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Sedimentary Facies and Plate Tectonics of Equatorial Pacific[1]

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Abstract Facies patterns of post-Eocene equatorial Pacific pelagic sediments indicate northward motion of the Pacific plate of about 3 cm/year with respect to the earth's spin axis, whereas the age gradient of volcanoes in the Hawaiian chain indicates a northward component of motion of the plate with respect to a hot spot in the subjacent asthenosphere of about 6 cm/year. The discrepancy is ascribed to southward motion of the upper part of the asthenosphere with respect to the spin axis.

To examine this possibility more closely, a theoretical isopach map is generated for post-Eocene equatorial sediments, to compare with thicknesses known from drilling and seismic studies. In the model, sediment accumulation rates at all depths are several times faster close to the equator than farther away. The sedimentation model is combined with a plate-motion model with the following elements: (a) Pacific plate moves westward away from the rise crest at 10 cm/year; (b) sea floor deepens gradually as it moves away from the rise, with constant crustal-age versus depth relation; (c) plate moves northward with respect to the earth's spin axis at 3 cm/year; and (d) hot spots in the asthenosphere, which give rise to chains of volcanoes, move southward with respect to the spin axis, with same speed. The model isopachs correspond fairly well to the known sediment thicknesses.

Details of pre-Oligocene motions of the plate versus the earth's spin axis are uncertain, but mid-Cretaceous volcanoes have been shifted about 30° north. Northwest motion of the plate over hot spots in the asthenosphere at about 5 cm/year generated seamount chains parallel with the Line Islands in the period between about 30 and 100 m.y. ago.

INTRODUCTION

The motion of a lithospheric plate can be described in various frames of reference, for example, with respect to adjacent plates, with respect to the spin axis of the earth, or with respect to the subjacent asthenosphere (Fig. 1). If we can specify each of these plate motions, then we can deduce the other elements in the network of vector triangles that links the frames of reference (Fig. 2). For example, if we know the motion of a plate with respect to the earth's spin axis and with respect to the asthenosphere, we can deduce the motion of the asthenosphere with respect to the earth's spin axis. There is no reason to suppose that any one of these elements—plates, spin axis, or asthenosphere—remains fixed with respect to any other. The spin axis, of course, generally is believed to have a fairly stable attitude with respect to the plane of the earth's orbit about the sun.

MOTIONS OF PACIFIC PLATE

The Pacific lithospheric plate is a favorable place to attempt to connect the several frames of reference because several of the requisite classes of data are available to describe the history of plate motion, at least over the past 30-40 m.y. The data needed to specify the motion of the plate in each frame of reference are summarized in Table 1.

Before the interlocking of the three reference frames is considered, each type of relative plate motion shown in Table 1 is discussed separately.

Plate Versus Plate

The motion of the Pacific plate with respect to adjacent plates across the East Pacific Rise is now reasonably well established in the northeast Pacific for the past 80 m.y. on the basis of magnetic anomaly patterns (Atwater and Menard, 1970). Magnetic patterns in the northwest and south Pacific are known in somewhat less detail (Hayes and Pitman, 1970; Herron, 1971; and Pitman *et al.*, 1968), and older patterns in the central and western Pacific (Fig. 3) are just beginning to be uncovered (Larson, R., personal commun.) and dated (Winterer *et al.*, 1971a). Deep-sea drilling results (McManus *et al.*, 1970; Fischer *et al.*, 1971; Winterer *et al.*, 1971b; Tracey *et al.*, 1971; Hays *et al.*, 1972; van Andel *et al.*, 1971; Winterer *et al.*, 1971a; von Huene *et al.*, 1971; and Scholl *et al.*, 1971) can be used to extend the crustal age pattern beyond the magnetic anomaly pattern. Where neither magnetic nor drilling data are available, the crustal-age versus depth relation of Sclater *et al.* (1971) can be used, after taking into account the isostatic effects of the sediment cover and anomalous crustal areas, *e.g.*, seamounts and plateaus (Fig. 4).

