40. MESOZOIC MAGNETIC ANOMALIES, OCEANIC PLATEAUS, AND SEAMOUNT CHAINS IN THE NORTHWESTERN PACIFIC OCEAN[1]

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INTRODUCTION

Leg 32 of the Deep Sea Drilling Project was planned with three main objectives. One was to date the magnetic lineations of the oceanic crust east of Japan and west of the Hawaiian Ridge from the age of sediments lying on basement. The lineations were predicted to be a record of sea-floor spreading during a period of late Mesozoic reversals of the magnetic field. A second interest was to establish Mesozoic and Cenozoic biostratigraphic reference sections for the northwestern Pacific by continuously coring the sedimentary sections on Shatsky and Hess rises. Presumably, planktonic fossils that otherwise would not survive dissolution in the deep ocean might be preserved on top of these submarine plateaus. The third objective was to determine the age and paleolatitude of Kōko Guyot, in the Emperor-Hawaiian Seamount chain. Cores of the basalt underlying the guyot would be used to test a current theory of the origin of seamount chains.

The actual sedimentary rocks encountered on the leg, as well as the operating capabilities and weather, were not always as anticipated. It remains convenient, however, to present our sedimentary, biostratigraphic, and tectonic history of the northwestern Pacific Ocean in terms of the original objectives even though not all of them were met.

AGE OF MESOZOIC MAGNETIC ANOMALIES

Background

One of the outstanding successes of the Deep Sea Drilling Project has been the dating of magnetic anomaly lineations through the recovery of fossiliferous sediment overlying the basement basalt. In several instances there have been some uncertainty whether the sediment lies nonconformably on extrusive basalt generated at the mid-ocean ridge or whether the basalt is intrusive and thereby younger than the true crust. Evidence is accumulating that the great majority of contacts either are of sediment on extrusive basalt, or are of very shallow intrusives penecontemporaneous with crust generation (Moberly, in preparation). Other possible sources of error, such as assignment of the correct biostratigraphic age and uncertainty of the depth to a particular sediment sample above basement, discussed by van Andel and Bukry (1973), appear to be more important than uncertainties over the nature of the contact. There have been modest revisions of the time scale originally proposed by Heirtzler et al. (1968) for the past 80 m.y. (for example Berggren, 1972; Sclater et al., 1974); however, the present best calibration is within a few percent of the one originally proposed.

Magnetic lineations discovered in the western Pacific and on the border of the western North Atlantic did not fit within the Cenozoic sequence. These are northeast-striking lineations east of Japan (Uyeda et al., 1967); northwest-striking lineations west of the Hawaiian Ridge (Hayes and Pitman, 1970); east-striking lineations north of the Phoenix Islands (Larson and Chase, 1972); and northeast-striking lineations off the southeastern United States (Vogt et al., 1971).

Larson and Chase (1972) correlated these Japanese, Hawaiian, and Phoenix magnetic lineations and used their geometry to propose a late Mesozoic history for the Pacific Ocean crust. Larson and Pitman (1972) correlated the Keathley lineations with these Pacific ones, and on the basis of scanty evidence from DSDP biostratigraphy proposed a geomagnetic time scale for Mesozoic magnetic anomalies M-1 (about 112 m.y.B.P.) through M-22 (about 148 m.y.B.P.). During several million years of Middle to Late Cretaceous time, after the M sequence and before the latest Cretaceous through Cenozoic ones, the earth's magnetic field apparently was of dominantly normal polarity.

Objectives of Leg 32

We planned several holes on the Japanese and Hawaiian lineation patterns of the northwestern Pacific that would test the contention of Larson and Chase (1972) that these lineations are all expressions of the same magnetic reversal sequence recorded at two different spreading centers. These sites would also test and further calibrate the late Mesozoic reversal time scale of Larson and Pitman (1972). Initially, the time scale had two points of control. Site 166 was drilled between M-7 and M-8 of the Phoenix set, where the oldest sediment is late Hauterivian or early Aptian in age. In the western North Atlantic, Oxfordian and Callovian sediments were cored just west of the Keathley anomalies at Sites 100 and 105.

The Pacific Advisory Panel of JOIDES had a number of secondary reasons to drill in the western Pacific. It was hoped that basalts recovered from these sites could be examined radiometrically and paleomagnetically to gain more insight into age calibration and tectonic reconstructions, respectively. Little sediment had been recovered in the deep western Pacific during DSDP

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phases I and II, and modifications to D/V *Glomar Challenger* had been planned so as to overcome some of these difficulties. Fossiliferous sediment could be used to improve Mesozoic biostratigraphy and to record such events as the transit of the Pacific lithospheric plate under the equatorial zone of high productivity or under the Kuroshio Extension Current.

The upper sedimentary section from the youngest site on the Hawaiian lineations should also yield the age of the Hawaiian Ridge at that point, because the magnetic anomalies are overlain by the Hawaiian archipelagic apron. This part of the Hawaiian Ridge lies between Midway Islands and the Hawaiian-Emperor "bend," and is in an area where the age progression along the chain appears to be nonlinear.

Leg 32 and Subsequent Information

Of the four sites located on Mesozoic magnetic anomalies (303, 304, 307, and 311, Figure 1), the first three successfully cored the Mesozoic sediment section, penetrated volcanic basement, and achieved basal age estimates of varying precisions. Site 311 bottomed in volcanic sandstone of Oligocene age and will be discussed in the section on island chains.

The post-Mesozoic sediments at Sites 303 and 304 are diatom-radiolarian oozes of Neogene age, whereas the uppermost sediment at Site 307 is mainly a thin, unfossiliferous brown clay (Figure 2). These sediments are underlain, probably unconformably, at all three sites by mid-Cretaceous cherty pelagic clays that grade down to cherty nannofossil oozes. This lithology is underlain by weathered basalts that were cored at all three sites, although the basalt-sediment contacts were never recovered. The basalts are very fine grained, and at Sites 303 and 307 consist of several flow units, the latter site containing a large amount of hyaloclastite. The basalts are moderately to highly altered, the upper portion at Site 307 being a "tholeiitic claystone" containing 13% H_2O. Despite this sometimes extreme alteration, it is possible to determine, especially from the trace elements of the less-altered samples, that the rocks were originally tholeiitic basalts, similar to basalts being generated at present-day ridge crests (Marshall, this volume).

Although the basement contacts were not sampled at Sites 303 and 304, sediment was recovered from no more than three meters above this contact in both cases. These samples have been dated by their calcareous microfossils at both sites, although the preservation and diversity of fossils at Site 304 is far superior to that at Site 303. At both sites the foraminifera give a Barremian or Hauterivian age, while the nannofossils are Hauterivian or Valanginian. The basalt at Site 304 has a calcite vein containing crustacean coproliths that are closely related to the species *Favreina salevensis* that is widespread in Late Jurassic limestones. Since the favereinids at Site 304 are not conspecific with *Favreina salevensis*, they are of limited stratigraphic value, but the possibility exists that Site 304 is somewhat older than the Early

