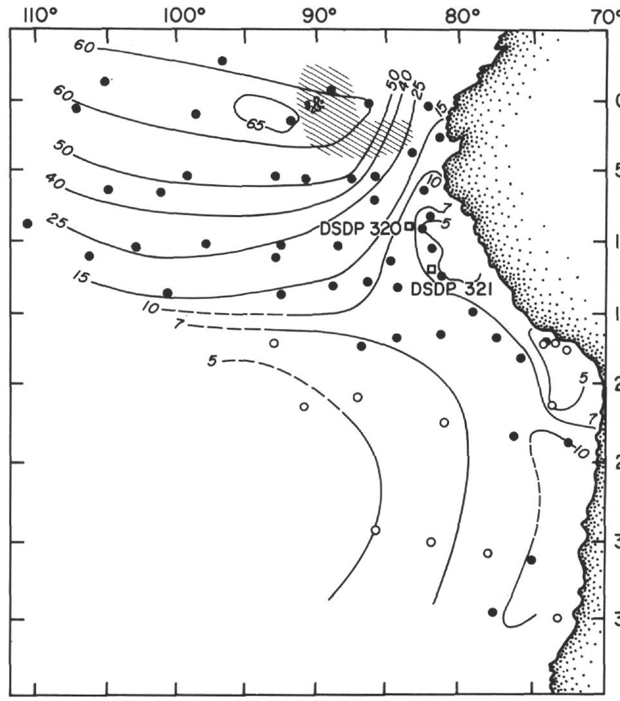

Figure 4. *Percent opal (calcium carbonate free) in surface sediments of the northeastern Nazca plate. Sample locations indicated by dots and open circles (radiolarians absent). Contour intervals are irregular. Note location of Sites 320 and 321.*

In Pliocene sediments, the quartz (opal and carbonate free) content ranges from 5.4% to 7.4% (Figure 3). It increased during the Pleistocene to 12.7% near the surface, which is approximately the value found in surface sediment in the vicinity of Site 321 (Figure 5). The change in Site 321 quartz values through time corresponds to the gradient of surface quartz values away from the continent, suggesting, again, that during late Cenozoic time the Nazca plate was farther west than it is today.

SUMMARY

The sedimentary facies at Site 321 indicate that deposition began near a spreading center. Late Eocene metalliferous sediments lie directly above the basalt and higher in the section at this site and at Site 320 to the north. The late Miocene metalliferous sediments at Site

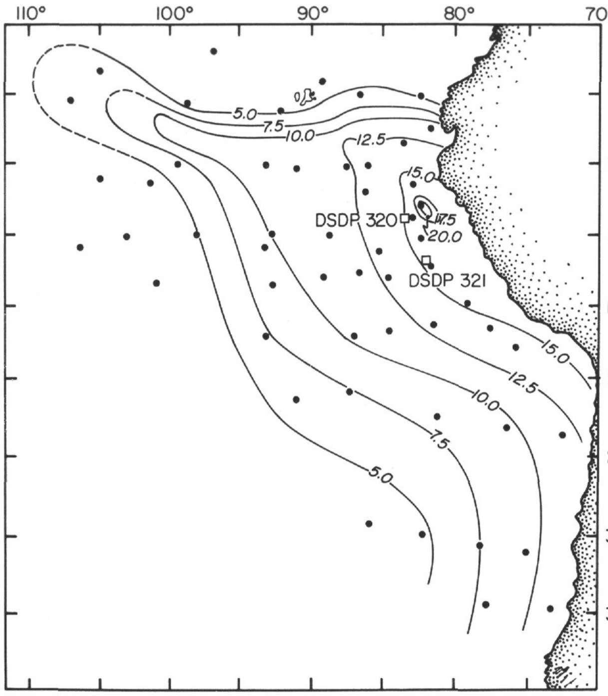

Figure 5. *Percent quartz (opal and carbonate free) in surface sediments of the northeastern Nazca plate. Sample locations are indicated by dots. Contour interval 2.5%. Note locations of Sites 320 and 321.*

321 indicate that the site was still influenced by ridge processes even after its formation 40 m.y. ago. The fossil Galapagos Rise was the probable source of metal-rich material found in these sediments (Chapter 5, this volume). Because the middle to late Miocene brown clays of Units 2 and 3 were deposited below the CCD, Site 321 was some distance out on the flank of the ridge at that time. Wind-transported volcanic ash from the Andean Mountains was deposited in higher concentrations in the late Miocene and Pliocene deposits than in younger deposits.

Terrigenous sedimentation began to influence the late Pliocene to early Pleistocene deposits of Site 321 (Figure 3). The illite content increased abruptly, implying an increased input of clay from terrigenous sources, either from fluvial or eolian transport. Sedimentation rates also increased dramatically approximately 1 m.y. ago from 0.33 to 2.1 cm/1000 yr, suggesting that influx of silts and clays from rivers was more important than eolian contributions.

The smectite content also decreased significantly in the late Pliocene, and this may have resulted from either a diminished ash contribution or a shift in the location of Site 321.

The opal content of Site 321 sediments decreased between 3.0 and 2.0 and 0.75 and 0.5 m.y. ago. Although the rate of opal influx in unknown during these periods, the preservation of delicate radiolarian tests and diatom frustrules is excellent, particularly within the latter interval (Chapter 5, this volume). The lower opal percentages in the sediment suggest that the high terrigenous sedimentation rates tend to dilute the siliceous contribution. Prince et al. (1974) calculate a hemipelagic sedimentation rate of 1.7 cm/1000 yr for the Holocene along the seaward wall of the Peru Trench at 8°S latitude. The 2 cm/1000 yr rate at Site 321 is averaged over the past 1 m.y.; it includes both glacial and nonglacial periods. Increased hemipelagic sedimentation rates usually mark glacial episodes.

Diatom frustules appear in the well-preserved siliceous fraction about 0.75 to 0.5 m.y. ago. We know that the Peru current, with its associated upwelling, was present during the later Pliocene and early Quaternary because of the cool water faunas found in the pelagic deposits in the lower continental slope opposite the Nazca Ridge (Kulm et al., 1974). Therefore, we conclude that Site 321 reached the influence of the upwelling region during late Pleistocene time.

The sedimentary data and natural remnant magnetism of both basalts and sediments from Site 321 (Chapter 5, this volume), together with the pattern of sea-floor magnetic anomalies (Herron, 1972), suggest that the Nazca plate moved relatively eastward with respect to the South American continent. The sedimentary data from the eastern edge of the Nazca plate suggest a rather uniform convergence rate during the past 5 m.y.

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