38. SEDIMENTARY AND TECTONIC EVOLUTION OF THE NORTHWESTERN PACIFIC[1]

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ABSTRACT

The results of Leg 32 of the Deep Sea Drilling Project are interpreted in terms of the past horizontal and vertical motions of the Pacific plate. The sediment record allows a relatively precise estimate of the times when different parts of the plate crossed the equatorial zone of high productivity. This is recorded by the sediments as an influx of siliceous sediments if the site lay below the carbonate compensation depth (CCD), or as an increase in the carbonate sedimentation rate if the site lay above the CCD during the equatorial passage. The upper opaque layer of seismic reflection profiles across the deep parts of the area also marks this equatorial crossing, as it is correlated with the chert layer that is the diagenetic product of the siliceous sediments deposited at the equator. The basement isochrons outlined by magnetic anomalies are rotated back to their original orientations using the parameters of the motion model based on the sediment record. These tectonic reconstructions are in accord with the magnetic inclinations of Leg 32 basalt samples and with the cross-sectional shapes of magnetic anomalies in the area.

INTRODUCTION

The drilling results of Leg 32 of the Deep Sea Drilling Project in the northwestern Pacific provide a set of data that allows us to reconstruct the evolution of that part of the ocean since the Early Cretaceous. This reconstruction follows three different lines:

Firstly, the sedimentary record is believed to reflect the tectonic evolution of that part of the Pacific plate. In that respect we shall interpret the vertical succession of different facies and the changes in rates of sedimentation in DSDP cores as being a direct consequence of the horizontal translation of the plate beneath different successive oceanographic environments.

Secondly, the correlation between the lithologic results and the seismic reflection profiles in the vicinity of the drill sites appears well established so that these results can be extrapolated over broad areas, allowing a regional interpretation of the "acoustic stratigraphy" in terms of plate motion.

Finally, ages of the Mesozoic magnetic anomalies have been obtained by dating the basement in several places. This provides the basis for calibrating the correlations of magnetic lineations over large areas of the Pacific Ocean.

In this paper we will combine these three different sets of data interpretations in order to try to define the motion of the northwestern Pacific plate since the Early Cretaceous. We will also attempt a reconstruction of the evolution of the spreading centers responsible for the configuration of the basement isochrons as they can be inferred from the magnetic data.

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SEDIMENTARY RECORD AND PLATE MOTION

The Mesozoic and Cenozoic sedimentary record from the Leg 32 sites reflects the motion of the Pacific plate with respect to an oceanographic environment characterized by horizontal and vertical zonations. The horizontal zonation is defined by the variations in the productivity of the surface waters while the vertical zonation results from the selective dissolution of carbonate material at depth. The sediments accumulating on the sea floor, which is moving both horizontally and vertically, should reflect this motion, and several studies recently have shown that such a scheme can be utilized for interpreting the sedimentary record of many areas of the Pacific (Winterer, 1973; Heezen et al., 1973; Berger, 1973; van Andel and Moore, 1974; van Andel, 1974; Lancelot et al., 1974).

The interpretation of the sedimentary record from Leg 32 sites is based on the model of Mesozoic and Cenozoic plate motion proposed by Lancelot et al. (1974; in prep.). That model defines the motion of the Pacific plate with respect to the equatorial zone of high productivity (Arrhenius, 1952, 1963) assumed by us to be, and to have remained in the past, fixed with respect to the spin axis of the earth. The model shows that the motion of the Pacific plate has followed three major successive phases since the Early Cretaceous. They can be summarized as follows:

1) from 125 to 70 m.y.—clockwise rotation around a pole at 30°N and 97°W at a rate of 0.69°/m.y.

2) from 70 to 40 m.y.—clockwise rotation around a pole at 11°N and 89°W at a rate of 0.57°/m.y.

3) from 40 m.y. to present—clockwise rotation around a pole at 67°N and 45°W at a rate of 0.5°/m.y.

The model can be used for determining the motion of the Leg 32 sites during the past 125 m.y. Figure 1 shows

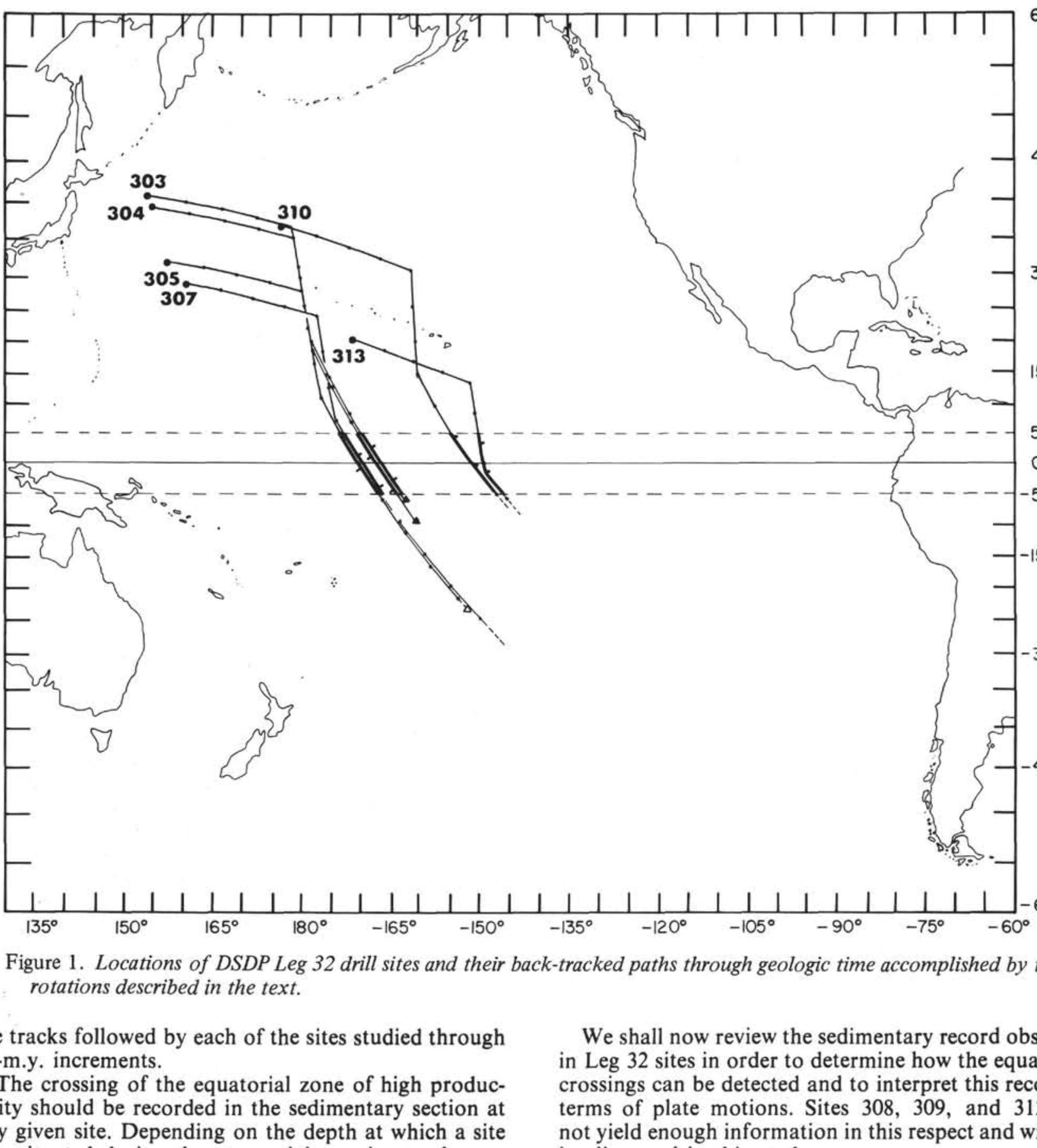

Figure 1. *Locations of DSDP Leg 32 drill sites and their back-tracked paths through geologic time accomplished by the rotations described in the text.*

the tracks followed by each of the sites studied through 10-m.y. increments.

The crossing of the equatorial zone of high productivity should be recorded in the sedimentary section at any given site. Depending on the depth at which a site was situated during the equatorial crossing, and more specifically, depending on its situation with respect to the carbonate compensation depth (CCD) at the time, the crossing can be recorded in different manners. If a site passed the equator while above the CCD, an increase in the rate of sedimentation should be noted at that time. If a site was below the level of the CCD during its crossing of the equatorial zone, the high productivity of the overlying waters will be reflected by the occurrence of relatively large amounts of siliceous microfossils in the sediments. In this case the crossing will be marked by the presence of either radiolarian ooze or abundant chert depending on whether conditions were favorable or not to chert formation at that time. (See discussion in Lancelot, 1973.)

We shall now review the sedimentary record observed in Leg 32 sites in order to determine how the equatorial crossings can be detected and to interpret this record in terms of plate motions. Sites 308, 309, and 312 did not yield enough information in this respect and will not be discussed in this study.

Sites 303 and 304 (Japanese Magnetic Lineations)

These two sites will be examined simultaneously as they are located relatively close to each other and hence show a very similar record.

