68. DEEP SEA DRILLING AND TECTONICS OF THE NAZCA PLATE

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INTRODUCTION

In the early days of plate tectonics, the interpretations of Nazca plate evolution were deceptively simple. The Nazca plate was included as part of a model illustrated by Isacks et al. (1968, fig. 1), which showed it as an entirely oceanic plate that formed at the crest of the East Pacific Rise and was carried eastward to South America and downward into the asthenosphere at the Peru-Chile Trench.

Its simplicity invited further studies, and these studies revealed complications which thereby destroyed the simplicity. Now it is understood that there are two aseismic ridges on the plate, the Carnegie and Nazca ridges. Are these the surface expressions of plumes from the mantle? Of more fundamental concern is the presence of the "fossil" rise (Herron, 1972a) or Galapagos Rise of others, which trends north-northwest in contrast with the north-northeast trend of the East Pacific Rise. Thus it is apparent that part of the history of the Nazca plate involves a jumping rise crest. But the jump from the "fossil" rise to the East Pacific Rise was not instantaneous. Evidence based on bathymetry (Anderson and Sclater, 1972; Mammerickx et al., 1974, 1975) and magnetic anomalies (Herron, 1972a) led to the conclusion that the "fossil" Galapagos Rise continued to spread long after the new East Pacific Rise had been established to the west. Indeed, based on seismicity and first-motion study of earthquakes, two spreading ridges may exist side by side today near Easter Island (Herron, 1972b; Anderson et al., in preparation).

Further complications appeared. Linear magnetic patterns, where identifiable, are much more complicated than expected, and in parts of the region, correlatable magnetic anomalies cannot be identified at all (Ade-Hall, this volume). The Galapagos Rise is a discontinuous feature, differing in crestal altitude from place to place, and not found at all at some latitudes (Von Herzen and Anderson, 1972). Refraction studies show that the Nazca plate is characterized by unusually high compressional wave velocities (Hussong et al., 1972; Johnson et al., 1973). Sediment cover is unusually thin throughout the plate. The eastern boundary of the plate is continuous only in that it is marked by a trench; large, unexplained gaps occur in shallow- and deep-focus seismicity and in historic volcanism (Kelleher, 1972). A layer of metal-rich sediments blankets the Bauer Deep, the depression between the inactive Galapagos Rise and the active East Pacific Rise (Dymond et al., 1973; Anderson and Halunen, 1974).

On New Year's Day, 1974, *Glomar Challenger* crossed the East Pacific Rise crest enroute to its first site in the Nazca plate. At this time, virtually nothing was known about sediments older than Pliocene in the plate. Only one site on the plate had been drilled previously, Site 157 on the Carnegie aseismic ridge, from which sediment cores as old as late Miocene were recovered (van Andel, Heath, et al., 1973). A major goal of Leg 34 was to add a new dimension to the study of the Nazca plate through the stratigraphy of sediments beyond the limit of piston cores.

THE BAUER DEEP: METALLIFEROUS SEDIMENTS, HIGH SEDIMENTATION RATES, AND ANOMALOUS WATER DEPTHS

Surface sediments of the Bauer Deep contain a high concentration of metalliferous particles (Dymond et al., 1973; Anderson and Halunen, 1974; Quilty et al., this volume). Metalliferous particles are found throughout the section at Site 319, but are concentrated in sediments which have accumulated below the calcite compensation depth (CCD). Sedimentation rates for metalliferous particles are approximately the same in the residual surface section where they are concentrated and in the underlying section where they are diluted by nanno ooze. The highest sedimentation rates for metalliferous particles are found at the base of the sediment section, presumably reflecting proximity to the rise crest (see Boström and Peterson, 1969). The correlation between high sedimentation rate of metalliferous particles and proximity to a spreading center, observed at Site 319 and at Sites 159-162 on the west flank of the East Pacific Rise (Cronan et al., 1972), and the presence of Pb-isotope ratios in the sediments similar to those in magmatic Pb (Dasch et al., 1971) suggest that the metals originated at the rise crest, passed through a seawater phase, and were precipitated on the flanks of the rise (Boström and Peterson, 1969; Dymond et al., 1973). The sedimentation rate for metalliferous particles might be expected to diminish near the top of the section as the crust is transported away from the rise crest. It does not diminish, possibly because the rise crest jumped from a position east of the site to a new position west of it, so that now the Bauer Deep is much closer to an active rise crest than are sediments of the same age on the west flank of the East Pacific Rise at 10° N, sampled on Leg 16. Alternatively, hydrothermal circulation associated with the jump in the spreading center could account for the maintenance of high accumulation rates for metalliferous particles in the Bauer Deep (Anderson and Halunen, 1974).