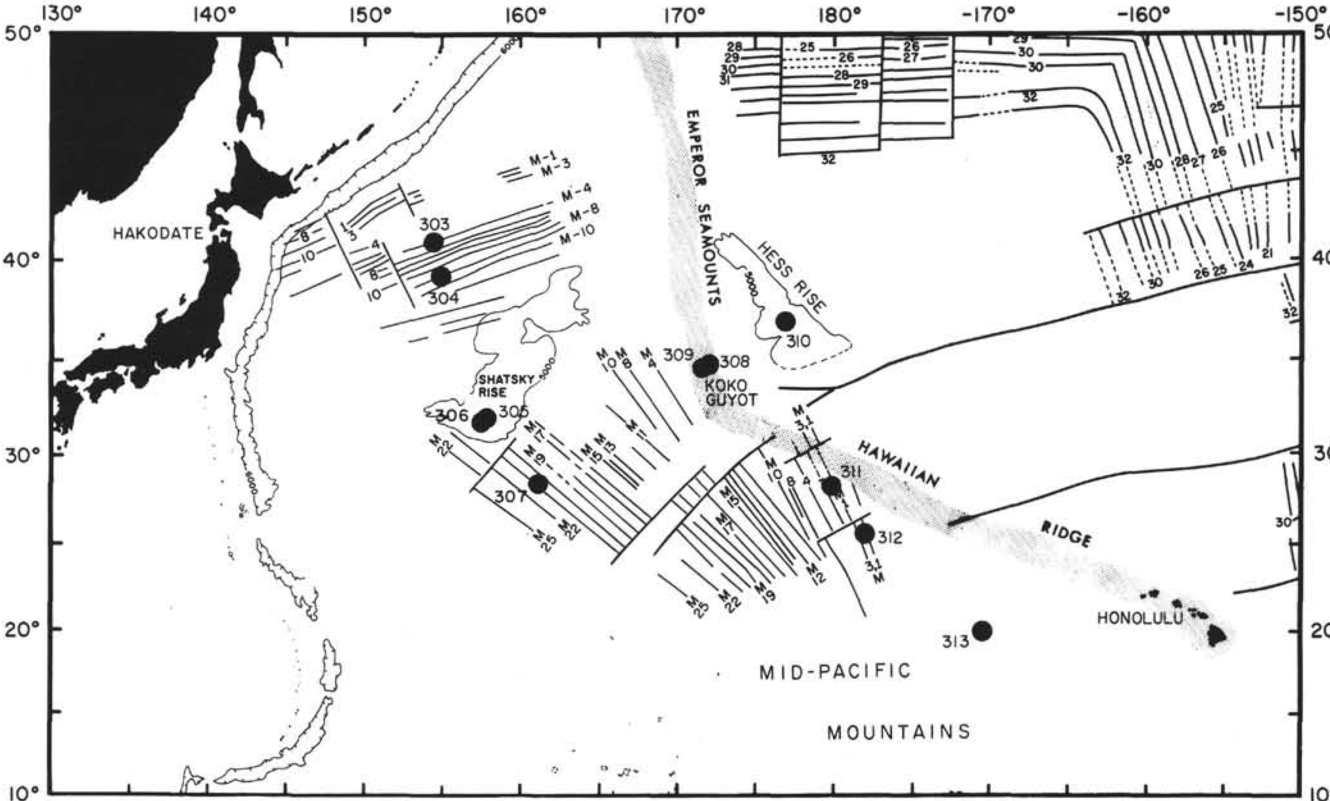

Figure 1. *Chart of the northwestern Pacific showing Leg 32 site locations relative to the magnetic lineations, rises, and seamount chains of the area.*

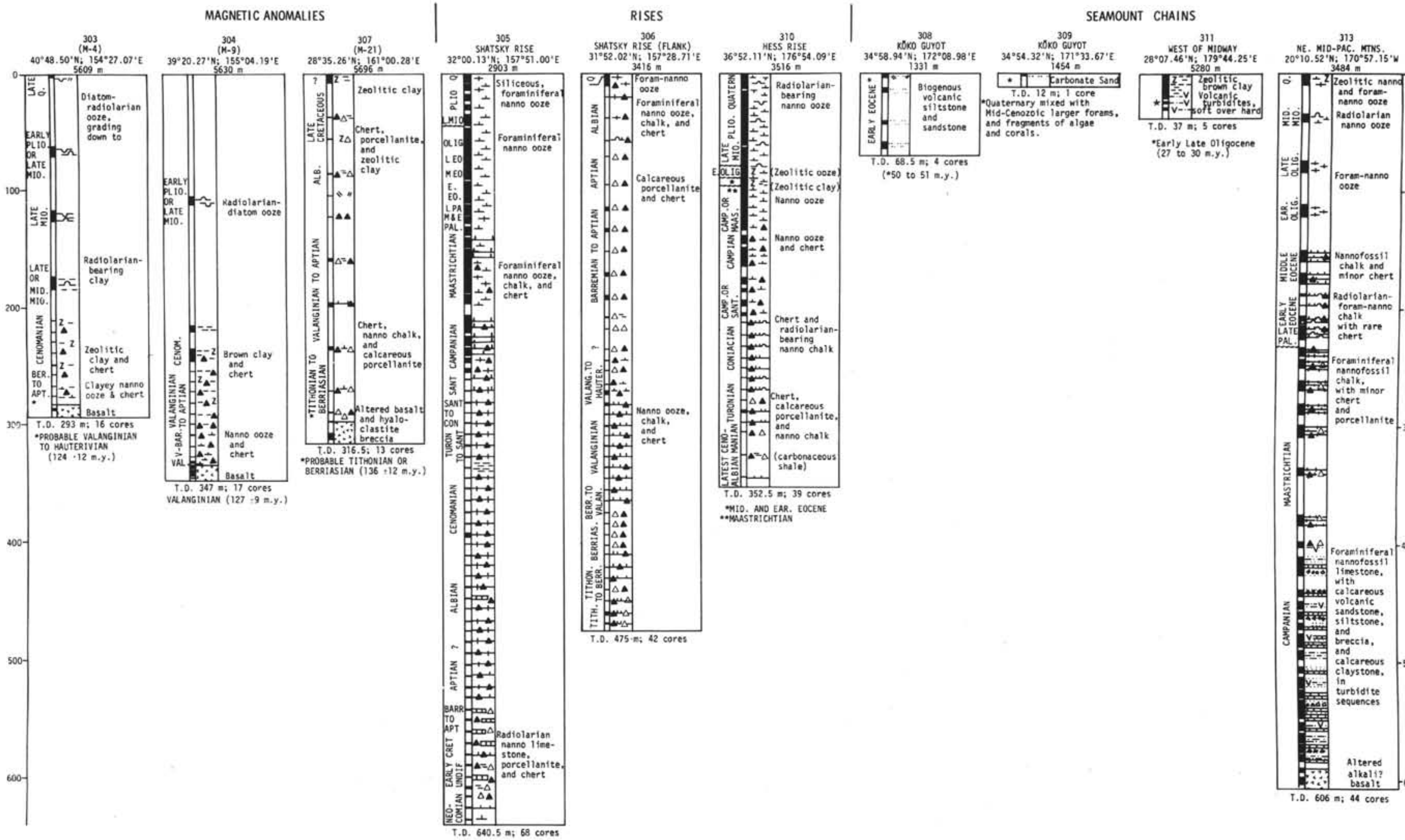

Figure 2. *Summary diagram showing the paleontologic ages, lithologies, and recovered intervals of the Leg 32 holes as functions of depth beneath the sea floor.*

Cretaceous age given by the nannofossils and foraminifera (Lehmann, this volume). For the present we will accept the Barremian to Valanginian age from the overlying sediments as the most likely basement age.

Site 303 lies on magnetic anomaly M-9 and Site 304 is located on anomaly M-4 of the Japanese magnetic lineation sequence. This information, when combined with the early Aptian or late Hauterivian age determined at Site 166 (Leg 17) between anomalies M-7 and M-8, is still best fit by the magnetic reversal time scale proposed by Larson and Pitman (1972). Because of the multistage range of the fossils and the usual mismatch of nannofossil and foraminiferal ranges, the time scale represented by the diagonal line in Figure 3 is not the only one that will satisfy these data, but it appears to be the most likely one.

A significantly poorer basement age determination was made at Site 307, where the problem is mainly a lack of recovered calcareous sediments near the basement contact. The oldest fossils at Site 307 are Radiolaria whose occurrence is rare and diversity is poor. They are pre-early Valanginian in age and are known to coexist with Tithonian to early Valanginian nannofossils recovered on Legs 17 and 20. They are probably Berriasian in age because the oldest nannofossils that were recovered from 20 meters higher in the section are late Valanginian or early Hauterivian, and the general Cretaceous sedimentation rates down to that level are relatively high. By an extrapolation of the same argument, basement is probably also Berriasian in age. This age is not well enough determined to be used as a calibration point for the Mesozoic reversal time scale, but a comparison with the established time scale is interesting.

Site 307 was drilled on anomaly M-21 of the Hawaiian lineation sequence that has been predicted to

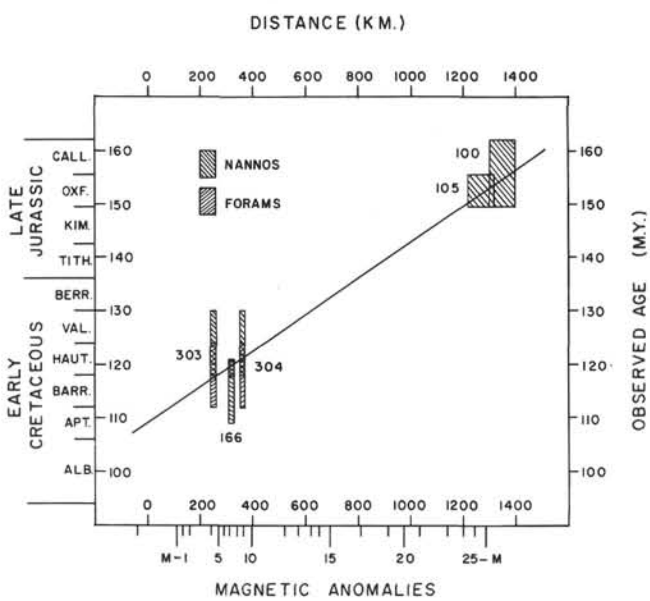

Figure 3. *Plot of cross-strike distance across the Hawaiian lineation pattern versus geologic age of the oldest sediments recovered from various DSDP holes on M-lineations (from Larson and Hilde, in press).*

be Tithonian or Kimmeridgian in age from the Larson and Pitman (1972) time scale. This age range cannot be excluded at Site 307 because of the poor sediment recovery and the preliminary nature of the radiolarian stratigraphy. The geology of the hole, however, suggests an age of 5 to 10 m.y. younger than the predicted age. This discrepancy could result for the following reasons. (1) Our best estimate of the basement age may be too young because of the poor recovery. (2) A nondepositional interval may have occurred after extrusion of the basalt at Site 307. (3) The calibration of the radiometric time scale of the latest Jurassic and earliest Cretaceous may be significantly in error. Some combination of these possibilities is probably the explanation for the discrepancy in basement age.