Figure 2 summarizes the drilling results for the two sites. We present these data as a lithology versus subbottom depth diagram (on the left side) as well as a lithology versus age diagram (on the right side) in order to establish correlations with the geographic track followed by the sites (Figure 1). The black lines alongside the lithology versus age diagram represent the time during which the site was transiting between 5°S and 5°N of latitude according to the model.

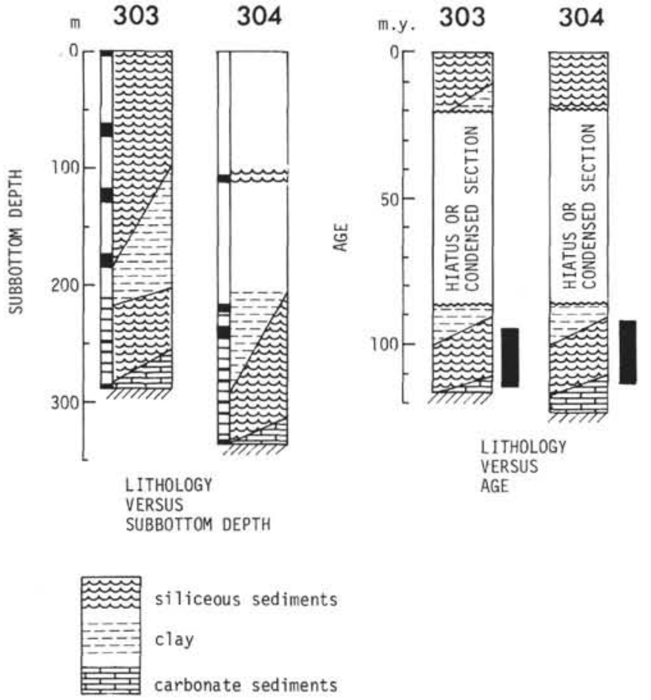

Figure 2. *Drilling results for Sites 303 and 304 plotted as a function of depth in the hole (left side) and as a function of geologic age (right side). Black line designates time range of equatorial transit (5°S - 5°N) of the site according to the model.*

At both sites the sedimentary history starts with the deposition during Hauterivian to Barremian times of carbonates with lesser amounts of siliceous organisms (converted into chert). This represents the "ridge flank" sedimentation that followed crust generation at the ridge crest. The fact that this first stage is represented only by a relatively thin layer suggests that the sites subsided below the CCD rather soon. This can be explained by either a shallow CCD or a relatively deep ridge crest at the time, or a combination of the two factors. An estimate of 2700 meters for the depth of the ridge crest, following the basement depth versus age empirical curves of Sclater et al. (1971) would allow us to locate the CCD at about 3700 meters during the Hauterivian-Barremian time. The same authors, however, point out that a fast-spreading ridge could lie somewhat deeper than 2700 meters. Since the spreading rate along the fossil Japanese spreading center is inferred from the model to be relatively fast (~4 cm/yr, half rate), the depth of the CCD cannot be accurately determined, and we did not attempt any detailed paleodepth "backtracking" (Berger, 1973) for these sites. Figure 3 is merely a schematic reconstruction of the subsidence history of the area of Sites 303 and 304 in relation to the horizontal motion of the Japanese spreading center (now subducted beneath the Kuril and Aleutian Island arcs). The sites reached the equatorial zone after sinking below the CCD, and the crossing of that high productivity zone during the Aptian-Cenomanian is characterized by the deposition of abundant siliceous organisms. These organisms were then diagenetically recrystallized into chert.

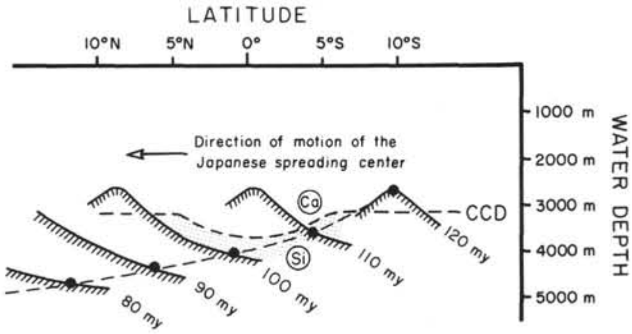

Figure 3. *Schematic reconstruction of the manner in which Sites 303 or 304 subsided down the ridge flank while crossing the paleo-equator during the Early Cretaceous.*

Figure 3 shows that regardless of the actual depth of the carbonate compensation level, the relative depression of that surface beneath the equatorial zone could not have been much more than about 500-600 meters, as the fast northward motion of the Japanese spreading center resulted in a relatively gentle subsidence curve for Sites 303 and 304 that are located on the southern flank of the moving ridge. If the CCD intersected with the subsidence curve, carbonates would be present in the sediments corresponding to the equatorial crossing.

The transition between the ridge flank carbonate sediments and the siliceous equatorial deposits is characterized by a gradual upward decrease in the amount of carbonate while the chert becomes progressively more abundant. The increase in silica content does not appear to be due to the decreasing dilution by carbonate components as the rate of sedimentation remains approximately constant during the facies change (Figure 4). It thus suggests an absolute increase in the amount of silica reaching the bottom, associated with the increased productivity beneath the equatorial zone.

After leaving the equatorial zone, the sites transited across the vast low productivity areas that characterize the mid-latitude North Pacific. This transit, that lasted for the entire Late Cretaceous, the Paleogene, and the lowermost Neogene, is reflected in the sediments by the deposition of a thin layer of deep-sea pelagic clay. A very low rate of sedimentation, the lack of stratigraphic control because of the rarity of fossils, and discontinuous sampling make the detailed interpretation of the sedimentary history difficult. It is not known if this interval represents only a highly condensed section or if it is associated with a sedimentary hiatus. If the latter is the case, the boundaries of the hiatus cannot be precisely determined. In any case, even if a hiatus accounts for most of the compression of this stratigraphic interval, it clearly correlates with a period during which the sites were situated in an area characterized by very low rates of sedimentation. Erosion due to strong bottom current activity might have been an aggravating factor for the drastic shortening of this sedimentary section.

About the middle to late Miocene the sites reached the northwest Pacific zone of high productivity associated with the Kuroshio Extension Current. This corresponds to a rapid accumulation of radiolarian and

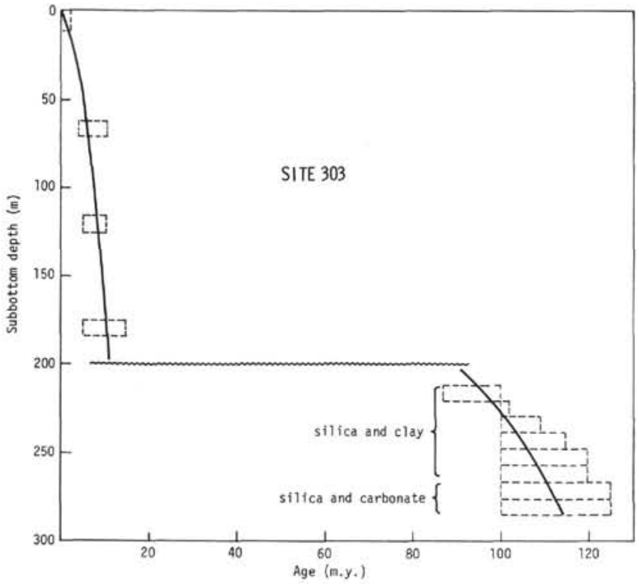

Figure 4. *Sedimentation rate curve for Site 303.*

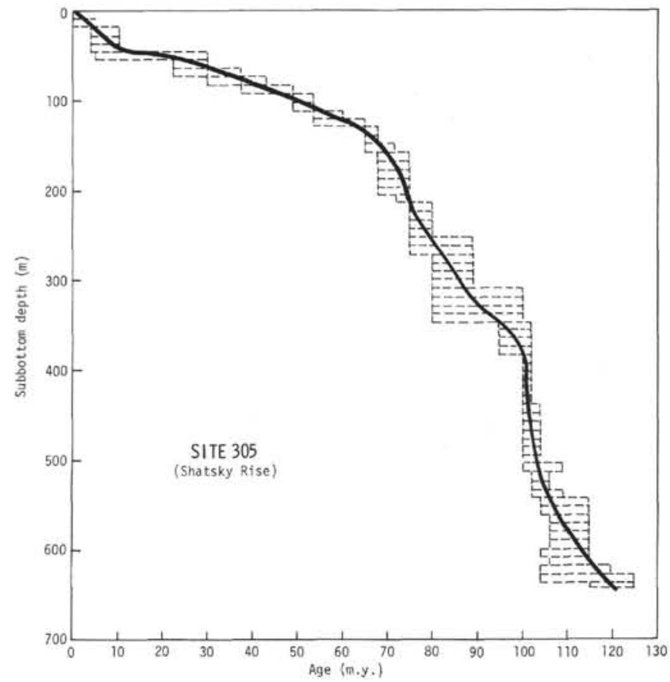

Figure 5. *Sedimentation rate curve for Site 305 on Shatsky Rise.*

diatom ooze that represents the upper half of the sedimentary section at both sites. The uppermost part of the section of Site 303 shows an upward gradual increase in the amount of volcanic ash that also reflects the decreasing distance from the Japanese and Kuril volcanic arcs during latest Tertiary and Quaternary times. It is not entirely clear if the increase in the amount of siliceous remains deposited in the post middle Miocene time corresponds indeed to the motion of the plate under the northern productivity zone, or if it merely marks the onset of that productivity. The latter is suggested by the synchronous increase in productivity noted at Site 192 (Creager, Scholl, et al., 1973) located at the northern end of the Emperor Seamount Chain, an area that the model would predict to have been under the present-day path of the Kuroshio Extension Current for most or all of the Tertiary. Not enough is known at present about the actual time of this onset to solve the question but, in any case, the motion model shows a good agreement with the lithostratigraphy observed at Sites 303 and 304.