The total sedimentation rate above the CCD at Site 319 is much higher than rates for other sites at the same latitude above the CCD (Quilty et al., this volume). This high rate may be explained in part by transport of sediments from adjacent ridges because the calcareous sediments show signs of reworking (Quilty et al., this volume), and profiler records around the site show evidence of ponding (Yeats and Heath, this volume; Erlandson, 1975). Another factor may be high biologic productivity. The upper west flank of the Galapagos

Rise at this latitude may have been a zone of much higher biologic productivity or, alternately, of a deeper lysocline than the east flank (Sites 320, 321) or the lower west flank (Sites 75, 76) (Tracey, Sutton, et al., 1971; Quilty et al., this volume).

The oldest sediments at Site 319 are early Miocene in age, about 16.5 m.y. old, but the age of crust at 4250 meters depth should be 25 m.y. based on the relationship between age and depth (Menard, 1969; Sclater et al., 1971) as modified for the Nazca plate by Mammerickx et al. (1975, fig. 5). A theoretical curve for the Galapagos Rise assuming a spreading half-rate of 12.3 cm/yr from 6-16 m.y. would provide a better fit to the basal sediment age at Site 319, but this rate is probably too high, and the crust in the Bauer Deep would still be too deep for its age (Ade-Hall, this volume). The basalt directly beneath the sediments is relatively fresh, suggesting that it was not exposed to seawater for the millions of years necessary if the sediment age and the Sclater-Francheteau age are both correct. Radiometric dating includes Ar^{40}/Ar^{39} plateau ages close to the sediment ages (Hogan and Dymond, this volume) in addition to other ages which are considerably older. Magnetic anomalies are indistinct in the Bauer Deep and cannot be dated; their low amplitude compared with East Pacific Rise anomalies indicates the Bauer Deep was formed on the crest of the Galapagos Rise (Ade-Hall, this volume). Detailed bathymetry around Site 319 (Yeats and Heath, this volume) shows a strong northwest trend of ridges and basins, similar to the trend on the lower east flank of the Galapagos Rise near the Peru-Chile Trench, but discordant to the north-northeast trend of the nearby East Pacific Rise. An alternative hypothesis for the lack of magnetic anomaly correlation and the northwest trend of the topography is tectonic disruption.

The evidence is clear that the Bauer Deep formed on the Galapagos Rise, which was then spreading in a northeasterly direction, but beyond this conclusion, the evidence is ambiguous. The Bauer Deep was undoubtedly affected by the appearance of the East Pacific Rise to the west of it, but the heating associated with this event should make the Bauer Deep shallower than expected, not deeper. The mystery is unsolved.

SITES 320 AND 321: THE PERU CURRENT AND SOUTH AMERICA

The only complete sedimentary section at the eastern edge of the Nazca plate was recovered at Site 321. The top of the nanno ooze section at Site 321 is marked by a prominent seismic reflector which is also found in the vicinity of Site 320 (Figure 1). The correlation of this reflector to stratigraphy at Site 321, together with sedimentation rates determined from the limited coring at Site 320, permits the use of both sites in the determination of sedimentation rates and the ages of various changes in lithology reflecting the approach of the South American continent.

Direct evidence of the approach of the continent is provided by volcanic ash, possibly from Andean volcanoes (Donnelly, this volume) and terrigenous sediments which crossed the Peru-Chile trench presumably in the suspended state or by atmospheric transport (Rosato et al., in press; Kulm et al., this volume; Quilty et al., this volume). This evidence must be separated from the evidence provided by the sharp lithologic break at the top of the nanno ooze caused by the depression of the site below the CCD and the sharp faunal break caused by upwelling associated with the north-flowing Peru (Humboldt) Current.