During Leg 32, the M series of anomalies was extended to M-25 through the identification of some older anomalies of smaller amplitudes on Pacific magnetic records that had been brought onboard for planning purposes. The current status of dates on the M series anomalies in the Pacific and Atlantic oceans has been summarized by Larson and Hilde (in press) and is shown in Figure 3.

Keys to the original paleolatitudes and subsequent motions of these sites are contained in the remanent magnetic vector directions of the basalts, the stratigraphy of the overlying sediments, and the magnetic anomalies in the vicinities of these sites. By analyzing magnetic anomaly profiles near the site locations, it is estimated (Larson and Lowrie, this volume) that Sites 303 and 307 are normally magnetized and that Site 304 is reversed. These estimates, combined with the remanent magnetic inclination of the basalts, yield the following paleolatitudes: Site 303 = 6°S, Site 304 = 11°S, Site 307 = 6°N. The cross-sectional shapes of the anomaly profiles yield concordant paleolatitude information at each of the three sites (Figure 4). This information all supports a net northward motion of the Pacific plate since the Mesozoic.

The paleolatitudes of Sites 303 and 304 obtained from the above methods are in very close agreement with paleolatitudes predicted by a model developed from the sedimentary stratigraphies of other DSDP holes on the Pacific plate and the configurations of Pacific island chains (Lancelot and Larson, this volume). Figure 5 shows the six relevant Leg 32 sites rotated back to their original paleolatitudes via this model. The paths of these "backtracked" sites were obtained by rotations about three successive poles of motion determined from the shapes and general ages of Pacific island chains that were supposedly generated as the Pacific plate moved over various fixed "hot spots" in the mantle. While we do not speculate on the physical basis for these "hot spots," it does appear that they have defined an absolute reference frame for the past few million years (Minster et al., 1974; Solomon and Sleep, 1974), and this model assumes that they have marked a fixed reference frame for the past 125 m.y. The heavy portions of the backtracked paths in Figure 5 between latitudes 5°N and 5°S mark the various times that these sites passed beneath the equatorial zone of high productivity. For the deep sites (303, 304, and 307) this crossing is marked by an influx of siliceous sediments that have been

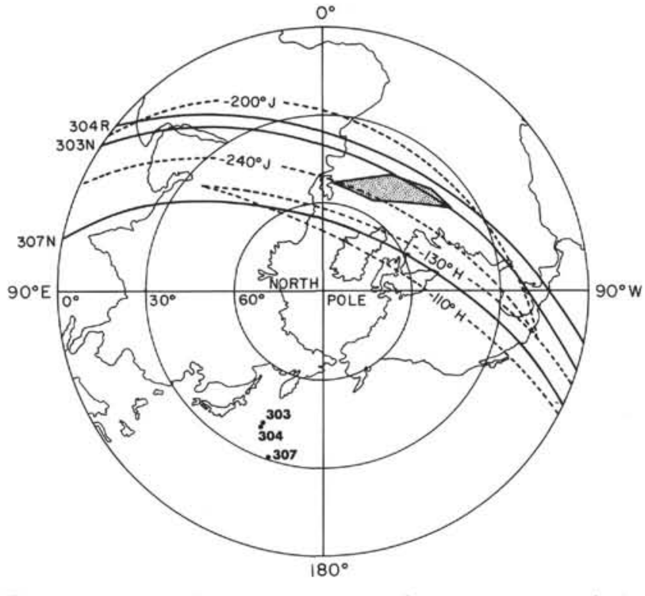

Figure 4. *Azimuthal equidistant polar projection of the Northern hemisphere with paleomagnetic pole location data from rock magnetization and magnetic anomaly studies. Dots labeled 303, 304, and 307 are the site locations. The irregular polygon (stippled) encloses the paleomagnetic pole location for the Pacific plate from M-1 to M-10 time (Larson and Chase, 1972). 303N, 304R, and 307N are the Northern Hemisphere portions of small circles along which paleomagnetic poles for the Pacific plate may lie assuming that the sites are normally (N) or reversely (R) magnetized, and that the remanent inclination directions were generated by an axial dipole. -200°J, -240°J, -110°H, and -130°H are the Northern Hemisphere positions of great semicircles that enclose paleomagnetic pole locations derived from the cross-sectional shapes of the C1405 and C1007 profiles, respectively (Larson and Lowrie, this volume).*

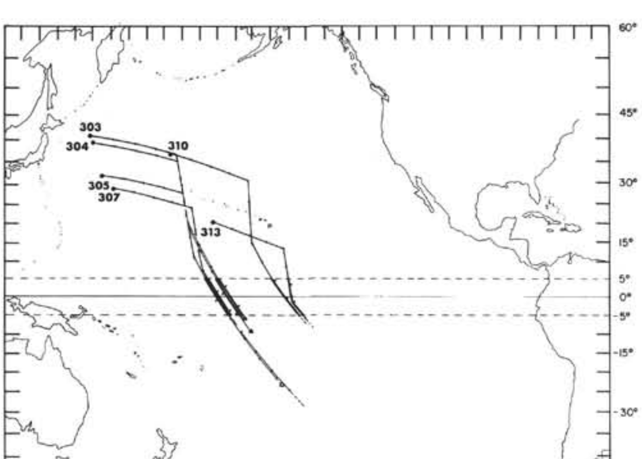

Figure 5. *Locations of six DSDP Leg 32 drill sites and their backtracked paths through geologic time accomplished by the rotations described by Lancelot and Larson (this volume).*

diagenetically altered to cherts, whereas the shallow sites (305, 310, 313) show marked increases in their carbonate sedimentation rates (Figure 2).

Figure 6 shows the Pacific plate boundaries determined from magnetic lineations and fracture zones rotated back to various geologic times on the basis of this sedimentary model. The site locations of 303 and 304 shown in Figure 6c and 6b are the paleolatitudes of these sites determined independently from the remanent magnetic inclinations of basalts recovered at these sites. Perfect correspondence of these measurements would be indicated by Sites 303 and 304 plotting exactly on the Pacific-Kula plate boundary in Figures 6c and 6b. The discrepancy in both cases is considerably less than 5° of latitude.

There are data to establish the sedimentary model back only into Early Cretaceous time (~125 m.y.), but it should be pointed out that a simple extrapolation of this model is at variance with the paleolatitude information from Site 307 (Figure 5). Since an extrapolation of the model would predict a paleolatitude somewhat south of 20°S latitude, and the measured paleolatitude of Site 307 is about 6°N, this may indicate that a marked change occurred in Pacific plate motion between the Late Jurassic and Early Cretaceous.

GEOLOGIC RECORD ON OCEANIC PLATEAUS

Background

The accumulation of planktonic fossils on the sea floor, and the paleoecologic and biostratigraphic data that can be derived from them, depends on the interplay between production of skeletons in surface waters and their dissolution in deeper water (Berger, 1970) modified by deep-sea processes of erosion and redeposition.

Elevated parts of the sea floor have been especially significant for micropaleontological studies. Depths less than the lysocline allow a high net rate of accumulation. Merely high productivity may not result in equally useful assemblages, as fertile areas tend to have poor preservation of fossils (Berger, 1971). Not all elevated areas are equally useful; for example, those close to continents may have a great dilution of the planktonic record by detrital sedimentation, and there is only a very young record on the mid-ocean ridges.