Sites 305 and 306 (Shatsky Rise)

The discussion of these two sites is combined here because the two of them have sampled most of the section present on the rise, although basement was not reached. As the sediment recovered consists mainly of carbonates with variable amounts of siliceous microfossils, it appears clear that the upper part of the rise remained above the CCD during the past 120 m.y. The crossing of the equatorial zone is then marked only by an increase in the rate of sedimentation. Such an increase can be observed on the rate of sedimentation curve between about 65 and 105 m.y. (Figure 5). According to the model this period corresponds with the time during which Shatsky Rise was transiting from about 10°S to 10°N. This indicates a wider high productivity zone than the one observed at the previous sites. It might be explained in two ways. Either the width of the equatorial high productivity zone varied with time, or the relatively shallow depth of the rise was the determinant factor controlling that width. What is most important for our model is that the period of high rate of sedimentation appears well centered on the predicted equatorial crossing. Of course, some of the changes in the rate of sedimentation values could, at least in part, be explained by overall changes in the productivity in the entire ocean, but comparison of several sites covering a wide range of latitudes shows that the main factor influencing the rate of sedimentation on elevated areas remains the crossing of the equatorial zone (Lancelot et al., in preparation).

Site 307 (Northwestern Hawaiian Lineations)

The sedimentary record from Site 307 is relatively difficult to interpret because of the very poor recovery experienced in the entire section and because of difficulties in age determination of the upper half of the section. From the basement up, the section consists of calcareous sediment and chert overlain by chert and zeolitic clay and finally zeolitic clay. Our interpretation of this record in terms of plate motion is similar to that of the lower part of Sites 303 and 304. During Neocomian time, calcareous and siliceous microfossil remains were deposited on the ridge crest and flank near the equator. Then, during the early Late Cretaceous the site passed under the equatorial zone. Being already below the CCD level, that area collected mainly siliceous microfossils during the equatorial transit, and most of them have been transformed into chert. Finally, from the latest Cretaceous through the present time, the site was in the mid-latitude low-productivity area of the northern Pacific and at such a depth that only a thin layer of zeolitic deep-sea clay was deposited during this interval. Figure 6 shows these results in a manner similar to the diagram presented for Sites 303 and 304.

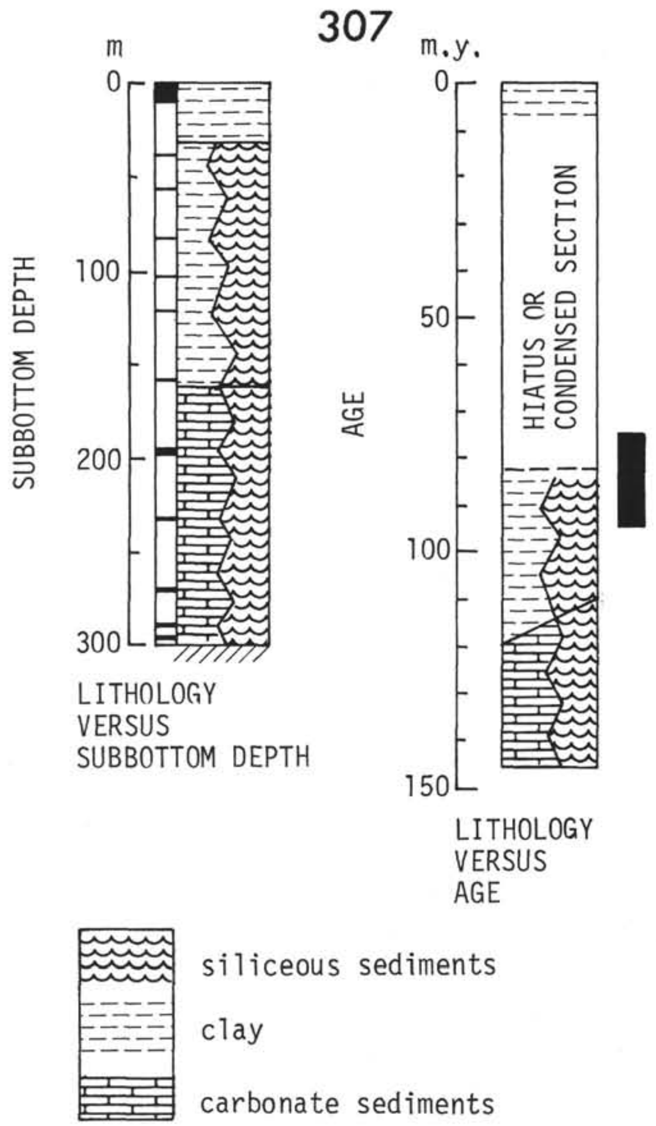

Figure 6. *Drilling results for Site 307 plotted as a function of depth in the hole (left side) and as a function of geologic age (right side). Black line designates time range of equatorial transit (5°S - 5°N) of the site according to the model.*

There appears to be some discrepancy between the age of the predicted equatorial crossing and the observed lithology at the corresponding time. In particular, the chert-rich layers seem to extend back in time to as far as the Early Cretaceous. Moreover, the youngest chert recovered is apparently as old as early Late Cretaceous while the model predicts that the site should have left the equatorial zone a little later, sometime during the Campanian. We do not feel, however, that these discrepancies are well established enough so that either the model should be considered invalid or a separate motion history involving some breaking of the plate during the Cretaceous should be invoked for Site 307. The relative amounts of chert and other lithologies appear strongly biased toward the high chert content at this site because of the very poor recovery. It is well known that when a mixture of relatively soft sediment and hard chert is cored, generally only the chert is recovered while the softer material is washed away under the high pressure circulation required for cutting the core. Because of these considerations, we believe that the relatively large amounts of chert recovered in the carbonate section present in the lower part of the hole could still represent a normal ridge-flank sedimentation while the upper cherts, found in zeolitic clays, represent the equatorial crossing. The upper, chert-rich section, mixed with zeolitic clay, which we believe represents the equatorial crossing, is apparently of Aptian-Cenomanian age (based exclusively on radiolarian age determinations), while the model predicts it to be of Cenomanian-Campanian age. It should be noted, however, that the uppermost chert has not been sampled and was inferred to lie at a subbottom depth of 33 meters, a level at which the drill encountered a very hard formation. As the first chert sampled at 38 meters is very poorly dated, not much is known of the actual age of the youngest chert; hence not much is known of the actual time at which the site left the equatorial zone.

Site 310 (Hess Rise)

The lithology of the sediments recovered on Hess Rise is comparable to that of Shatsky Rise, and the site is believed to have remained above the level of the CCD during most of the time represented by the sampled record. In the upper section, however, the site must have been very close to the CCD as the very low rates of sedimentation observed during the early Oligocene and middle Eocene time correspond to the deposition of clayey zeolitic nannofossil ooze and nannofossil-bearing zeolitic clay in which the calcareous microfossils are poorly preserved.

Because of the relatively monotonous aspect of the sediments, calcareous ooze with variable amounts of radiolarians and chert, evidence for the crossing of the equatorial zone should be obtained from the variations in the rate of sedimentation as it was observed at Sites 305 and 306 on Shatsky Rise. The steepest part of the rate of sedimentation curve (Figure 7) corresponds to the early Late Cretaceous (Cenomanian) time when the site was below the equatorial zone as predicted from the model. The curve remains quite steep for most of the Late Cretaceous, although the site is supposed to have left the latitude of 5°N around 88 m.y. ago (Turonian). As the same pattern can be observed at Site 305 on Shatsky Rise, it seems reasonable to imagine that in both cases, because of the relatively shallow water depth (considerably less than the CCD), the high productivity belt was wider than the one observed in deeper waters. In any case the steepest part of the curve seems to correspond to the oldest part of the section, between about 90 and 100 m.y., a time interval during which the model places the site under the equatorial zone. The inflexion point of the curve at about 70 m.y. marks the beginning of the transit under the mid-latitude low-productivity area. This inflexion is of course greatly exaggerated by the presence of a hiatus in the vicinity of the Cretaceous-Tertiary boundary which is of worldwide significance and is observed at almost any latitude in the Pacific, even under the equator. Nevertheless, the extremely low rates of sedimentation observed during the middle Eocene and early Oligocene times reflect very low

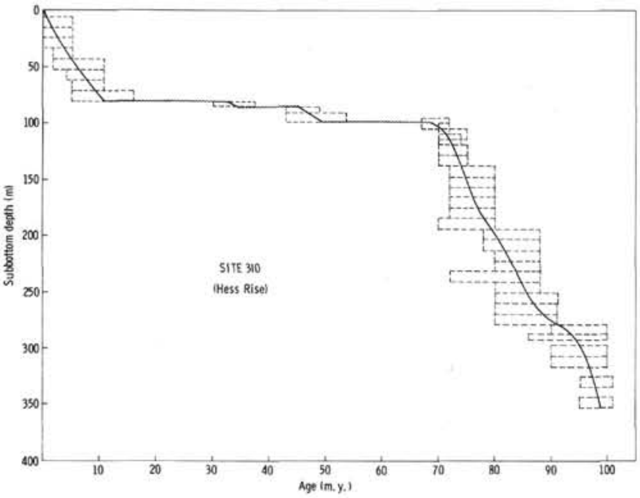

Figure 7. *Sedimentation rate curve for Site 310 on Hess Rise.*

productivity in the surface waters. The sedimentation rate becomes high again during the middle Eocene and early Oligocene and increases even more during the Plioquaternary. The relatively thick Pliocene and Quaternary section might correspond to the time when the site approached the southern boundary of the North Pacific high-productivity zone related to the presence of the Kuroshio Extension Current.