Kulm et al. (1974) and Molina-Cruz (1975) have summarized studies of the modern Peru Current and associated zone of upwelling, including evidence that south of the Nazca Ridge the upwelling is supplied by north-flowing Subantarctic Water whereas north of this area (north of 15°S), the upwelling is supplied by south-flowing Equatorial Subsurface Water. These studies suggest that the zone of upwelling associated with the Peru Current system today is at least 100 km wide, although the system expels cool waters into adjacent currents to the west, thereby extending the effects of coastal upwelling.

At Site 321, the contact between nanno ooze of late Oligocene age and overlying unfossiliferous zeolitic clay marks the passage of the site below the CCD. The clay is overlain by siliceous clay and siliceous ooze, rich in radiolarians, diatoms, and silicoflagellates; the siliceous fauna ranges in age from late Miocene to Quaternary. The absence of equatorial radiolarian indicator species in the Quaternary fauna, suggests that this fauna, at least, is of cool-water aspect. A similar siliceous fauna is found in the shallow cores from Site 320, and throughout the section at Site 157, on the Carnegie Ridge just south of the Equator. The oldest siliceous faunas at Site 157 are late Miocene, as at Site 321, but unlike Site 321, they are associated with calcareous fossils because Site 157 never dropped below the CCD (van Andel, Heath, et al., 1973). According to Quilty et al. (this volume), this siliceous fauna and the cool-water foraminifera may indicate augmented influence of southern waters during the late Miocene. This may have reflected a smaller flow through the Drake Passage at this time, but this cannot be demonstrated conclusively (Quilty et al., this volume; H. Sachs, personal communication, 1975).

The width of this area of southern cool-water influence, as based on the siliceous faunas at Sites 157 and 321, may be calculated for the late Miocene, assuming the base of the siliceous assemblage at Site 321 marked the passage of the site into the western edge of the area dominated by the current about 10 m.y. ago. Site 157 is about 490 km west of the Peru-Chile Trench axis, and Site 321 about 330 km west of it. If the present 10 cm/yr rate of convergence of the Nazca plate with South America (Minster et al., 1974) was the same for the last 10 m.y., the western edge of the system in the late Miocene was about 1330 km west of the axis of the Peru-Chile Trench at Site 321 and 1490 km west of it at Site 157.

The seismic reflector that marks the top of the nanno ooze at the east edge of the plate is recognized in many seismic lines in the area. The reflector dies out westward toward the Galapagos Rise and does not appear on the Nazca Ridge (Kulm et al., 1974, fig. 5). The sediment section at Site 320 is thicker than that at Site 321 despite the fact that it is considerably younger (Figure 2a). Isopachs of the sediment section above the reflector (Figure 2b) show that much, but not all, of the northward increase in thickness takes place in the siliceous section