Oceanic plateaus are areas of the sea floor that have accumulated thicker sediments than the adjacent deep-sea floor (Ewing et al., 1966; Kroenke, 1972). Their crust is much thicker than average oceanic crust (Den et al., 1969; Furumoto et al., 1973). Ontong-Java and Manihiki plateaus, and Shatsky, Hess, and Magellan rises total about 2% of the area of the Pacific Ocean Basin (Figure 7). Kerguelen Plateau, Broken Ridge, and the ridges northwest and southeast of Iceland are among similar features elsewhere. Their elevation which allows better preservation of fossils also isolates them from mixing and dilution by turbidity currents. As a result the plateaus have proved to be among the most useful of oceanic sites for matching zonations based on foraminifers, nannofossils, and radiolarians (Fischer, Heezen, et al., 1971; Winterer, Riedel, et al., 1971; Winterer, Ewing, et al., 1973). Cores recovered from the complete penetration of Magellan Rise also have

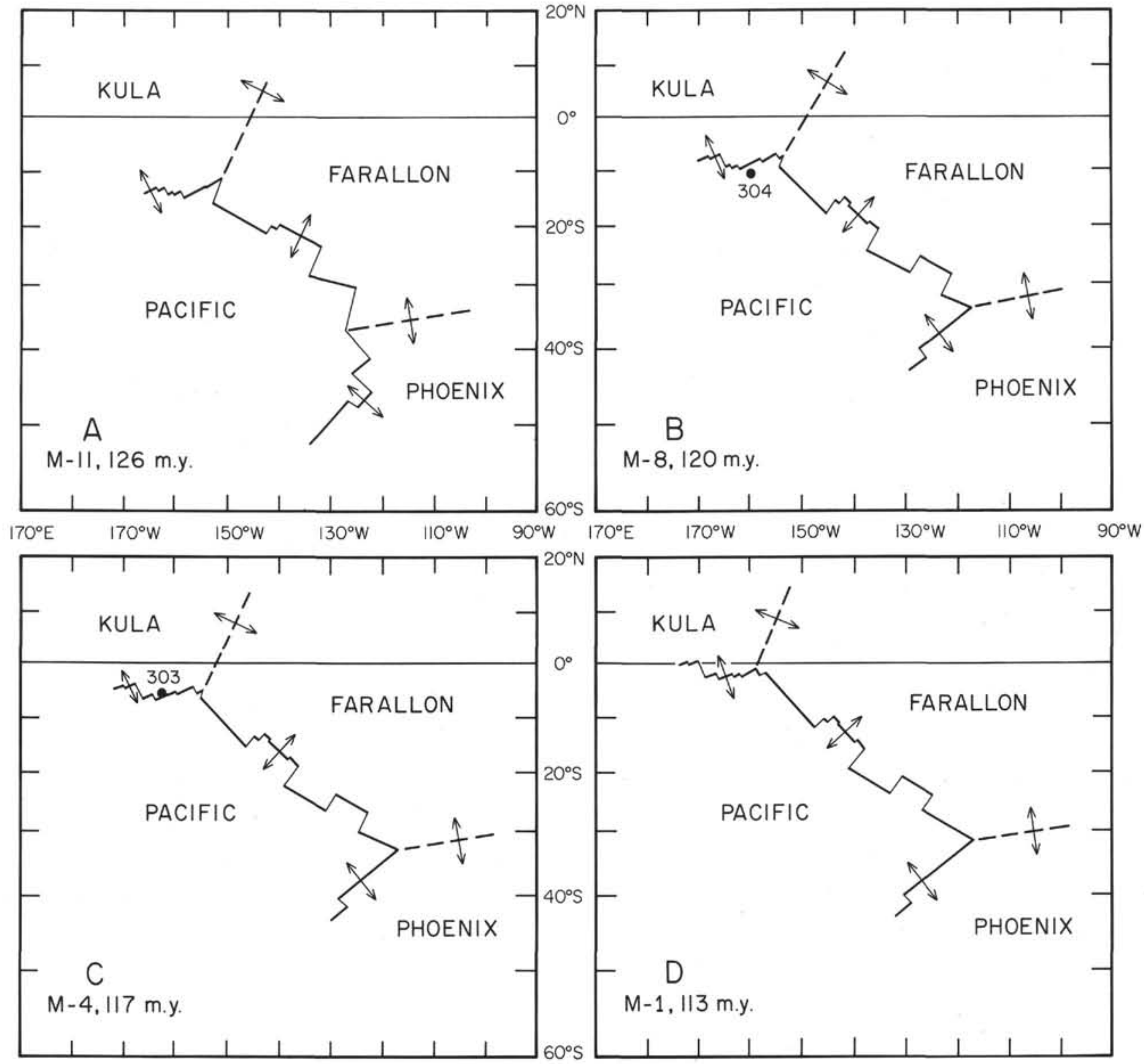

Figure 6. *(a) M-11 isochron rotated back to its time of formation at 126 m.y. (b) M-8 isochron rotated back to its time of formation at 120 m.y. Site 304 is the paleolatitude of this site determined from the remanent magnetic inclination of the basalts at the bottom of the hole. (c) M-4 isochron rotated back to its time of formation at 117 m.y. Site 303 is the paleolatitude of this site determined from the remanent magnetic inclination of the basalts at the bottom of the hole. (d) M-1 isochron rotated back to its time of formation at 113 m.y. (from Lancelot and Larson, this volume).*

been useful for paleotemperature and petrographic interpretations (Coplen and Schlanger, 1973; Douglas and Savin, 1973; Bass et al., 1973).

Objectives of Leg 32

It was believed that a well-placed site on Shatsky Rise would offer the best opportunity in the North Pacific for the preservation and recovery of a fossiliferous pelagic section from within the Paleogene through the entire Cretaceous and into Jurassic sediments. At Hess Rise the deepest sediments were expected to be somewhat younger, but coring throughout the section would be important to recover a record of fossil floras and faunas of the Central North Pacific Water Mass during the Neogene.

The successful isotopic, diagenetic, and petrologic studies on cores from other plateaus indicated several additional objectives for Leg 32 drilling on Shatsky and Hess rises. The passage of these regions under the equatorial zone of high productivity would be recorded in increased accumulation rates. The age of transit would help constrain reconstruction of the northward and rotational movement of the Pacific lithospheric plate relative to the equator. Cores, especially if oriented, would add paleomagnetic data for the tectonic reconstructions. More complete descriptions of paleo-

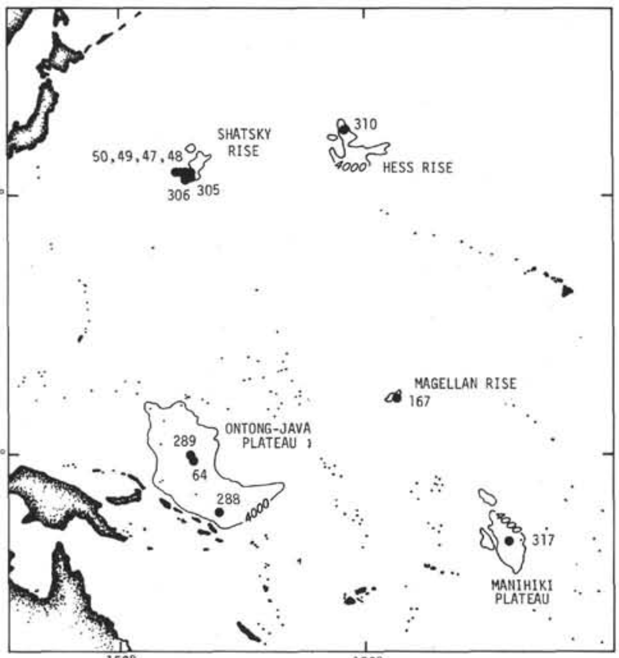

Figure 7. *Oceanic plateaus in the Central and Western Pacific outlined by the 4000-meter depth contour. DSDP sites indicated by dots.*

oceanographic objectives and the necessary dissolution and isotopic studies necessary for them are listed in the individual site reports.

Leg 32 and Subsequent Information

Site 305 was drilled near the crest of Shatsky Rise where seismic reflection profiles showed a moderately stratified section about 0.77 sec thick over a fairly smooth acoustic basement. Five cores of upper Neogene sediments have radiolarians, coccoliths, and foraminifers present and useful for zonation. Unfortunately, this is the part of the section of least potential value, and all the deeper samples, or lack of samples, are deficient in one or more ways.

The mid-Cenozoic unconformity reported on Leg 6, where the sites had upper Miocene resting on middle Eocene to middle Maestrichtian, is not as extensive at Site 305, where it is upper Miocene on upper Oligocene. Regretably, no radiolarians remain in the Paleogene oozes, and many of the calcareous Paleogene nannofloras and microfaunas are not well preserved (Luterbacher, this volume; Bukry, this volume; Toumarkine, this volume).

Samples of a nearly complete Cretaceous section were recovered; from probable Valanginian through late Maestrichtian, according to the calcareous fossils and, in particular, the foraminifera. Recovery was so poor, especially in the very cherty section, that there is almost no material to provide a reference section for the scientific community.

When the bit wore out after penetrating 640 meters of sediment, of which the lower 400 meters were cherty, we decided to move down the southwest flank of Shatsky Rise to core the remaining unsampled beds and basement (Site Reports, Sites 305 and 306, this volume). The reflection profile there showed that the opaque section was thinner than where we had cored it at Site 305, yet the transparent layer above basement and through which we had not cored appeared the same. At Site 306 the transparent layer, however, proved as cherty as the opaque layer above it, and our penetration of 475 meters ended about 100 meters above basement.

Floras and faunas are generally scanty in the Lower Cretaceous rocks recovered from Site 306. Of particular biostratigraphic interest, however, is the association of nannofossils and radiolarians in the lowest cores, where the nannofossils in Cores 41 and 42 are earliest Berriasian in age. The radiolarian faunas (Foreman, this volume) are correlated with those of Site 196, a deep-water location in the western Pacific drilled on Leg 20, whose Core 5 had no co-occurring calcareous fossils and whose radiolarians were thereby of unknown age, though possibly as old as Late Jurassic.