Site 311 (Western Hawaiian Chain Archipelagic Apron)

Because of the very shallow penetration achieved at that site (37 m), the sediment record does not yield information pertinent to the timing of the crossing of the equator for that area. We include here the discussion of the results of this site, however, as they provide interesting information about the relative motion of the plate in relation to the Hawaiian volcanic center.

This site was drilled about 60 miles southwest of a large unnamed seamount which is part of the Hawaiian chain and located about 180 miles west-northwest of Midway. The drill encountered and was stopped by a series of volcanogenic turbidites immediately overlain by pelagic sediments of early late Oligocene age (27-30 m.y.). Seismic profiles (see site chapter, this volume) obtained by both *Glomar Challenger* and *Kana Keoki* show clearly that the top of the turbidite section correlates with a reflector that is traceable up to the flank of the seamount. Therefore, there is no doubt that the source of the volcanic material found in the turbidites is that seamount. This allows a good determination of the minimum age of the latest volcanic activity on that seamount. This age (27-30 m.y.) is about 10 to 12 m.y. older than the radiometric age obtained from drilling on Midway (Ladd et al., 1967). This finding shows clearly that 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, 1972; Clague and Jarrard, 1973). It seems most probable that recurrent volcanic activity may occur along seamount chains. This has been observed before along other chains (Clague and Jarrard, 1973; Johnson and Malahoff, 1971) as well as on Horizon Guyot (Winterer, Ewing, et al., 1973). If this is the case, the age of Midway Island might be misleading when used to determine the rate of motion of the plate with respect to the Hawaiian "hot spot." Figure 8 shows that the age of the volcanic activity at Site 311 would fit a relatively regular age progression from Hawaii to Koko Seamount 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.

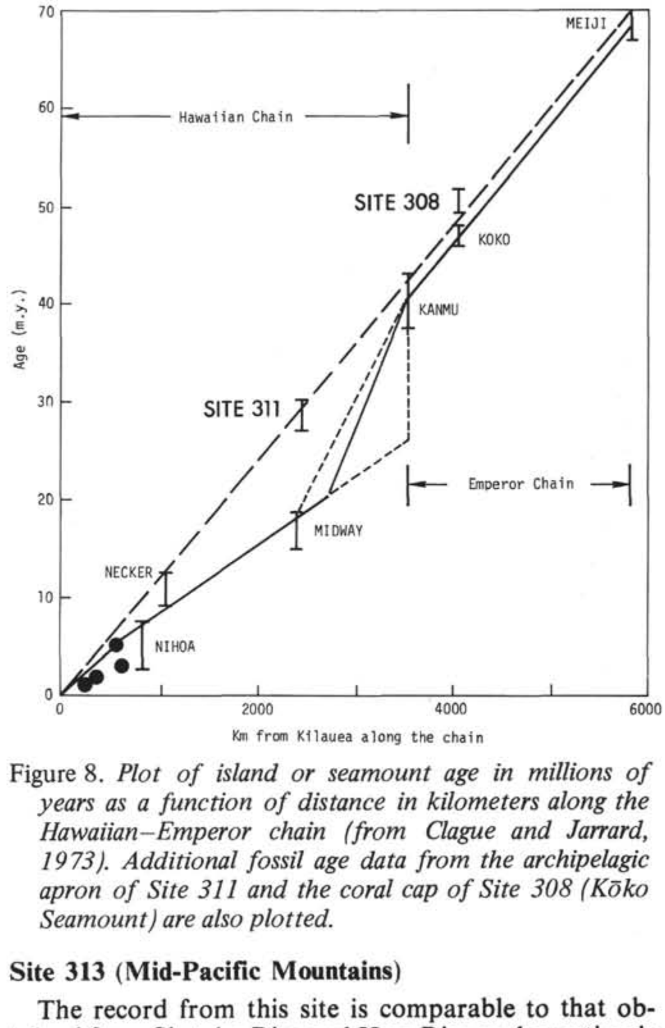

Figure 8. *Plot of island or seamount age in millions of years as a function of distance in kilometers along the Hawaiian–Emperor chain (from Clague and Jarrard, 1973). Additional fossil age data from the archipelagic apron of Site 311 and the coral cap of Site 308 (Kōko Seamount) are also plotted.*

Site 313 (Mid-Pacific Mountains)

The record from this site is comparable to that obtained from Shatsky Rise and Hess Rise as the section is predominantly calcareous, indicating that the site remained above the CCD during all the time that corresponds to the sampled record. The rate of sedimentation curve (Figure 9) shows a reasonably good agreement between the model and the sediment record, although the interpretation is complicated by the occurrence of a hiatus during part of the equatorial transit. The model predicts the site to have transited from 5°S to 5°N latitude between about 77 and 56 m.y. During that time the rate of sedimentation reached a maximum. The lowermost part of the curve (below 400 m subbottom depth), however, has to be discarded because there the extremely high rates of sedimentation are clearly due to

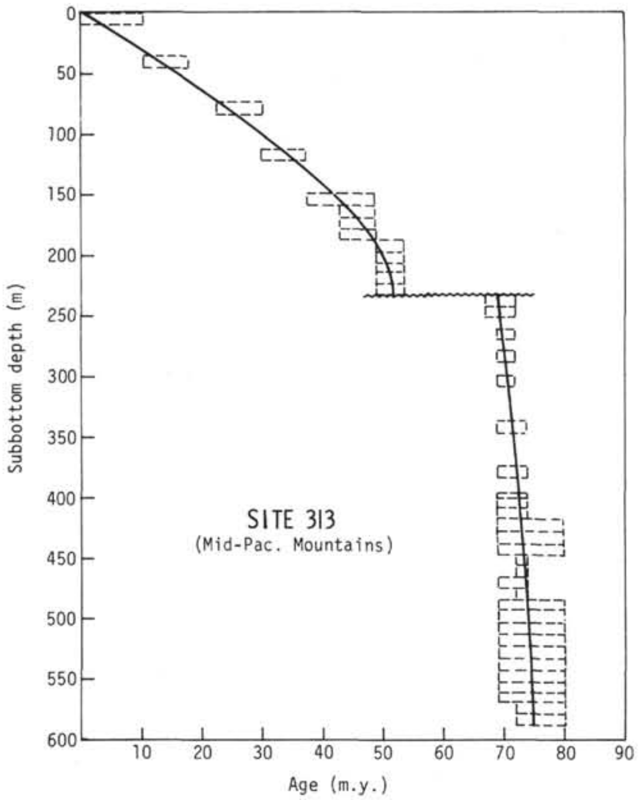

Figure 9. *Sedimentation rate curve for Site 313 in the Mid-Pacific Mountains.*

the deposition of massive turbidite sequences. The presence of the hiatus corresponding to the Paleocene and early Eocene times precludes any good definition of the time when the site left the equatorial zone and reached the low-productivity area responsible for the relatively flat shape of the upper part of the curve. Nevertheless, we believe that this hiatus does not result from the transit of the site under the mid-latitude low-productivity area for two reasons. First, there is ample evidence from previous DSDP legs for the oceanwide and possibly worldwide extension of that lower Tertiary hiatus at almost any latitude. In fact, it can be noted that the same hiatus is visible on Magellan Rise and Horizon Guyot (Winterer, Ewing, et al., 1973a, b) and that it merely tends to be restricted to the lowermost Tertiary in the elevated high-productivity areas, that is, when a given site on a plateau is close to the equator during the corresponding time. It appears to extend more in time at sites which are deep and beneath low-productivity areas during that same time. The second reason that favors a good correlation of the sediment accumulation rate with the predicted equatorial transit regardless of the presence of that hiatus is that a slight steepening of the curve can be observed already on the "young side" of the hiatus, at a time when the site was just out of our arbitrarily chosen equatorial zone (5°S to 5°N). We feel that the case here is similar to that of Sites 305 and 310, on Shatsky Rise and Hess Rise, respectively, where we already noted that because of a relatively shallow depth, the equatorial high productivity zone is probably wider than in the deeper parts of the basin, although it might be also related to relative changes of the zone width with time for other oceanographic reasons.