The resulting crustal-age map (Fig. 5) is drawn

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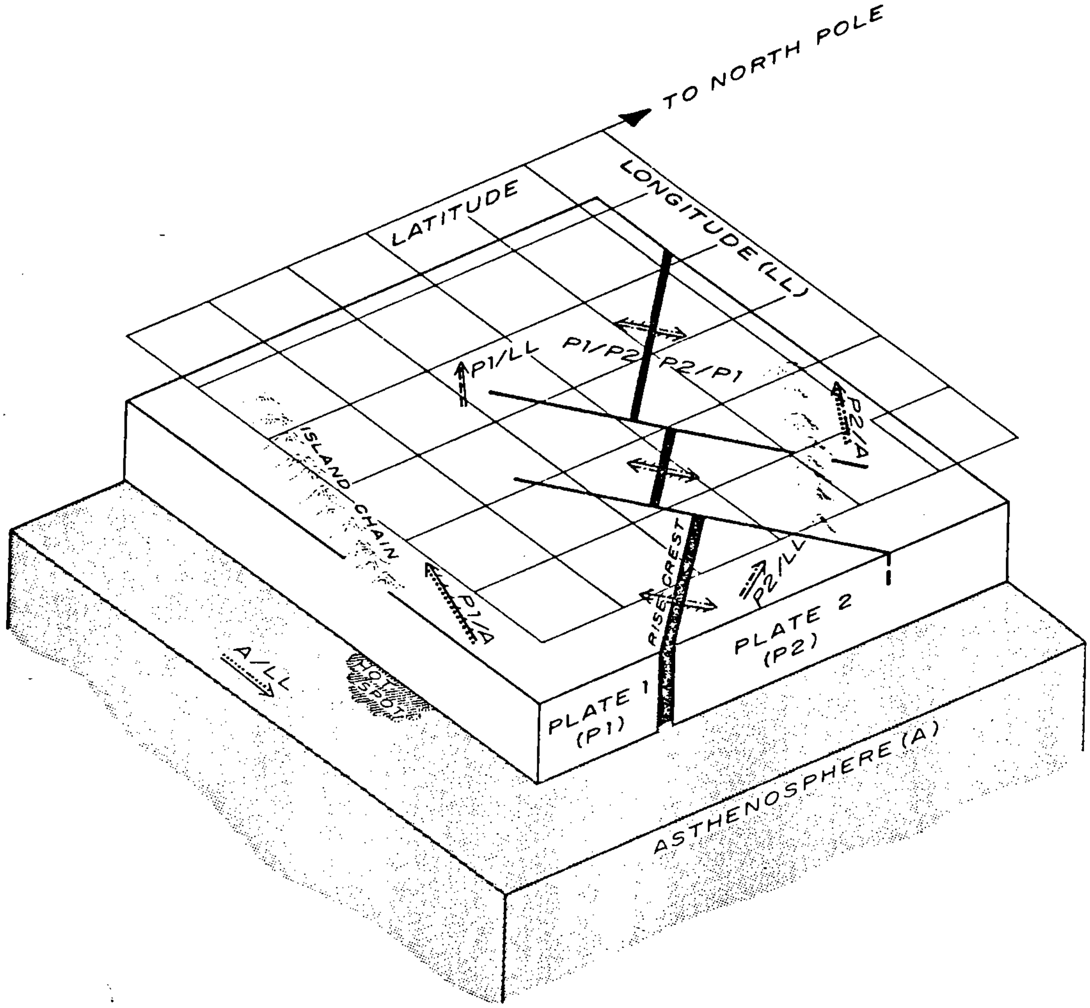

P1, Plate 1; P2, Plate 2; A, Asthenosphere;
LL, Latitude-Longitude Grid Around Earth's Spin Axis.