Our recovery of a Neogene section at Hess Rise was satisfactory, but poor weather and cherty Mesozoic sediments combined to frustrate our effort to reach many of our other objectives (see Site Report, Site 310). The Neogene has provided a good record of paleo-oceanographic events and of the evolutionary history of planktonic foraminifera (Vincent, this volume). Both Hess and Shatsky rises have calcareous as well as siliceous fossils so that zonations based on different fossil groups have been compared directly, and with good agreement. For some Neogene species the stratigraphic limits appear to be the results of dissolution and for some others the limits reflect changes in surface-water temperatures.

The Paleogene section on Hess Rise is thin, zeolitic, and contains at least six unconformities or greatly compressed sections. Sediments are stained by ferromanganese oxides. Calcareous microfossils and nannofossils are strongly corroded (Luterbacher, this volume) and siliceous fossils are lacking; further evidence of poor conditions for sediment accumulations during the early Cenozoic (Matter, et al., this volume).

The Upper Cretaceous section is thick on Hess Rise, partly because of the transit of the plateau under the equator in the Santonian or Coniacian. All stages and most of the important zones from Maestrichtian or early Campanian down to early Cenomanian have been identified from the planktonic foraminifers (Caron, this volume). The foraminifers in the upper part of this Cretaceous interval show effects of partial dissolution and they are contaminated by younger sediment that fell down the hole. In the lower part they are better preserved. Unfortunately, the amount of sediment recovered is very small, consisting almost entirely of core-catcher samples.

Studies of the biogenic sediments from Shatsky and Hess rises show the roles of paleogeography, paleo-oceanography, and diagenesis in these calcareous and siliceous rocks. Many of the suggestions and conclusions of earlier investigators of deep-sea cherts are substantiated by the results of Keene (this volume): the importance of sediment texture and composition, the nature of the silica phases precipitated, the biogenous source of most silica, and the successive stages in precipitation and replacement.

At both Shatsky and Hess rises the diagenetic process in carbonates is progressive dissolution of the more delicate coccoliths, planktonic foraminifers, and micrite with concurrent precipitation of calcite as overgrowths and cement on the more robust fossils. Moderate compaction and lithification occur. Matter et al. (this volume) describe the importance of strontium analyses coupled with examination of sediment texture in describing the history of lithification of carbonate sediments. In their examination of Shatsky Rise cores, the low strontium values of pore waters of the deepest carbonates recovered are interpreted as resulting from dissolution of previously precipitated low-strontium cement. Examination of the texture supports this view.

A number of additional points remain unknown, such as the nature of basement under these plateaus and the time and latitudinal position of their origin. Also, for some points of interest there is now more information but the interpretation is still speculative. One of these is the extent of the mid-Miocene unconformity and the reason for it. Is it specifically a problem of the northwestern Pacific, or of the Miocene, or part of a broader problem of erosion or nondeposition on elevated parts of the sea floor? A second problem is the origin of the black carbonaceous shales in the early Cenomanian of Hess Rise (310A, Core 17) and Shatsky Rise (305, Core 37) and also in the Aptian or Barremian of Shatsky Rise (305, Core 65, and 306, Core 13). The green to black shales contain pyrite or siderite and some fragments have enough organic matter to burn briefly when a match is applied. Similar evidence of stagnant, anaerobic conditions in the deep sea of mid-Cretaceous time was found on DSDP Leg 11 (Hollister, Ewing, et al., 1972), and is not uncommon in the Tethyan facies of Europe (A.G. Fischer, personal communication).

By the end of phase III drilling in the Pacific, all five large plateaus have been cored. Figure 8 is a summary of that activity. At the current time from the available geophysical and drilling data, it appears that plateaus form as thick piles of volcanic rocks at the mid-ocean ridge system where locally the rate of rifting cannot keep pace with the rate of magma generation (McKenzie and Sclater, 1971). Excepting Ontong-Java, whose Cretaceous paleogeography is not well known, four of five of these older Pacific plateaus appear to have formed near the triple point of a Mesozoic spreading system. Thus, crude modern-day analogs may be the Galapagos volcanic platform and its association with the Galapagos-East Pacific Rise triple point, or the Azores platform associated with the North America, Europe, Africa triple point in the central Atlantic. Later they are cut by high-angle faults and locally by igneous bodies. The dominantly carbonate pelagic sediments lithify to limestones (Schlanger and Douglas, 1974). These oceanic sediments covering a thick crust might be incorporated into continents in two ways (Moberly and Kroenke, 1974): as irregular continental margins left behind during initial rifting of continents (Bahamas), or as masses of sediment and igneous rocks obducted at convergent margins of continents or island arcs (Maliata).

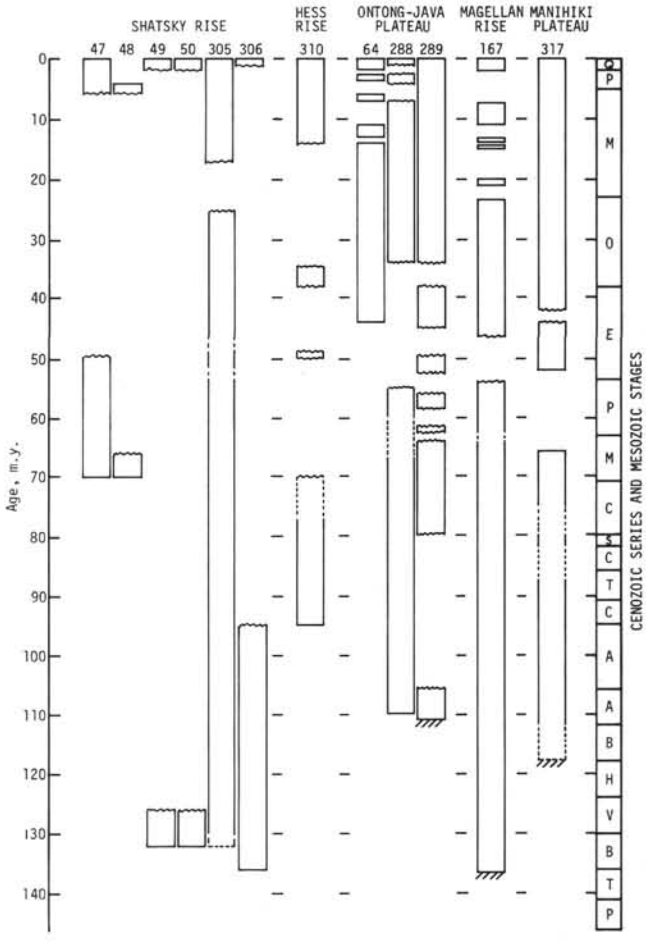

Figure 8. *Known stratigraphic record on oceanic plateaus of the Central and Western Pacific. Wavy-lined gaps in columns are from known unconformities, or from such compressed sections that the recovery of cores could not distinguish them from unconformities. Straight-lined gaps show incomplete coring and so may or may not include unconformities. Dashed outlines of columns are parts of sections where it is uncertain that the particular stratigraphic unit is present, such as where ages determined by two fossil groups are in conflict. Solid-lined outlines of columns show presence of sediment of appropriate age, but in no way are indications of the abundance or preservations of fossils in the record, which indeed may be poor. Drilling at Sites 167, 289, and 317 ended in basalt.*

ORIGIN OF LINEAR SEAMOUNT CHAINS

Background

Scientists have speculated about the alignment of volcanoes since von Humboldt in 1803 noted the line of Mexican volcanoes and was "tempted to believe that the subterranean fire had forced an opening through an enormous crevice which exists in the interior of the earth at a latitude of 18°59′ to 19°12′ [N] and which stretches from the Pacific to the Atlantic Ocean" (quoted in Kellner, 1963, p. 60). Although not of the earth-encircling scale of volcanism along the mid-ocean ridge system and along the young cordillera and island arcs, nevertheless the lines of volcanic islands, seamounts, guyots, and atolls such as those along the Hawaiian Ridge and the Emperor Seamounts are major features on earth. These chains are especially conspicuous in the Pacific Ocean. For several chains, observations of actual volcanism, as well as geomorphic evidence and radiometric dates, indicate that the chains lengthen by the progression of volcanism at an end. The two principal explanations for this apparent progression of volcanism along the sea floor have been that a fracture propagates across the oceanic lithosphere providing conduits for successive volcanoes (Dana, 1849; Betz and Hess, 1942; Hess, 1954; Menard, 1964), or that there has been lateral movement of the lithosphere over a continued source of magma so that successive new volcanoes erupt above the source and are moved away, with the magma source fixed in the mesosphere (Wilson, 1963; Morgan, 1971, 1972a, 1972b; Jackson et al., 1972). Another possibility is that the return flow of convection is in the asthenosphere (Moberly and Khan, 1969), allowing a combination of the hot-spot and propagating-fracture theories, that a hot region of the moving asthenosphere would lengthen tensional fractures and thereby initiate a succession of magma sources (McDougall, 1971).