ACOUSTIC STRATIGRAPHY AND PLATE MOTION

The acoustic stratigraphy of the northwestern Pacific is relatively simple and consists of four of the units defined by Ewing et al. (1968) for most of the Pacific Ocean; namely: (1) an upper transparent layer, (2) an opaque layer (often referred to as Horizon A′), (3) a lower transparent layer, and (4) the acoustic basement. Previous DSDP legs have already partly recognized the lithostratigraphic significance of this acoustic stratigraphy. In particular, the opaque layer has been correlated with massive chert accumulation in most of the North Pacific, and the upper transparent layer has been recognized to correspond with different lithologies in various parts of that ocean, while not much has been learned about the nature of the lower transparent layer in the oldest parts of the Pacific (Fisher et al., 1971; Winterer et al., 1971; Winterer, Ewing, et al., 1973a, b; Heezen, MacGregor et al., 1973). The diachronous nature of the top of the opaque layer has been noted by Fisher et al. (1971) and Heezen, MacGregor, et al. (1973). These authors pointed out that this time transgression of the age of the youngest chert in the sedimentary column probably resulted from the crossing of the equatorial zone by different sites at different times and interpreted the chert as indicative of the presence of calcareous sediments deposited under the equator (Heezen et al., 1973). Our interpretation follows the same line; however, because of a better recovery in Leg 32 drill holes, we were able to show that the top of the opaque layer corresponds generally with the youngest equatorial chert in the section. It is generally not associated with equatorial carbonate as the older parts of the Pacific plate were already below the CCD when they crossed the equatorial zone. Moreover, the correlation between the age of the youngest chert and the top of the opaque layer is very well established everywhere on the Pacific plate. We know, however, that the age of the youngest chert does not always correspond with the age of the youngest massive accumulation of siliceous organisms, as chert formation has been recognized to be triggered by particular environmental conditions that do not occur in the entire stratigraphic column and is especially rare in post-Eocene sediments. This remark is especially useful when interpreting the acoustic record in the central and eastern Pacific where, due to the extreme rarity of post-Eocene chert, no opaque layer is to be observed on crust younger than Eocene, while silica may be present in the sediments in the form of radiolarian and diatom ooze. In the case of the northwestern Pacific, however, as the equatorial crossing of all the area studied here occurred during the Cretaceous, when chert formation seems to have been common, the correlation between the chert and the opaque layer can be used in a straightforward manner in order to interpret the acoustic stratigraphy in terms of plate motions.

A typical acoustic section of the northwestern Pacific is shown schematically on Figure 10 with its location appearing on Figure 11. Examples from actual seismic

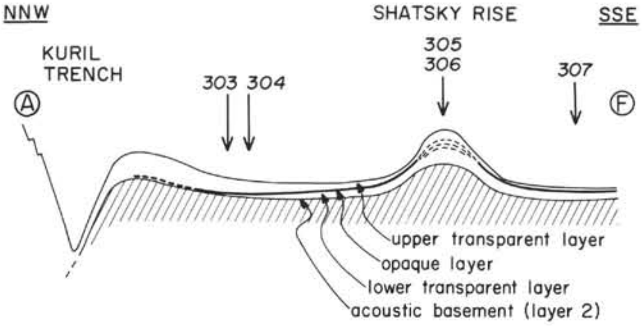

Figure 10. *Schematic acoustic section across the northwestern Pacific showing variations in the upper transparent, opaque, lower transparent, and basement layers as well as the locations of Sites 303, 304, 305, 306, and 307.*

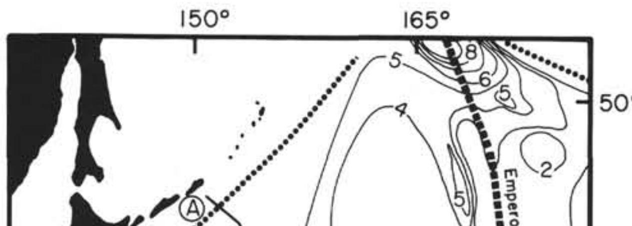

Figure 11. *Isopach map (from Lancelot et al., in preparation) showing total sediment thickness in a part of the northwestern Pacific contoured in tenths of seconds and the locations of the reflection profiles shown in Figure 12.*

reflection profiles appear on Figure 12 (see also the underway data chapter by Larson et al. this volume). The total sediment thickness in the basin (Figure 11) varies roughly from 0.2 to 0.5 sec with an average a little below 0.4 sec. The drilling results allowed a good control on the interval velocities (see Site Report chapters), and we can consider that in most of the basin the total sediment thickness varies roughly from 200 to 400 meters, while it reaches over 1000 meters on Shatsky Rise. Within this sediment section we can recognize the acoustic units defined previously, namely, an upper transparent layer, an opaque layer, a lower transparent layer, and the acoustic basement. The corresponding lithologic units have been clearly identified at Leg 32 sites, and the drilling results show that although the opaque layer and the acoustic basement always correspond with chert and basalt, respectively, lateral facies variation is the rule within the upper and lower transparent layers. These results can be summarized as follows:

1) The upper transparent layer consists mainly of siliceous ooze in the northern part of the area (Sites 303 and 304). The uppermost part of the section in the vicinity of the trenches shows a gradual upward increase in the amount of volcanic ash. The lowermost part shows a gradual decrease in the amount of siliceous microfossils and correspondingly an increase in the clay content. In the southern part of the area this layer consists exclusively of pelagic zeolitic clay.

2) The opaque layer consists of chert, generally associated with zeolitic pelagic clay and occasionally carbonate sediment.

3) The lower transparent layer consists mainly of calcareous sediment, with chert present in variable amounts. Toward the south (Site 307) some pelagic clay might also be present in this unit, intercalated between the basal carbonate sediment and the massive chert of the opaque layer.

4) The acoustic basement consists of basalt that is believed to represent the top of the oceanic crust (layer 2) generated at the ridge crest of either the Japanese (north of Shatsky Rise) or Hawaiian (south of Shatsky Rise) spreading centers.

On Shatsky Rise, the acoustic units described above lose their individuality. This corresponds to a definite change in the lithology as the entire section consists of calcareous sediment with variable amounts of chert. The chert is relatively diluted within the carbonate section due to high rates of sedimentation, and the opaque layer is not observed on the rise. The top of the chert-rich section is recorded acoustically by the presence of a relatively thin reflector. Chert is relatively abundant in the entire lower part of the sediment section, but its distribution is probably regular enough so that no drastic change in acoustic impedance occurs below the top of the chert-rich section. As a result, the lowermost interval observed above the basement, although rich in chert, is relatively transparent.

One of the most striking characteristics of the acoustic units defined above is that they are essentially diachronous. This results directly from the tectonic evolution of the sea floor and can be interpreted in terms of both vertical and horizontal plate motion.

The basement age changes regularly as a function of the distance from the ridge crest according to sea-floor spreading concept. The first sediments that are deposited on top of that basement consist of a layer of carbonates. Again, the ages of the boundaries of that layer are controlled by a sea-floor spreading type of evolution. The lower boundary is the basement, the upper boundary corresponds to the time at which the sea floor sinks below the CCD. If the CCD level were constant in time and space, the age variation of the upper boundary of this layer should be parallel to that of the basement. The age of the opaque layer is directly related to the crossing of the equatorial zone. It is thus evidently diachronous and its age variations are not expected to be parallel to the age variations of the basement. Only the top of the uppermost unit is an isochron and corresponds to the present-day sediments.

If the surface waters exhibited no geographical variations in productivity, the succession of sedimentary layers would merely reflect the subsidence of the oceanic crust away from the ridge crest at a rate that could be estimated from the curves of Sclater et al. (1971). The basic record would consist of a layer of carbonates, representing the ridge flank sedimentation, overlain by a layer of pelagic clay, corresponding to the deep basin sedimentation below the CCD. In that case, the sediment thickness should regularly increase toward the areas of older crust, away from the spreading centers. In fact, this increase in the total sediment thickness might be relatively small whenever the subsidence brings the sea-floor rapidly below the CCD level (shallow CCD and/or deep ridge crest) because of the very low rates of accumulation recorded in the pelagic deep-sea clays.

In the northwestern Pacific we can observe that different areas of the basin crossed the equatorial zone of high productivity at different times. As this equatorial crossing is marked by the presence of the opaque layer in the sediment section of the seismic profiles, the level at which this opaque layer is observed above the basement should be a function of the time elapsed between crust generation and equatorial crossing. Across the Japanese lineations, the age of the crust increases toward the south and, as the plate has been moving mainly toward the north-northwest during the Mesozoic, this time difference increased toward the south. Correspondingly, the opaque layer can be observed higher in the sedimentary section in the southern areas, while it is very close to the basement toward the north (Figure 10). At a point where equatorial crossing and crust generation occurred at the same time, that is, when the ridge crest was beneath the equator, the opaque layer gradually disappears where siliceous organisms were diluted within the ridge flank carbonate sediments. Therefore, toward the north the base of the upper transparent layer might be composed of both equatorial and ridge flank carbonates. Most of the upper transparent layer in the south consists of pelagic clay and is always very thin. Toward the north under the influence of the high productivity associated with the Kuroshio Extension Current, a thick wedge of siliceous ooze makes up most of that upper transparent layer. Near the Kuril trench the proximity of the island arcs is responsible for some volcanogenic contribution in the uppermost sedimentary section and the sediment thickness reaches a maximum.