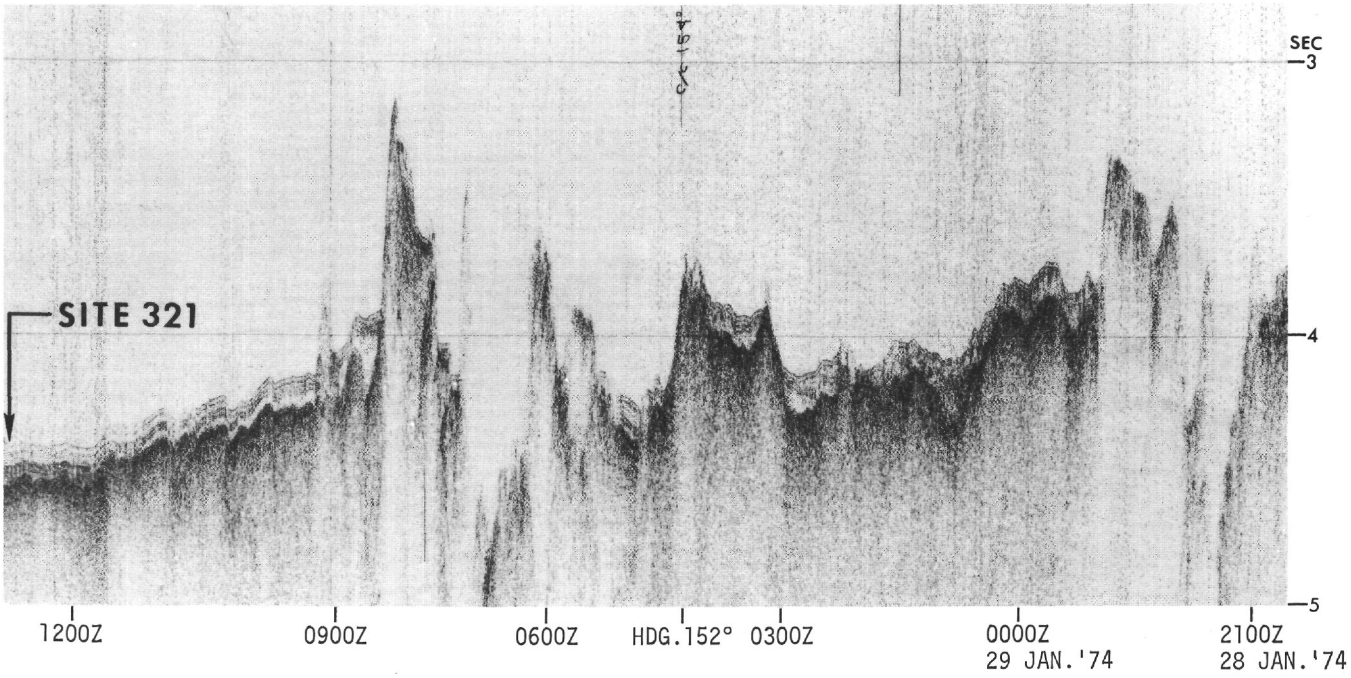

Figure 1. Glomar Challenger *airgun survey approaching Site 321, 4-sec sweep. Prominent reflector within sediments near Site 321 (left side of figure) is the top of the nanno ooze section based on physical properties. Reflector discontinuous elsewhere. Sharp topographic breaks from 2300 to 0800 Z mark the Mendaña Fracture Zone.*

deposited below the CCD; this may be due to greater biologic productivity of the siliceous sediments in the more northerly site. The thicker carbonate section at the more northerly site may also be due to the equatorial increase in biologic productivity. The sea floor at both sites was above the CCD for approximately the same length of time, about 20 m.y., but at Site 321 the time was earlier.

Both sites subsequently passed through the CCD, Site 321 at about 20-25 m.y. ago and Site 320 at an estimated 10 m.y. ago (Quilty et al., this volume). In contrast, Site 157 on the Carnegie Ridge remained above the CCD throughout the time of sediment deposition at the site, from late Miocene to the present, and Piston Core Y71-6-12P on the Nazca Ridge and Piston Core Y71-6-24P on the lower continental slope (but formerly on the Nazca Ridge) were above the CCD during the early Pliocene and the Quaternary (Kulm et al., 1974). This indicates that the aseismic Carnegie and Nazca ridges were topographically prominent during the late Tertiary, perhaps as prominent as they are today. This is illustrated schematically in Figure 3, which shows stratigraphic sections in the eastern Nazca plate in their relative topographic positions. The apparent upward migration of the CCD can be explained by slow subsidence of the eastern portion of the Nazca plate as it cooled; the absolute depth of the CCD could have remained the same from late Miocene until today.