Objectives of Leg 32

During the planning of Leg 32 the proposal was made to test some of these theories by drilling on the flanks of Kōko Guyot, one of the southern Emperor Seamounts. The following assumptions were made: (1) The Emperor and Hawaiian chains were continuous. (2) The initial rapid extrusion of tholeiitic basalts, followed within a very few million years by alkalic eruptions, that characterizes the mode of volcanism of the principal Hawaiian Islands, also was the mode of volcanism of the older Hawaiian and Emperor volcanoes. (3) Cores of tholeiitic lavas would sample the initiation of volcanism of a particular volcanic edifice. (4) Cores of alkalic lavas would sample a slightly later stage of volcanism of a particular edifice. According to the plume theory, a plume and hot spot is fixed deep in the mantle so there would be little if any differential movement between plumes and the earth's axis of rotation. Therefore, volcanoes formed above the same plume would have the same paleolatitude. Paleomagnetic measurements on oriented cores could be compared to the latitude of the active Hawaiian volcanoes, Moana Loa and Kilauea. The cores could also be radiometrically dated to test whether volcanism is monotonic and linear along the chain (Jackson et al., 1972). Winterer (1973) showed that many linear features in the Pacific are concentric with the Emperor or the Hawaiian alignments, and it became obvious that information bearing on the origin of those chains would have implications for directions and rates of movement of the entire Pacific lithospheric plate.

Leg 32 and Subsequent Information

Two sites were occupied on Kōko Guyot, 308 on the east edge of the sedimentary cap and 309 on the west edge. We were not able to penetrate the firm sediments to core lavas at either of these shallow sites of the volcanic pile, so we did not satisfy our Leg 32 objective of determining the original paleolatitude of Kōko Guyot.

The sedimentary rocks that were recovered in our four cores at Site 308, however, provided fossils that are older than the radiometric ages of rocks that had been dredged from the seamount by Scripps ARIES expedition. The nannofossil flora of the *Discoaster lodoensis* Zone is of early Eocene age, about 50 to 51 m.y.B.P. In order to have a volcanic foundation on which the sediments lie, the actual date of the beginning of volcanism is about 10% older than the 46 m.y. K/Ar ages (Figure 9).

Traces of shallow-water sediments of late Oligocene age were recovered from Site 309 (Hottinger, this volume), mixed with younger planktonic fossils. Some parts of Kōko Guyot under or upslope from Sites 308 and 309 remained in shallow water for more than 20 m.y., and thus volcanism probably recurred substantially after the Eocene. The great variety of volcanic rocks, ranging from alkali basalt to trachyte to phonolite (Clague, 1974) may have resulted from the long span of time for differentiation.

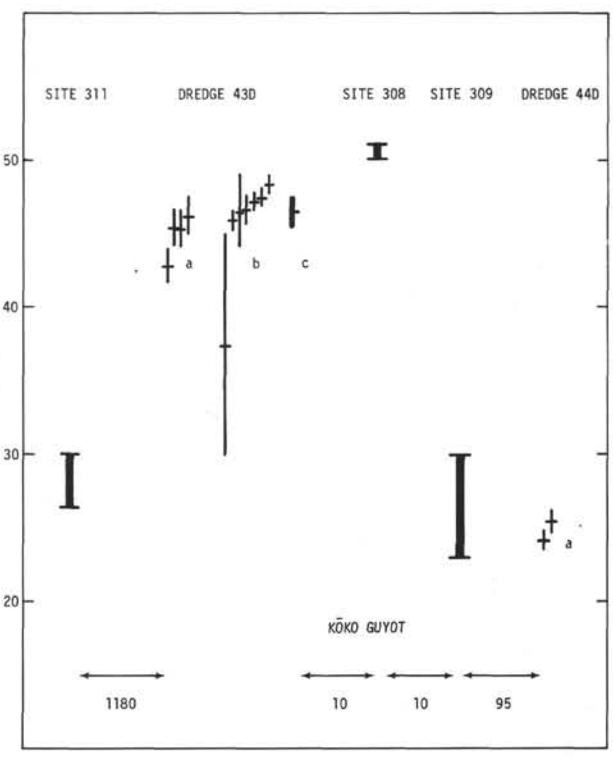

Figure 9. *Range of ages at Kōko Guyot and at Site 311. Ages for Sites 308, 309, and 311 are from fossils obtained during Leg 32 drilling. They represent the range of the zonal ages used in this volume (mainly from Bukry, this volume). The possible error from uncertainty of the age of the biostratigraphic boundary is not included, but may be on the order of ±2 m.y. (van Andel and Bukry, 1973). Scripps ARIES dredge-hauls 43D and 44D provided rocks dated by Clague and Dalrymple (1973) by (a) conventional K/Ar methods, and by (b) $^{40}Ar/^{39}Ar$ methods; (c) is the weighted mean of (b).*

The sedimentary rocks recovered from Site 308 were formed in shallow water, according to the paleoecologic interpretations of the benthonic foraminifers (Ferrer, this volume) and bryozoans (Cheetham, this volume). Fragments of fossil algae and corals in the sandstones, and the well-rounded basalt grains support the same conclusion (Matter and Gardner, this volume; Moberly and Keene, this volume). The flat top of this seamount was formed in shallow water by truncation of the top of a volcano and by paralic sedimentation around it before subsidence. That has been the orthodox theory for the origin of guyots (Hamilton, 1956). There is no evidence at Kōko Guyot to support ideas that some guyots may result mainly from constructional processes of volcanism in deep water (Nayudu, 1962). However, for such a huge volcanic edifice, which must be a composite of several shields, some volcanism from circumferential vents around one or more of the calderas may have contributed to the flat-top shape (Simkin, 1972).

The main reason for drilling at Site 311 was to date the youngest of the M magnetic anomalies, but, as at Site 309, the loss of part of the drilling equipment ended our operations before reaching the primary objective. Site 311 was on the archipelagic apron of an unnamed seamount of the Hawaiian Ridge just east of longitude 180°. This seamount lies 240 km west of Midway Islands. The turbidite sandstones and siltstones that were cored from the apron are composed mainly of hyaloclastic glass, both palagonitized and fresh, that represent a time of volcanism on the seamount (Moberly and Keene, this volume). Nannofossils of the *Sphenolithus distentus* Zone were recovered from the volcanic sediments, and thus indicate an age of about 27 to 30 m.y. for the last stages of volcanism along the adjacent Hawaiian Ridge (Figure 9).

The age of volcanism at Site 311 that had been predicted by extrapolation of the Hawaii to Midway rate of progression was only 19 or 20 m.y., and the results serve further to warn students of volcanic chains of the complexities in their histories.

At Site 313, in a saddle amongst guyots and seamounts in the eastern Mid-Pacific Mountains, the age of volcanism again poses difficulties for interpretation in terms of a simple progression of volcanism that records the passage of a lithospheric plate across a melting anomaly. Mid-Cretaceous fossils are known along the Mid-Pacific Seamount chain both east and west of Site 313. The Coniacian volcanism recorded at the site may be explained either as a recurrence of volcanism, resembling the histories of Horizon Guyot (Site 171, Winterer, Ewing, et al., 1973) or perhaps that of Kōko Guyot as discussed above. The basalt recovered is not tholeiitic (Marshall, this volume) and so may not represent the original volcanism. The rapid penetration of material (not recovered) below the basalt may have been sediment, so that basement was not reached. If true, that would also mean more than one time of volcanism.

An alternate explanation if basement was indeed reached is that volcanism proceeded both eastward from the central Mid-Pacific Mountains toward Site 313, and southwestward from Horizon Guyot toward Site 313. That possibility also is difficult to fit into the simpler versions of the hot-spot theory, although the Mid-Pacific Mountains are considerably less linear than most Pacific Seamount chains.

The Campanian date of the eastern Mid-Pacific Mountains at Site 313 also bears on the problem of volcanism. Matthews et al. (1974) have shown that the Mid-Pacific Mountains formed and sank in the Cretaceous. The alignment of these volcanoes is distinctly different from the Line Islands and northern Emperors. Moreover, volcanism in the Line Islands appears to be coeval (Jackson, Schlanger, et al., in press). Thus it appears that volcanism is not necessarily monotonic along all chains, nor need it necessarily be aligned perpendicular to the known spreading ridges of the eastern Pacific (Pitman et al., 1974).

The Late Cretaceous volcanogenic sediments (Moberly and Keene, this volume) and their primary sedimentary structures, and the excellent preservation of Maestrichtian foraminifers (Caron, this volume) in contrast to the selective dissolution of Eocene foraminiferal assemblages (Toumarkine, this volume) are at present only isolated fragments of infomation. So are the data obtained by Hamilton (1956), Matthews et al. (1974), and expeditions in between those years. Considerable additional information from several areas of the Mid-Pacific Mountains will be needed before their history subsequent to their formation can be pieced together and applied to such problems as paleooceanography and whether or not parts of the lithosphere rise and fall through time.