MAGNETIC LINEATIONS AND PLATE MOTION

Isochrons of the Western Pacific

Figure 13 shows basement age isochrons in the northwestern Pacific area for 113, 117, 120, and 126 m.y. that are drawn from magnetic lineation and fracture zone information in this area. The magnetic lineations that are outlined are M1, M4, M8, and M11, respectively. Three different levels of confidence are shown in Figure 13, the solid lines being based on easily identified magnetic lineations and well-mapped fracture zone offsets. The dashed lines show where data exist that are not easily interpreted, while the dotted lines are mostly guesses as to the isochron locations. In general, the isochrons for the Phoenix lineations are drawn from Larson et al. (1972), while the Hawaiian lineations are after Hayes and Pitman (1970) and Larson and Chase (1972) as modified by Hilde (1973). The Japanese lineations are a modification of Hilde (1973) and Larson and Chase (1972).

The middle portion of the Japanese lineations is a well-mapped area with well-documented fracture zones as shown by Hilde (1973). In the western portion of these lineations, a trend is shown parallel to the central area, although Hilde (1973) is at variance with this. A marked change in trend along any particular lineation seems geometrically unlikely, and it is not clear that it is justified by the data. M1 and M4 in this area are not mapped features, as they have been subducted and presumably lie beneath Hokkaido. The eastern portion of the Japanese lineations is difficult to map because the lineations are pinching out in the area. M11 near Shatsky Rise is shown dotted although the next younger anomaly, M10, is definitely present just north of this position.

The connection of the Japanese and Hawaiian lineations down to 35°N latitude is accomplished by an extrapolation of the Hawaiian lineations and the assumption of a transform fault beneath Shatsky Rise after Hilde (1973). Between 35°N and 25°N, the Hawaiian lineations are quite well known, although the location of M1 north of the Mendocino Extension has not been determined. The identification of the lineations between the two fracture zones that form the Mendocino Extension is based on one line in Hilde (1973). These data, although sparse, show well-formed anomalies and appear to be a reasonable interpretation. South of about 15°N, the Hawaiian lineations cannot be mapped, either because of the presence of the Mid-Pacific Mountains, or because the extension of the Murray Fracture Zone offsets the lineations in an unknown manner. The offsets on the Hawaiian lineations are drawn to reproduce offsets of anomaly 32 across the Murray and Molokai fracture zones to the east.

The connection of the Hawaiian lineations M1, M4, and M8 to the Phoenix lineations assumes that a magnetic bight existed just east of the Phoenix lineations at about 170°W longitude. The M11 isochron assumes that an unstable ridge-ridge-transform triple point existed at that time that reorganized to a ridge-ridge-ridge triple point at M8 time in the vicinity of Magellan Rise. The main portion of the Phoenix lineations consists of very well delineated features as described in Larson et al. (1972). The extension of M11 to the west of the western fracture zone is done on the basis of unpublished data and is somewhat tentative. However, it is quite certain that lineations slightly older than M11 do extend to the west in this manner.

Magnetic Lineation Rotations

By using the three consecutive rotations that have been described above, the basement isochrons have been rotated back to their original positions in the Pacific. These isochrons now outline some of the spreading centers and transform faults that bounded the Pacific plate in the Early Cretaceous. If the rotations are correct and

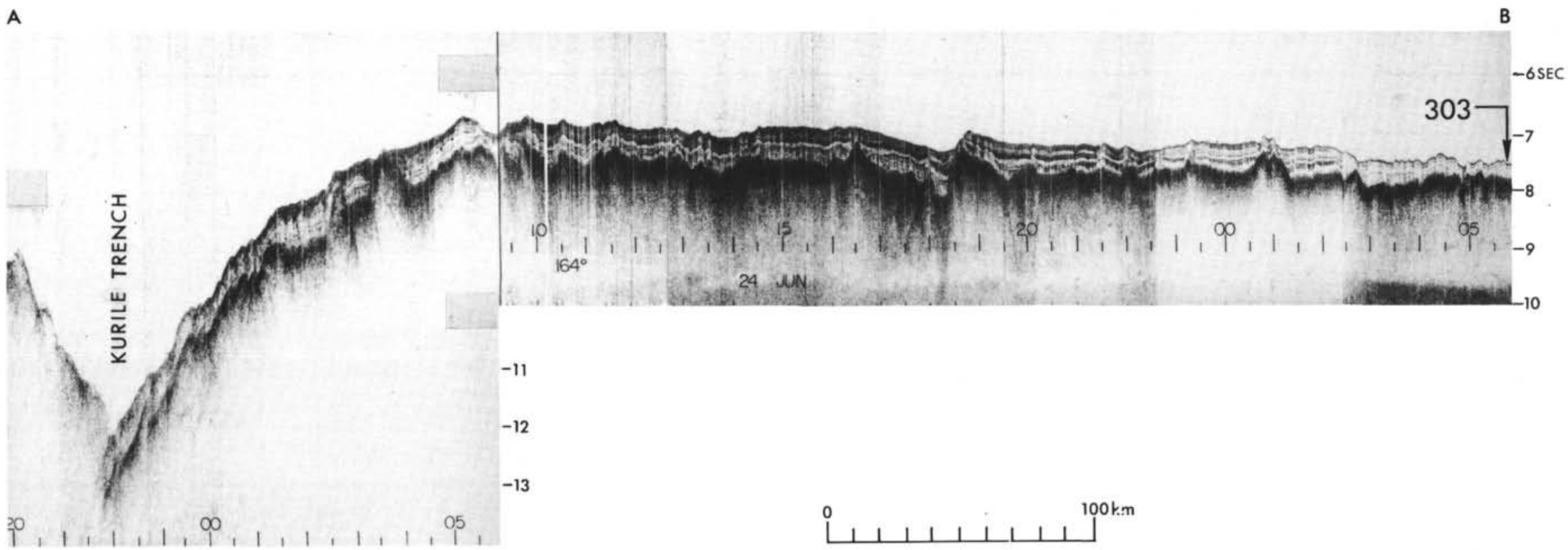

Figure 12. *Seismic reflection profile across the northwestern Pacific (see location on Figure 11) made by* Conrad *14 from A to B and by* Glomar Challenger *32 from B across Shatsky Rise to F.*