FIG. 1—Relative motions among two drifting spreading plates and a moving asthenosphere. Three frames of reference are relevant to Plate 1: Plate 1 *versus* Plate 2; Plate 1 *versus* earth's spin axis; and Plate 1 *versus* hot spot in asthenosphere. From these can be deduced hot spot *versus* spin axis, Plate 2 *versus* spin axis, Plate 2 *versus* hot spot.

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to fit the known magnetic, drilling, and bathymetric data, and doubtless will change as new data become available, especially in areas more than about 100 m.y. old. The old region of the Pacific plate is the region of greatest development of seamount chains, and newer lavas from these tend to obscure the older crust on which they are built.

The age pattern in the eastern Pacific, north of the equator, is the best controlled part of the map, and it presents certain problems of interpretation. The average half-rate of spreading at the rise crest for the past 50 m.y., measured between successive pairs of fracture zones (Fig. 6), increases from about 3.5 cm/year north of the Surveyor fracture zone at about 45°N to about 10 cm/year south of the Clipperton fracture zone, near the equator. The faster rates near the equator are due in part to the greater distance of that part of the Pacific plate from the poles of rotation for the motion between the Pacific plate and the plates paired with it on the opposite side of the rise crest during the time from about 5 to 50 m.y. ago, but the faster rates also may be due in part to eastward jumping of the East Pacific Rise spreading center, not only over the past 5-10 m.y., as suggested by Sclater *et al.* (1971), Herron (1971), and Hays *et al.* (1972, p. 910-913),

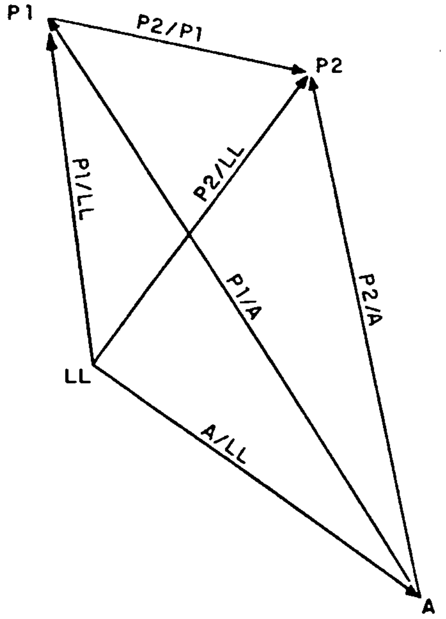

FIG. 2—Vector triangles for motions diagrammed in Figure 1. *P1*, Plate 1; *P2*, Plate 2; *A*, asthenosphere, with hot spot; *LL*, latitude-longitude grid around earth's spin axis.

Table 1. Sources of Data Needed to Describe Pacific Plate Motions

Reference Frame	Direction of Motion	Rate of Motion
Plate versus plate	Fracture-zone orientation	1. Spreading rate at rise crest a. from spacing of dated magnetic anomalies b. from crustal ages at drill sites c. from crustal age versus depth relations 2. Strike-slip rate a. geodetic b. from geologic data 3. Convergence rate Generally by deduction from adjacent pairs of plates of Class 1 or 2
Plate versus spin axis	1. Paleomagnetic polar-wandering curve a. from seamount surveys on seamounts of known age (radiometric, paleontologic) b. from cored deep-sea basalt of known age c. from cored sediments of known age 2. Paleoequators, from sedimentary facies	1. Paleomagnetic polar-wandering curve a. from seamount surveys on seamounts of known age (radiometric, paleontologic) b. from cored deep-sea basalt of known age c. from cored sediments of known age 2. Paleoequators, from sedimentary facies
Plate versus asthenosphere	Trends of seamount chains that formed over "hot spots" in the asthenosphere	Age progression of seamounts in chain 1. from radiometric data on seamount volcanic rocks 2. from capping fossils a. *in situ* b. transported onto adjacent deep-sea floor