At the present time many of the earlier generalities about the origin of island chains are in doubt and need careful reevaluation (Shaw and Jackson, 1973; Runcorn, 1973; Jackson, in press; Walcott, in preparation; Winterer, in preparation). A current summary of data bearing on the age of the Emperor-Hawaiian chain is shown in Figure 10, largely taken from Clague et al. (in press) and including data from Leg 32. Clearly, the age progression of the volcanic activity along seamount chains on the Pacific plate cannot always be directly utilized in order to determine the rate of motion of the plate over a fixed "hot spot," following the Wilson-Morgan hypothesis (Wilson, 1963; Morgan, 1972b; Clague and Jarrard, 1973). It seems more probable that recurrent volcanic activity may occur along seamount chains. This has been observed before along other chains (Clague and Jarrard, 1973) as well as on Horizon Guyot (Winterer, Ewing, et al., 1973). If this is the case, the 17 m.y. age of Midway Islands might be misleading when used to determine the rate of motion of the plate with respect to any Hawaiian "hot spot." Figure 10 shows that the age of the volcanic activity at Site 311 would fit a relatively regular progression in age from Hawaii to Kōko Guyot of about 8.5 cm/yr and that no major change in the rate of progression of the volcanic activity has to take place between Midway and the southern end of the Emperor Seamount chain if Midway is considered to be the result of a renewed volcanic activity during the early Miocene. Age data from the Emperor Seamounts north of Kōko are very sparse,

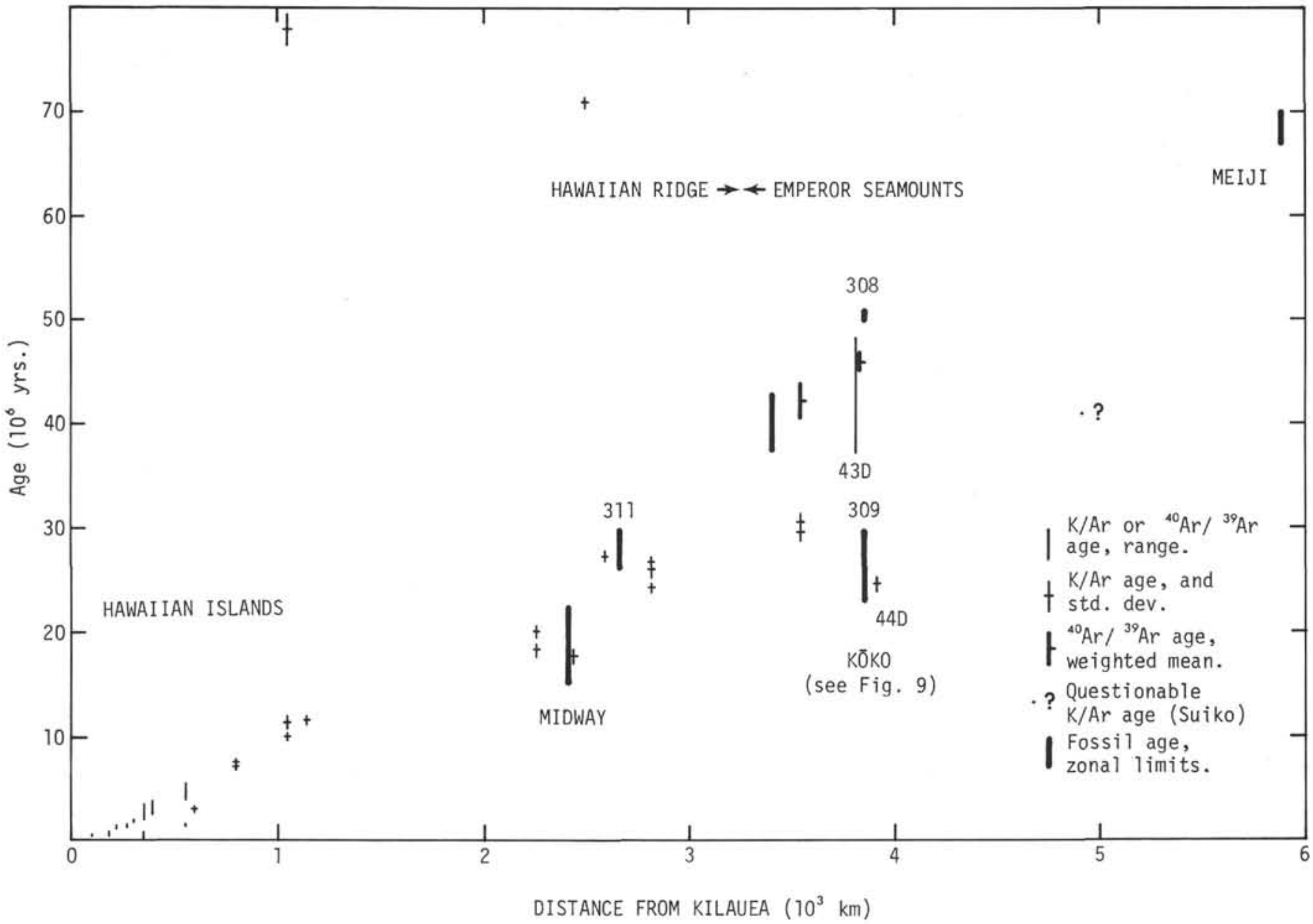

Figure 10. *Ages of volcanism along the Hawaiian-Emperor chain as a function of distance from Kilauea Volcano, Hawaii. Data from Figure 8 (Kōko Guyot and Site 311), from Clague et al., in press, and from references in Clague, 1974. Nontholeiitic lavas (presumably later than ridge-tholeiite volcanism), shallow-water fossils (on a volcanic foundation), and altered lavas (from which argon may have leaked) would all give ages younger than the initial volcanism along the ridge. The two ages older than 70 m.y. may be from Cretaceous seamounts crossed later by the Hawaiian Ridge.*

however, Figure 10 shows that this same 8.5 cm/yr rate of progression also fits the age of Meiji, the northernmost of the Emperor Seamounts.

In summary, the information from Leg 32 supports the concept that volcanism is progressive, and also recurrent along a chain. The information, however, does not support any one proposed mechanism for progression more than another among fixed hot spots, gravitational anchors, return flow in the asthenosphere, or propagating fractures.

REFERENCES

Bass, M.N., Moberly, R., Rhodes, J.M., Shih, C.-y., and Church, S.E., 1973. Volcanic rocks cored in the Central Pacific, Leg 17, Deep Sea Drilling Project. *In* Winterer, E.L., Ewing, J.I., et al., Initial reports of the Deep Sea Drilling Project, Volume 17: Washington (U.S. Government Printing Office), p. 429-503.

Berger, W., 1970. Planktonic foraminifera: selective solution and the lysocline: Marine Geol., v. 8, p. 111-138.

———, 1971. Sedimentation of planktonic foraminifera: Marine Geol., v. 11, p. 325-358.

Berggren, W.A., 1972. A Cenozoic time scale—Some implications for regional geology and paleobiogeography: Lethaia, v. 5, p. 195-215.

Betz, F., Jr., and Hess, H.H., 1942. The floor of the North Pacific Ocean: Geograph. Rev., v. 32, p. 99-116.

Clague, D.A., 1974. The Hawaiian-Emperor Seamount chain: its origin, petrology, and implications for plate tectonics: Ph.D. dissertation, University of California, San Diego.

Clague, D.A., Dalrymple, G.B., and Moberly, R., in press, Petrography and K/Ar ages of dredged volcanic rocks from the Western Hawaiian Ridge and the southern Emperor Seamount chain: Geol. Soc. Am. Bull.

Clague, D.A. and Jarrard, R.D., 1973. Tertiary Pacific plate motion deduced from the Hawaiian-Emperor Chain: Geol. Soc. Am. Bull., v. 84, p. 1135-1154.

Coplen, T.B. and Schlanger, S.O., 1973. Oxygen and carbon isotope studies of carbonate sediments from Site 167, Magellan Rise, Leg 32. *In* Winterer, E.L., Ewing, J.I., et al., Initial reports of the Deep Sea Drilling Project, Volume 17: Washington (U.S. Government Printing Office), p. 505-509.

Dana, J.D., 1849. Geology: U.S. Explor. Exped. Pacific, v. 10, 756 p.

Den, N., Ludwig. W.J., Murauchi, S., Ewing, J.I., Hotta, H., Edgar, N.T., Yoshii, Y., Asanuma, T., Hagiwara, K., Sato, T., and Ando, S., 1969. Seismic-refraction measurements in the Northwest Pacific Basin: J. Geophys. Res., v. 74, p. 1421-1434.