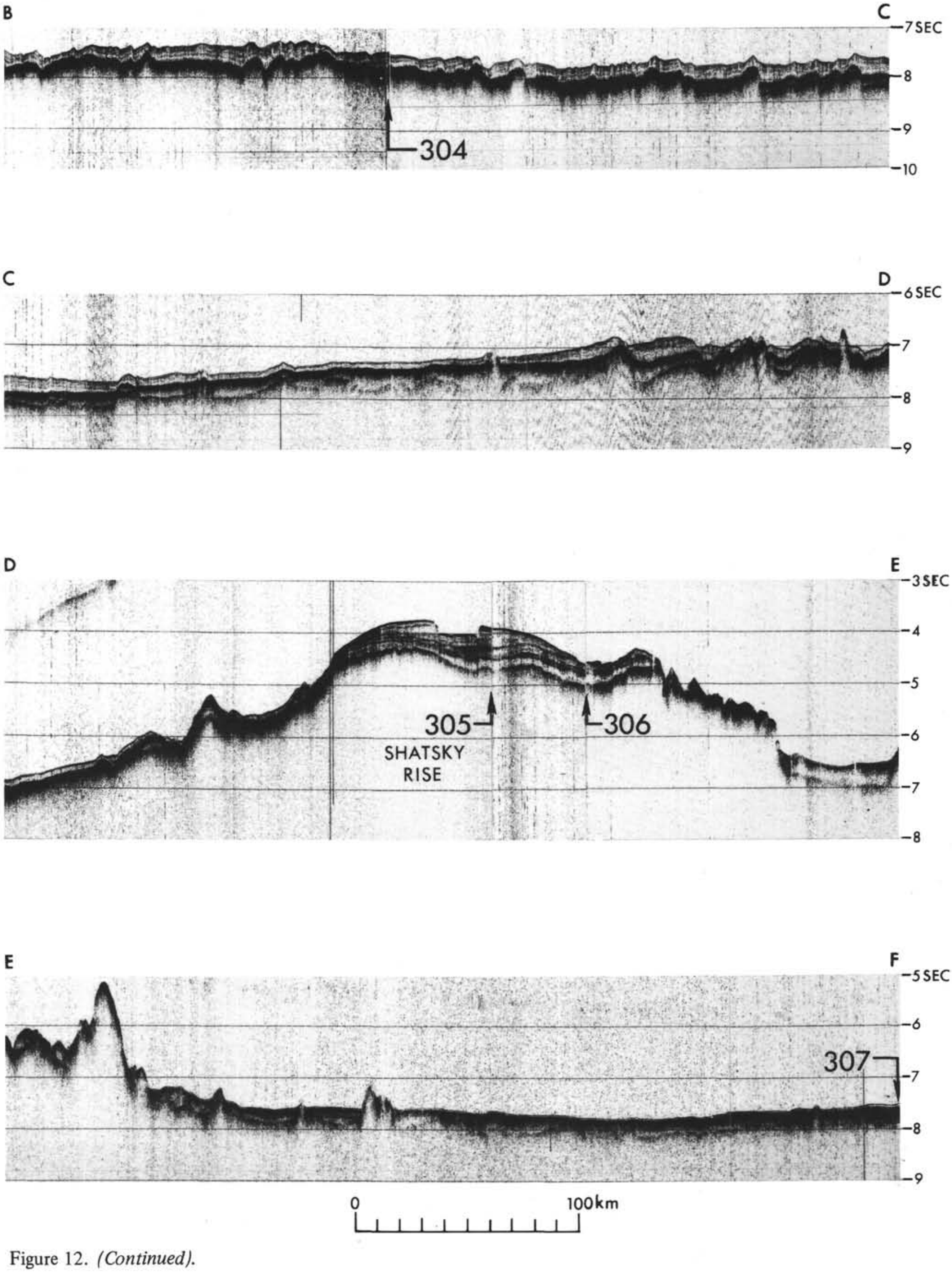

Figure 12. *(Continued).*

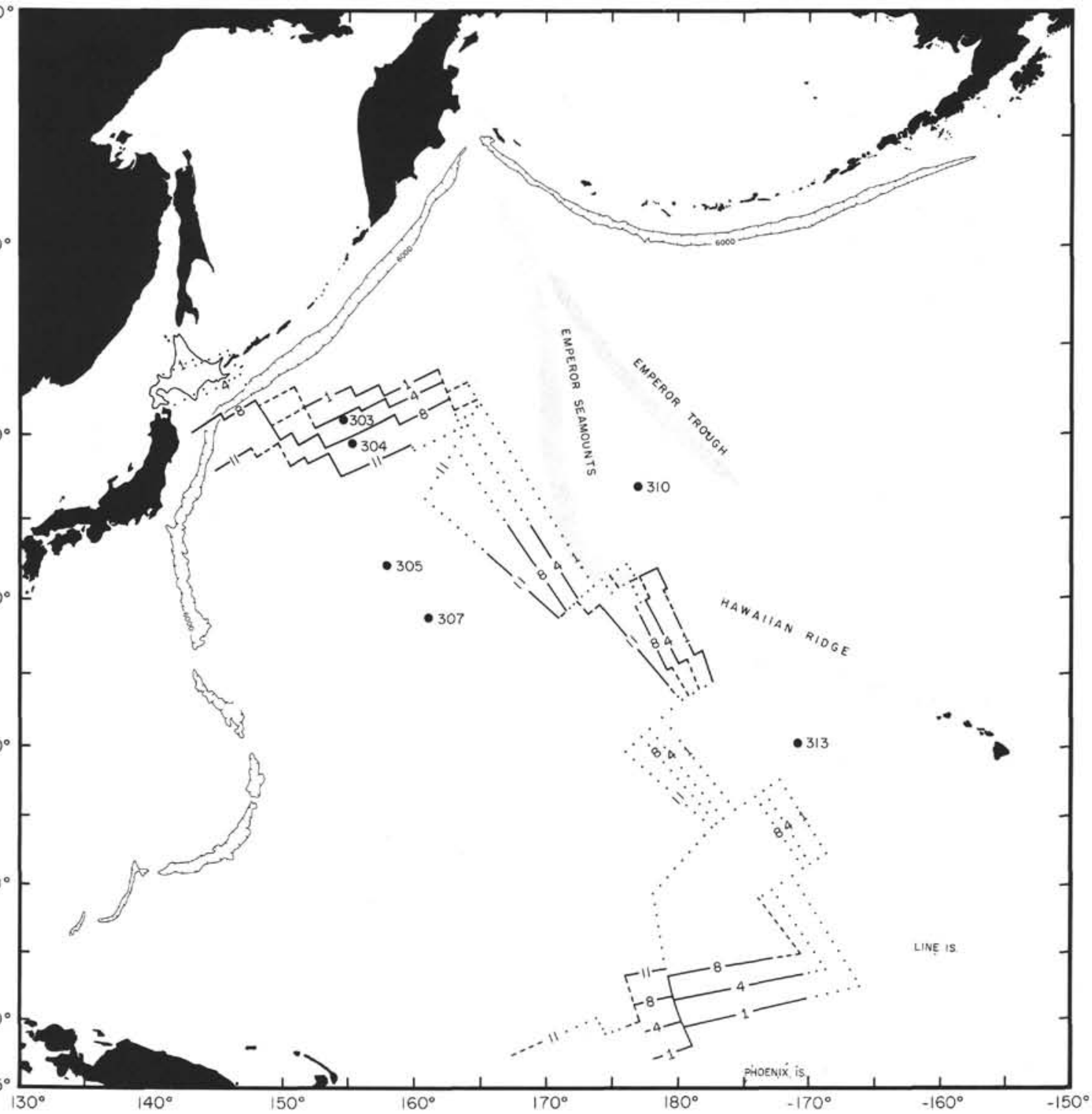

Figure 13. *Basement age isochrons of the northwestern Pacific outlined by anomalies M1, M4, M8, and M11 (equivalent to 113, 117, 120, and 126 m.y., respectively) and their associated fracture zones. Solid lines are the most confidently mapped features, while the dotted lines represent least confidence and the dashed lines an intermediate level.*

the Pacific plate has remained as a rigid entity for the last 126 m.y., then these results also show the paleolatitudes and azimuths of the plate boundaries at that time.

The most obvious result of this exercise is that the results obtained by rotating the isochrons back via an independent, paleomagnetic method (Figure 14) are in close accord with the results obtained by rotating the isochrons back via the sedimentary model (Figure 15). The reconstruction shown in Figure 15 was obtained by Larson and Pitman (1972) who superimposed the paleomagnetic pole locations of the Pacific and North American plates for 110-120 m.y. The Pacific pole location in that study was obtained by analyzing the cross-sectional shapes of the Phoenix, Japanese, and Hawaiian anomalies and contains no information about hot-spot trends or rates of rotation. The only assumption common to both models is that the Pacific plate has remained internally rigid for the past 120 m.y.

The results of both models show that the Pacific plate during the period 126-113 m.y. was being generated in the Southern Hemisphere and has subsequently rotated slightly in a clockwise fashion. The model under discussion can be checked further by comparison of the remanent inclination results achieved on Leg 32 basalts (Larson and Lowrie, this volume) with predicted paleolatitudes. The predicted paleolatitude of Hole 303A shown plotted on Figure 15(C) for M4 time is 6°S, in almost exact agreement with the 5.8°S paleolatitude measured on the basalts (Larson and Lowrie, this volume). Site 304 is shown on Figure 15(B) for M8 time to have a predicted paleolatitude of 9°S, in comparison with the 11°S paleolatitude measured on the basalts.

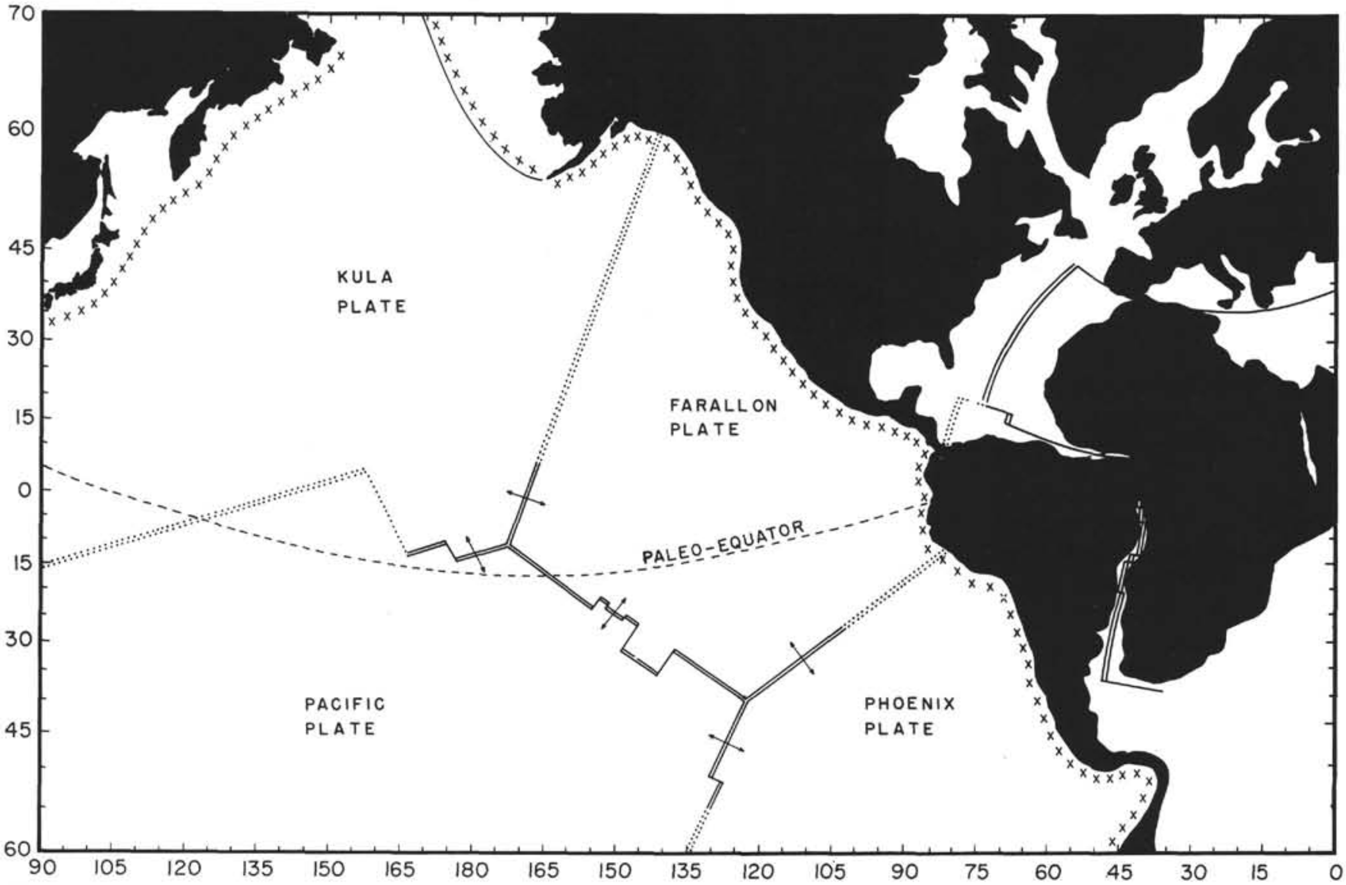

Figure 14. *Plate boundary configuration in the Pacific Ocean for 110 - 120 m.y. from Larson and Pitman (1972).*