Magmatic Sulfides

The relationship between metalliferous oxide sedimentation rates and proximity to the Galapagos Rise crest at Site 319 has already been noted. The presence of globules of magmatic sulfides in the underlying basalts (Mathez and Yeats, this volume) indicates that metals are concentrated locally in the basalts as metalliferous sulfides, in addition to concentration in the sediments as metalliferous oxides. The basalt glass at Sites 319 and 320 is saturated with respect to sulfur, and the globules formed as immiscible droplets in the silicate magma. Thus the sulfur is of magmatic rather than of juvenile origin. The density of the droplets was greater than that of the silicate magma, so how did they get so near the surface? The answer may be seen in the proximity of the globules to phenocrysts of plagioclase; possibly the droplets adhered by surface tension to these phenocrysts as they ascended to the surface from the magma chamber. This leads to the conjecture that the higher density magmatic sulfides that remained in the magma chamber were preserved as the plate cooled, resulting in copper deposits similar to those found in the Troödos Massif in Cyprus (Rona, 1973). This speculation may have important geophysical consequences and is a prediction that will only be resolved by deeper crustal drilling.

CONCLUDING REMARKS: REMAINING PROBLEMS

Leg 34 of the Deep Sea Drilling Project has answered some questions about Nazca plate geology and raised others. At Site 319, the high sedimentation rates for nanno ooze are inadequately explained, and the crust is too deep for its age. These problems may relate to the puzzle of two ridges spreading at the same time which requires a third plate between the Pacific and Nazca plates, on which some of the sediments at Site 319 were deposited. Was it a small, ephemeral plate like the one near Easter islands or was it the northern arm of the Antarctic plate?