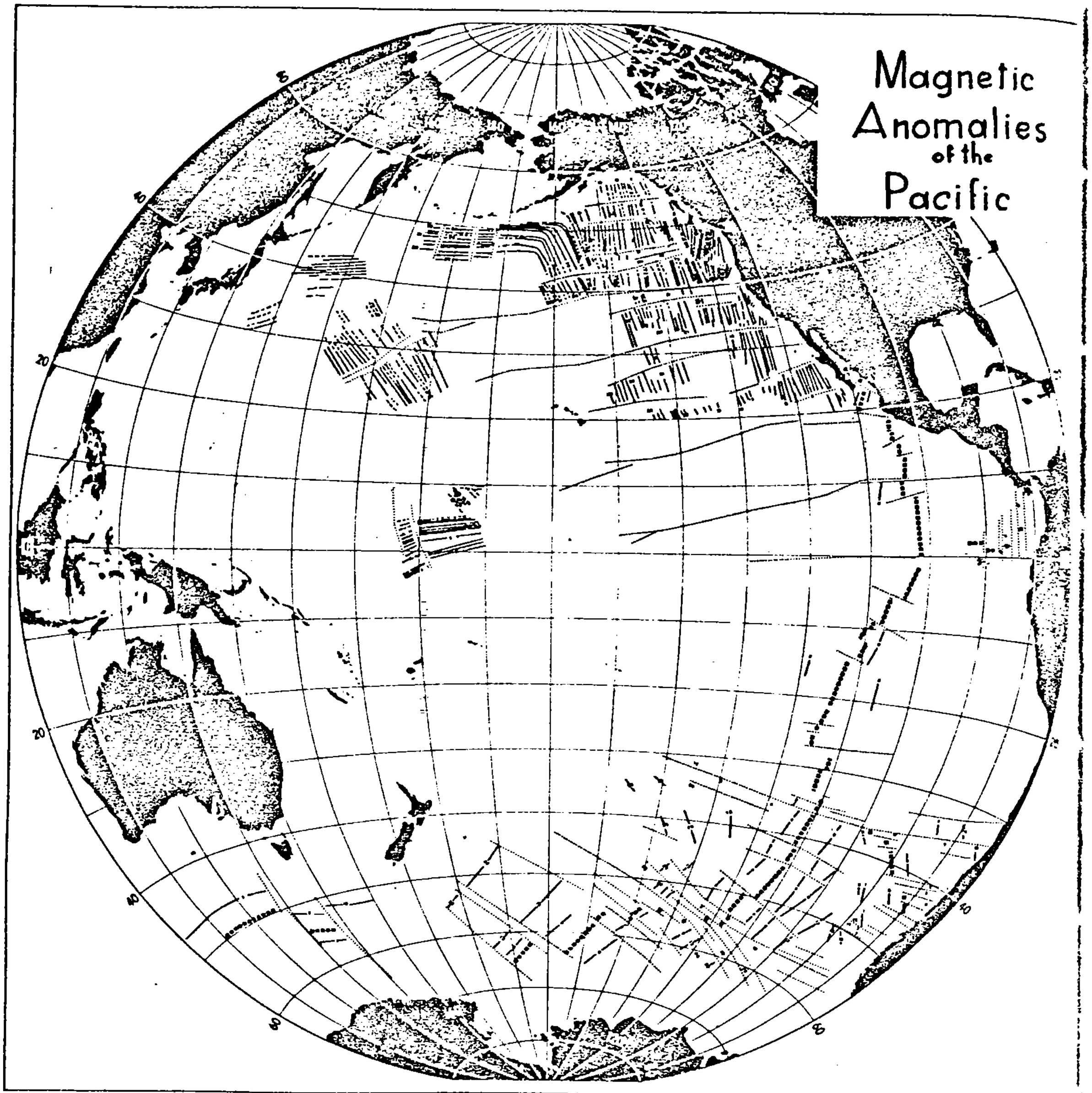

FIG. 3—Magnetic anomaly lineations in Pacific (after Atwater and Menard, 1970; Hayes and Pitman, 1970; Herron, 1971; Pitman *et al.*, 1968; and R. Larson, personal commun.). Heavy dashed lines, rise crest; medium-weight lines, magnetic anomalies; light dashed lines, fracture zones.