While these results for the Early Cretaceous are encouraging, we point out that an extrapolation of this model to the Late Jurassic will produce marked discrepancies between predicted paleolatitudes and both remanent magnetic inclinations and magnetic anomaly skewness results. Using an extrapolated version of this model, the predicted paleolatitude at Site 307 on anomaly M21 (~145 m.y.) is somewhat south of 20°S latitude. The remanent inclination of the basalt at this site indicates a paleolatitude of 5.6°N latitude, although this could be 5.6°S latitude if the polarity of the site has been misinterpreted. Magnetic anomaly skewness measurements near this site are in agreement with the 5.6°N paleolatitude estimate (Larson and Lowrie, this volume). Also, unpublished magnetic anomalies on the western extension of the Phoenix lineations show that the Late Jurassic part of this sequence (M20 to M25) has skewness corresponding to equatorial paleolatitudes. The extension of M11 on Figure 15(A) shows this plate boundary to be at 50°S latitude, which is about the paleolatitude that would result if the rotations were extrapolated back to Late Jurassic time. Since the discrepancies for the Late Jurassic are always in the same sense, they do not necessarily indicate that the model is incorrect and that the Early Cretaceous results are fortuitously agreeable. Rather, we suspect that the model has a valid basis back to the Early Cretaceous and that a marked change in Pacific plate motion occurred in Late Jurassic-Early Cretaceous time.

Tectonic Evolution

Accepting the model back to Early Cretaceous time allows one to view the evolution of the Pacific plate boundaries through small time increments from 126 to 113 m.y. At 126 m.y. (M11 time) the Pacific plate boundaries were all well south of the equator, and the two triple points present were probably both unstable structures with Shatsky Rise near the northern triple point and Magellan Rise near the southern one. Marked changes occurred between this situation and the one present at 120 m.y. (M8 time). By then, both triple points were nearly stable, ridge-ridge-ridge structures. This was accomplished on the northern structure by the transform fault becoming progressively shorter and on the southern one by a marked triple point jump. This was accompanied by an abrupt change in trend of nearly 20° on the Hawaiian spreading center at M10a time. The pattern that was established by M8 time progressed rather simply to 117 m.y. (M4 time). No changes in spreading direction occurred and the triple points did not change their aspects. The situation at 113 m.y. (M1 time) was again a simple progression of the previous picture. The northern triple point then appeared stable as the transform fault was completely eliminated. This aspect of the evolution is approximately the same as that proposed by Hilde (1973) for this structure. Rates and directions of motion appear to have remained constant.

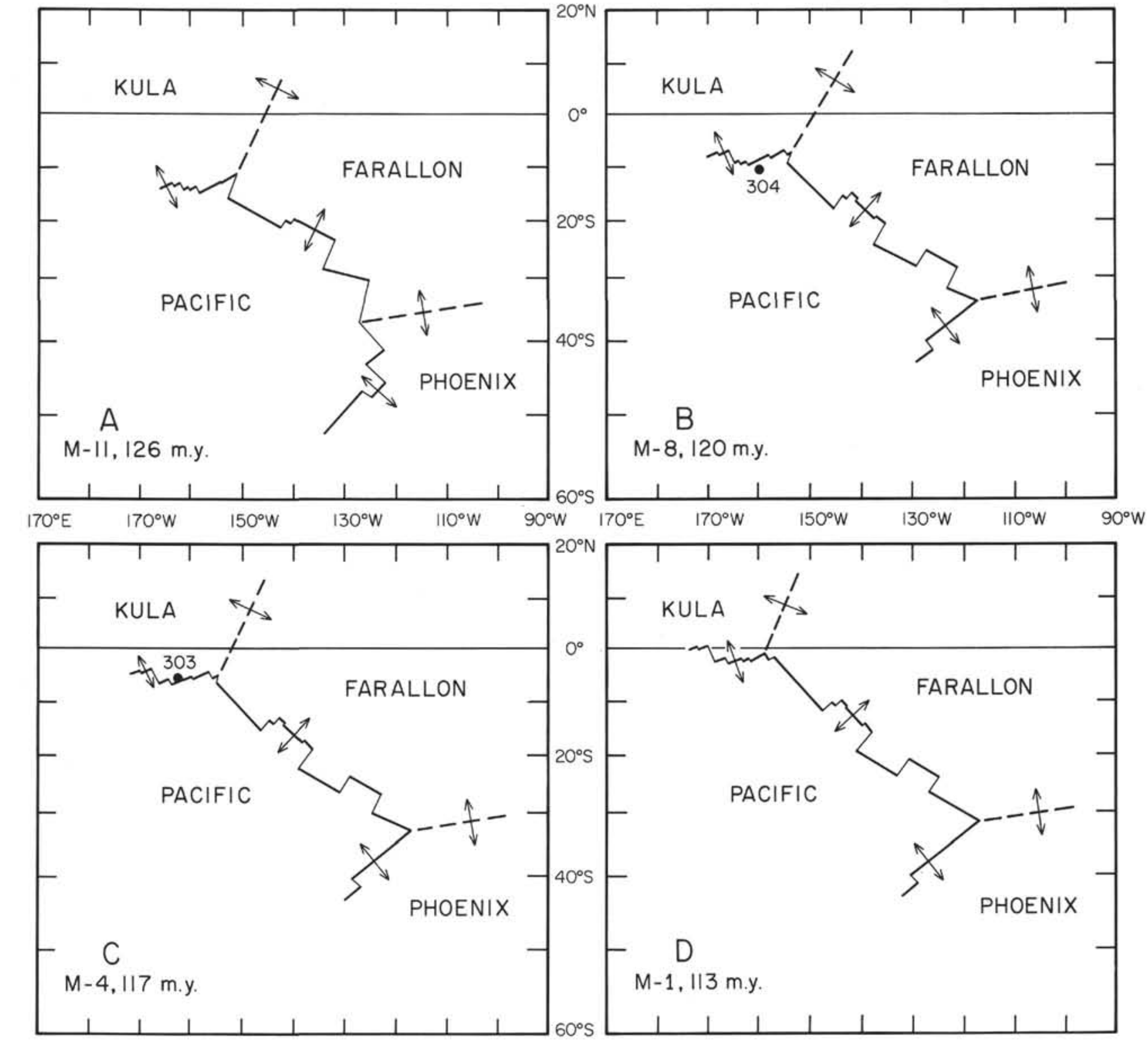

Figure 15. *(A) M-11 isochron rotated back to its time of formation at 126 m.y. (B) M-8 isochron rotated back to its time of formation at 120 m.y. Site 304 is the paleolatitude of this site determined from the remanent magnetic inclination of the basalts at the bottom of the hole. (C) M-4 isochron rotated 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.*

Throughout this period of time, the Pacific plate was moving northward at about the half spreading rate on the Phoenix lineations (~5 cm/yr). An expression of this is the approximately stable position of the Phoenix spreading center from M8 to M1 time. By contrast, the Japanese spreading center was moving north at about the sum of the half spreading rates on the Phoenix and Japanese lineations (5 + 4 = 9 cm/yr). This, in turn, means that the Kula plate to the north of the Japanese spreading center was moving northwards at 5 + 4 + 4 = 13 cm/yr from 126 to 113 m.y. This is approximately the same rate (16 cm/yr) measured for northward Kula plate motion during this time period, although the two measurements depend to a certain extent on the same data set.

SUMMARY

DSDP data collected on Leg 32 confirm the northward motion of the Pacific plate in the last 125 m.y. and refine the model of plate motion based on data collected on previous legs in the Pacific Basin. The opaque layer of Ewing et al. (1968) can be understood in the context of this model to mark the passage of the Pacific plate beneath the equatorial zone of productivity. The level of the opaque layer in the sedimentary section indicates the timing of this horizontal motion with respect to the age of the oceanic crust and the rate of subsidence of this crust down the flanks of the Cretaceous ridge systems. The model of plate motion based on sedimentary data allows the basement isochrons defined by

magnetic anomalies and fracture zone trends to be rotated back in a manner similar to the DSDP sites. The results of this manipulation are in close agreement with results obtained independently from remanent magnetic inclination directions of basalts and the cross-sectional shape of the anomaly patterns.

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