Douglas, R.G. and Savin, S.M., 1973. Oxygen and carbon isotype analysis of Cretaceous and Tertiary foraminifera from the Central North Pacific. *In* Winterer, E.L., Ewing, J.I., et al., Initial reports of the Deep Sea Drilling Project, Volume 17: Washington (U.S. Government Printing Office), p. 591-605.

Ewing, M., Saito, T., Ewing, J.I., and Burckle, L.H., 1966. Lower Cretaceous sediments from the Northwest Pacific: Science, v. 152, p. 751-755.

Fisher, A.G., Heezen, B.C., et al., 1971. Initial reports of the Deep Sea Drilling Project, Volume 6: Washington (U.S. Government Printing Office).

Furumoto, A.S., Wiebenga, W.A., Webb, J.P., and Sutton, G.H., 1973. Crustal structure of the Hawaiian Archipelago, northern Melanesia, and the Central Pacific Basin by seismic refraction methods: Tectonophysics, v. 20, p. 153-164.

Hamilton, E.L., 1956. Sunken islands of the Mid-Pacific Mountains: Geol. Soc. Am. Mem. 64.

Hayes, D.E. and Pitman, W.C., III, 1970. Magnetic lineations in the North Pacific, p. 291-314 *in* Hays, J.D. (Ed.), Geological investigations of the North Pacific: Geol. Soc. Am. Mem. 126.

Heirtzler, J.R., Dickson, G.O., Herron, E.M., Pitman, W.C., III, and Le Pichon, X., 1968. Marine magnetic anomalies, geomagnetic field reversals, and motions of the ocean floor and continents: J. Geophys. Res., v. 73, p. 2119-2136.

Hess, H.H., 1954. Geological hypotheses and the earth's crust under the oceans: Proc. Roy. Soc. London, ser. A., v. 222, p. 341-348.

Hollister, C.D., Ewing, J.I., et al., 1972. Initial reports of the Deep Sea Drilling Project, Volume 11: Washington (U.S. Government Printing Office).

Jackson, E.D., in press. Linear volcanic chains in the Pacific Basin. *In* The geophysics of the Pacific Ocean basin and its margin: Am. Geophys. Union Monogr.

Jackson, E.D., Schlanger, S.O., et al., in press. Initial reports of the Deep Sea Drilling Project, Volume 33: Washington (U.S. Government Printing Office).

Jackson, E.D., Silver, E.A., and Dalrymple, G.B., 1972. Hawaiian Emperor chain and its relation to Cenozoic circumpacific tectonics: Geol. Soc. Am. Abstr., v. 4, p. 177-178.

Kellner, L., 1963. Alexander von Humboldt: London (Oxford Univ. Press).

Kroenke, L.W., 1972. Geology of the Ontong-Java Plateau: Ph.D. dissertation, University of Hawaii.

Larson, R.L. and Chase, C.G., 1972. Late Mesozoic evolution of the western Pacific Ocean; Geol. Soc. Am. Bull., v. 83, p. 3627-3644.

Larson, R.L. and Hilde, T.W.C., in press. A revised time scale of magnetic reversals for the Early Cretaceous-Late Jurassic: J. Geophys. Res.

Larson, R.L. and Pitman, W.C., III, 1972. World-wide correlation of Mesozoic magnetic anomalies, and its implications: Geol. Soc. Am. Bull., v. 83, p. 3645-3662.

Mathews, J.L., Heezen, B.C., Catalano, R., Coogan, A., Tharp, M., Natland, J., and Rawson, M., 1974. Cretaceous drowning of reefs on mid-Pacific and Japanese guyots: Science, v. 184, p. 462-464.

McDougall, I, 1971. Volcanic island chains and sea floor spreading: Nature Phys. Sci., v. 231, p. 141-144.

McKenzie, D. and Sclater, J.G., 1971. The evolution of the Indian Ocean since the Late Cretaceous: Geophys. J. Roy. Astron. Soc., v. 25, p. 437-528.

Menard, H.W., 1964. Marine geology of the Pacific: New York (McGraw-Hill Book Co.).

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

Moberly, R., in preparation. Basement contacts, Phases I and II, Deep Sea Drilling Project.

Moberly, R. and Khan, M.A., 1969. Interpretation of the sources of the satellite-determined gravity field: Nature, v. 223, p. 263-267.

Moberly, R. and Kroenke, L.W., 1974. Geologic history on oceanic plateaus: Am. Assoc. Petrol. Geol. Abstr., v. 1, p. 64-65.

Morgan, W.J., 1971. Convection plumes in the lower mantle: Nature, v. 230, p. 42-43.

———, 1972a. Deep mantle convection plumes and plate motions: Am. Assoc. Petrol. Geol. Bull, v. 56, p. 203-213.

———, 1972b, Hot spots, plate motions, and polar wandering: Geol. Soc. Am. Abstr., v. 4, p. 202-203.

———, 1972c. Plate motions and deep mantle convection. *In* Shagam, R. et al. (Eds.), Studies in earth and space sciences, a memoir in honor of Harry Hammond Hess: Geol. Soc. Am. Mem. 132, p. 7-22.

Nayudu, Y.R., 1962. A new hypothesis for origin of guyots and seamount terraces. *In* Macdonald, G.A. and Kuno, H., (Eds.), The crust of the Pacific basin: Am. Geophys. Union Monogr. 6, p. 171-180.

Pitman, W.C., III, Larson, R.L., and Herron, E.M., 1974. Age of the ocean basins determined from magnetic anomaly lineations: Geol. Soc. Am., maps and text.

Runcorn, S.K., 1973. On the forces not moving lithospheric plates: Tectonophysics, v. 21, p. 197-202.

Schlanger, S.O. and Douglas, R.G., 1974. The pelagic ooze-chalk-limestone transition and its implication for marine stratigraphy. *In* Hsü, K.J. and Jenkyns, H.C. (Eds.), Pelagic sediments: on land and under the sea: Internat. Assoc. Sedimentol., Spec. Pub. 1, p. 117-148.

Sclater, J.G., Jarrard, R.D., McGowran, B., and Gartner, S., 1974. Comparison of the magnetic and biostratigraphic time scales since the Late Cretaceous. *In* von der Borch, C.C. and Sclater, J.G., et al., Initial Reports of the Deep Sea Drilling Project, Volume 22: Washington (U.S. Government Printing Office), p. 381-386.

Shaw, H.R. and Jackson, E.D., 1973. Linear island chains in the Pacific: result of thermal plumes or gravitational anchors?: J. Geophys. Res., v. 78, p. 8634-8652.

Simkin, T., 1972. Origin of some flat-topped volcanoes and guyots. *In* Shagam, R. et al. (Eds.) Studies in earth and space sciences, a memoir in honor of Harry Hammond Hess: Geol. Soc. Am. Mem. 132, p. 183-193.

Solomon, S.C. and Sleep, N.H., 1974. Some simple physical models for absolute plate motions: J. Geophys. Res., v. 79, p. 2557-2567.

Uyeda, S., Vacquier, V., Yasui, M., Sclater, J., Saito, T., Lawson, J., Watanabe, T., Dixon, F., Silver, E., Fukas, Y., Sud, K., Nishikawa, M., and Tanaka, T., 1967. Results of geomagnetic survey during the cruise of R/V ARGO in the western Pacific, 1966, and the compilation of magnetic charts of the same area: Tokyo Univ. Earthquake Res. Inst. Bull., v. 45, p. 799-814.

van Andel, Tj.H. and Bukry, D., 1973. Basement ages and basement depths in the Eastern equatorial Pacific: Geol. Soc. Am. Bull., v. 84, p. 2361-2370.

Vogt, P.R., Anderson, C.N., and Bracey, D.R., 1971. Mesozoic magnetic anomalies, sea-floor spreading, and geomagnetic reversals in the southwestern North Atlantic: J. Geophys. Res., v. 76, p. 4796-4823.

Walcott, R.I., in press. Gravity and the deformation of lithospheric plates, *in* The geophysics of the Pacific Oceanic basins and its margin: Am. Geophys. Union Monogr.

Wilson, J.T., 1963. A possible origin of the Hawaiian Islands: Canadian J. Phys., v. 41, p. 863-870.
Winterer, E.L., 1973. Sedimentary facies and plate tectonics of equatorial Pacific: Am. Assoc. Petrol. Geol. Bull., v. 57, p. 265-282.
_______, in press. Anomalies in the tectonic evolution of the Pacific. *In* The geophysics of the Pacific Ocean basin and its margin: Am. Geophys. Union Monogr.
Winterer, E.L., Ewing, J.I., et al., 1973. Initial reports of the Deep Sea Drilling Project, Leg 17: Washington (U.S. Government Printing Office).
Winterer, E.L., Riedel, W.R., et al., 1971. Initial reports of the Deep Sea Drilling Project, Volume 7: Washington (U.S. Government Printing Office).