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but from time to time during the Cenozoic as well. Where the sample spacing is coarse, the effect of such jumps is to increase the overall apparent rate of spreading on one side of the rise and to decrease it on the other, even though the addition of new crustal material at the rise crest remains symmetrical.

Arguments presented subsequently in this paper about the successive positions of paleoequators and the distribution and thickness of sediments deposited below the equator in the vicinity of the paleo-East Pacific Rise, are dependent on the pattern of fracture zones and crustal ages in the eastern equatorial Pacific, because it is from the crustal-age map that we derive the successive positions of the rise crest and of paleobathymetric contours.

Plate Versus Spin-Axis

Paleomagnetic data—Paleomagnetic data from surveys of seamounts near Japan (Francheteau *et al.*, 1970) show that during middle Cretaceous time (80-120 m.y. ago) the virtual geomagnetic pole, with respect to the Pacific plate, was at about 56°N, 34°W. The band of possible positions of the mid-Cretaceous paleomagnetic equator is about 25° wide, owing to the uncertainties in locating the pole (Fig. 7), and the dating on the seamounts is not yet fixed with certainty. Rudistid reef faunas dredged from several of the seamounts by the Scripps Institution of Oceanography during Leg V of *Aries* Expedition (J. Matthews, personal commun.) still are being studied and a precise paleontologic age determination is not yet available.

From paleomagnetic studies of sediment cores from JOIDES Drill Site 66, at 2°N, 166°W, Sclater and Jarrard (1971) derived a paleolatitude of about 30° in sediments of Cenomanian or Turonian (85-100 m.y.) age. The scarcity of biogenous material in these sediments (Winterer *et al.*, 1971b, p. 729-731; Heath and Moberly, 1971, p. 988-989) is consistent with accumulation beneath a region of low biologic productivity, probably at least 5° away from the equator.

Francheteau *et al.* (1970) have constructed a polar-wandering curve for the Pacific plate for the past 100 m.y., but great uncertainties attach to all but the Japanese seamount pole (V. Vacquier, oral commun., 1971).

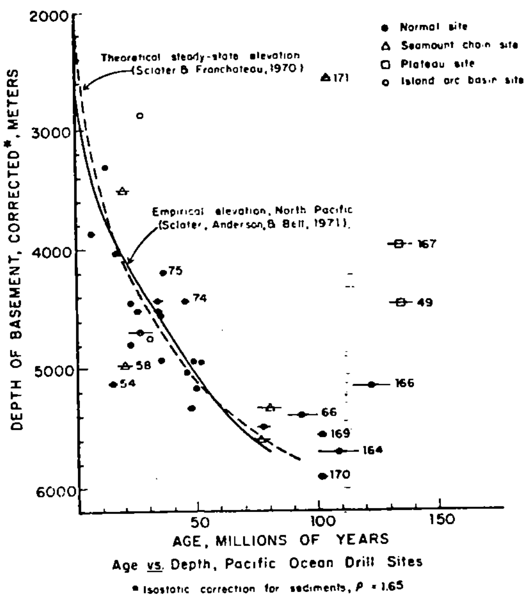
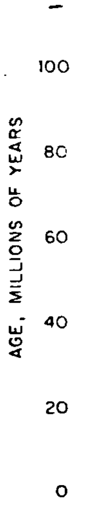


FIG. 4—Crustal age *versus* depth relation in eastern Pacific (after Sclater *et al.*, 1971, with depth to basement at Pacific drill sites—through Leg 17—shown). Isostatic correction for sediment thickness has been applied.