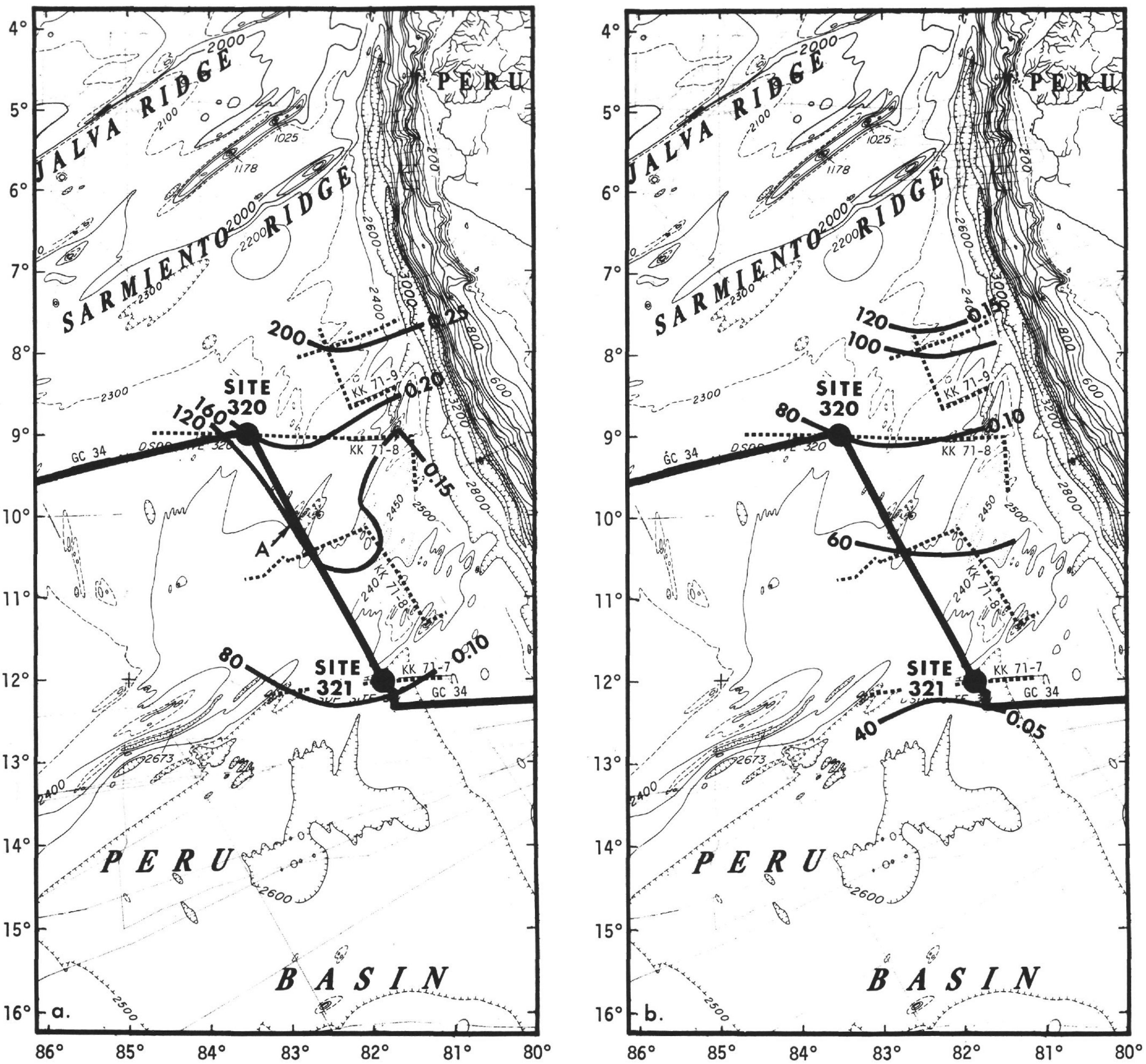

Figure 2. *Sediment isopachs in the vicinity of Sites 320 and 321. Isopachs in meters (left) and 2-way travel time in seconds (right). Railroad track symbol indicates ship's tracks used in isopachs:* Kana Keoki *lines are part of the International Decade of Oceanographic Exploration, sponsored by the National Science Foundation. Base map is from Mammerickx et al. (1974). Figure 1 extends from "A" to Site 321 on Leg 34 track.* (a) *Total sediment isopachs.* (b) *Sediment isopachs above major reflector.*

The phenomenon of two ridges close to one another and spreading at the same time may be due to the high spreading rate between the Nazca and Pacific plates which, according to Minster et al. (1974), is the highest in the world. The high spreading rate has been suggested by Anderson et al. (in preparation) as an explanation for the Easter plate. Other anomalous relations such as the northeast spreading direction for crust 16 m.y. old at Site 319 (as based on linear topography) may also be related to rapid spreading. Another problem is the occurrence of sediment isopach minima 200-400 km east of the crests of both the Galapagos and East Pacific rises rather than on the crests themselves (Ade-Hall, this volume).

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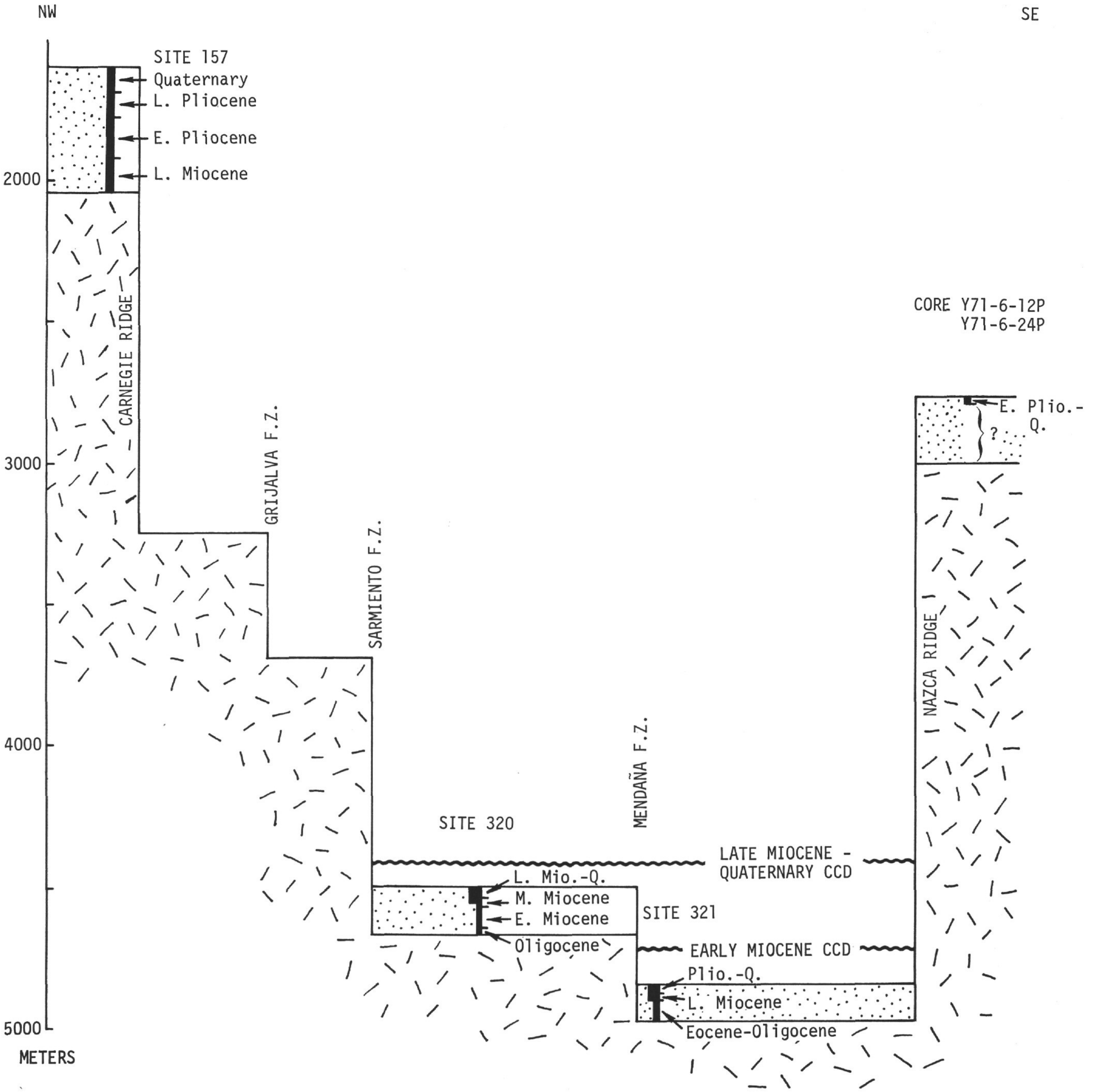

Figure 3. *Stratigraphic section of the northeastern Nazca plate from Carnegie Ridge to Nazca Ridge, showing relative position of the CCD in early Miocene time and from late Miocene to Quaternary. Heavy vertical lines indicate stratigraphic control for DSDP Sites 157, 320, and 321, and two piston cores on the Nazca Ridge. Heavy bar to the left of Sites 320 and 321 indicate that part of the section deposited below the CCD. Dots indicate sediments where cored.*

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REFERENCES

Anderson, R.N. and Halunen, J., 1974. Implications of heat flow for metallogenesis in the Bauer Deep: Nature, v. 251, p. 473-475.

Anderson, R.N. and Sclater, J.G., 1972. Topography and evolution of the East Pacific Rise between 5°S and 20°S: Earth Planet. Sci. Lett., v. 14, p. 433-441.

Anderson, R.N., Forsyth, D.W., Molnar, P., and Mammerickx, J., in preparation. Fault plane solutions of earthquakes on the Nazca plate boundaries and the Easter plate.

Boström, K. and Petersen, M.N.A., 1969. The origin of aluminum-poor ferromanganoan sediments in areas of high heat flow on the East Pacific Rise: Marine Geol., v. 7, p. 427-447.

Cronan, D.S., van Andel, Tj. H., Heath, G.R., Dinkelman, M.G., Bennett, R.H., Bukry, D., Charleston, S., Kaneps, A., Rodolfo, K.S., and Yeats, R.S., 1972. Iron-rich basal sediments from the eastern equatorial Pacific: Leg 16, Deep Sea Drilling Project: Science, v. 175, p. 61-63.

Dasch, E.J., Dymond, J.R., and Heath, G.R., 1971. Isotopic analysis of metalliferous sediment from the East Pacific Rise: Earth Planet. Sci. Lett., v. 13, p. 175-180.

Dymond, J., Corliss, J.B., Heath, G.R., Field, C.W., Dasch, E.J., and Veeh, H.H., 1973. Origin of metalliferous sediments from the Pacific Ocean: Geol. Soc. Am. Bull., v. 84, p. 3355-3372.

Erlandson, D., 1975. Sediment accumulation in structural traps in the southern Bauer basin, southeast Pacific (abstract): EOS, Am. Geophys. Union Trans., v. 56, p. 445.

Herron, E.M., 1972a. Sea-floor spreading and the Cenozoic history of the east-central Pacific: Geol. Soc. Am. Bull., v. 83, p. 1671-1692.

———, 1972b. Two small crustal plates in the South Pacific near Easter Island: Nature Phys. Sci., v. 240, p. 35-37.

Hussong, D.M., Johnson, S.H., Woollard, G.P., and Campbell, J.F., 1972. Crustal structure of the Nazca plate: EOS, Am. Geophys. Union Trans., v. 53, p. 413.

Isacks, B., Oliver, J., and Sykes, L.R., 1968. Seismology and the new global tectonics: J. Geophys. Res., v. 73, p. 5855-5899.

Johnson, S.H., Connard, G.G., Hussong, D.M., and Ness, G.E., 1973. Crustal structure of the north-central Nazca plate from seismic refraction: Geodynamics Conference of I.A.S.P.E.I., Lima, Peru.

Kelleher, J.A., 1972. Rupture zones of large South American earthquakes and some predictions: J. Geophys. Res., v. 77, p. 2087-2103.

Kulm, L.D., Resig, J.M., Moore, T.C., and Rosato, V.J., 1974. Transfer of Nazca Ridge pelagic sediments to the Peru continental margin: Geol. Soc. Am. Bull., v. 85, p. 769-780.

Mammerickx, J., Smith, S.M., Taylor, I.L., and Chase, T.E., 1974. Bathymetry of the south Pacific: chart 15: Scripps Inst. of Oceanography IMR Tech. Rept. 48A.

Mammerickx, J., Anderson, R.N., Menard, H.W., and Smith, S.M., 1975. Morphology and tectonic evolution of the east-central Pacific: Geol. Soc. Am. Bull., v. 86, p. 111-118.

Menard, H.W. (Ed.), 1969. Elevation and subsidence of oceanic crust: Earth Planet. Sci. Lett., v. 6, p. 275-284.

Minster, J.B., Jordan, T.H., Molnar, P. and Haines, E., 1974. Numerical modelling of instantaneous plate tectonics: Geophys. J. Roy. Astron. Soc., v. 36, p. 541-576.

Molina-Cruz, A., 1975. Paleo-oceanography of the subtropical southeastern Pacific during late Quaternary: a study of radiolaria, opal and quartz contents of deep-sea sediments: M.S. thesis, Oregon State University, Corvallis, Oregon.

Rona, P.A., 1973. Plate tectonics and mineral resources: Sci. Am., v. 229, p. 86-95.

Rosato, V.J., Kulm, L.D., and Derks, P.S., in press. Surface sediments of the Nazca plate: Pacific Sci.

Sclater, J.G., Anderson, R.N., and Bell, M.L., 1971. Elevation of ridges and evolution of the central eastern Pacific: J. Geophys. Res., v. 76, p. 7888-7915.

Tracey, J.I., Sutton, G.H., Nesteroff, W.D., Galehouse, J., von der Borch, C.C., Moore, T., Lipps, J., Ul Haq, B., and Beckmann, J.P., 1971. Initial Reports of the Deep Sea Drilling Project, Volume 8: Washington (U.S. Government Printing Office).

van Andel, Tj.H., Heath, G.R., Bennett, R.H., Bukry, D., Charleston, S., Cronan, D.S., Dinkelman, M.G., Kaneps, A., Rodolfo, K.S., and Yeats, R.S., 1973. Initial Reports of the Deep Sea Drilling Project, Volume 16: Washington (U.S. Government Printing Office).

von Herzen, R.P. and Anderson, R.N., 1972. Implications of heat flow and bottom-water temperature in the eastern equatorial Pacific: Geophys. J. Roy. Astron. Soc., v. 26, 427-458.