Drill data—One of the principal results of the deep-sea drilling program in the Pacific has been to demonstrate the progressive northward shift of biogenous sediments deposited during the past 40 m.y., beneath the equatorial belt of high biologic productivity. The existence of a thick equatorial bulge of acoustically transparent sediments was known from seismic reflection surveys (Ewing *et al.*, 1968) and the bulge also was known to be asymmetric, with the thickest sediments about 4° north of the equator (Fig. 8). The drilling results (Winterer *et al.*, 1971a; Tracey *et al.*, 1971; Hays *et al.*, 1972; van Andel *et al.*, 1971; Winterer *et al.*, 1971b) confirm the seismic picture and show the details of this movement, epoch by epoch, back to late Eocene time, about 40 m.y. ago. Beneath the region within a degree or two of the equator, rates of accumulation of biogenous sediments are commonly several times as rapid as in areas only 5° away (Fig. 13; Tracey *et al.*, 1971, p. 40, Fig. 17) and thus the time at which a drill site passed beneath the equator can be detected by noting the time at which accumulation rates of biogenous sediments were fastest, taking into account the history of changes in the depth of the calcium carbonate compensation level with respect to the sea floor at the site (Fig. 9).

The result of this type of analysis of the drill data is shown in Figure 10. The control for the past 30 m.y. is reasonably good, but for times previous to that data are scanty. There seems to be a real dearth of sediments with ages between 45 and 65 m.y. in the central Pacific (Winterer *et al.*, 1971a), and this makes nearly impossible the identification of inflection points in the sediment-

Fig. 5—Age of oceanic crust in Pacific.



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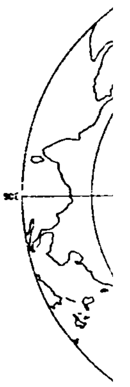

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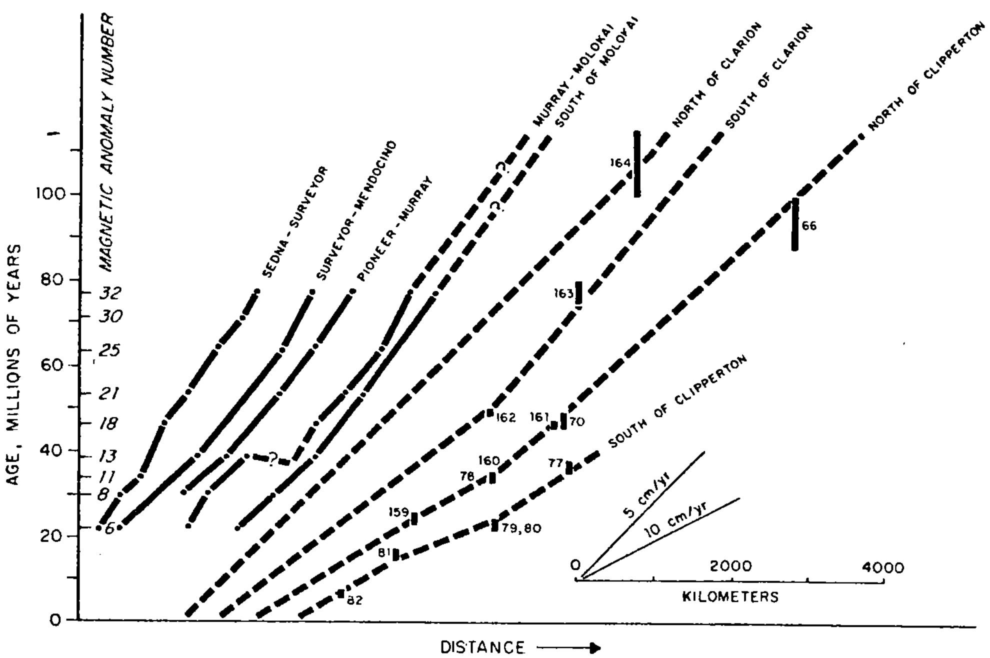

Fig. 6—Crustal age *versus* distance from rise crest for northeast Pacific. Grouped by fracture-zone-bounded blocks. Derived from spacing of magnetic anomalies (dots) and JOIDES drill sites (bars). For clarity, curves are spaced arbitrarily along distance axis; thus, curves do not extrapolate through origin.

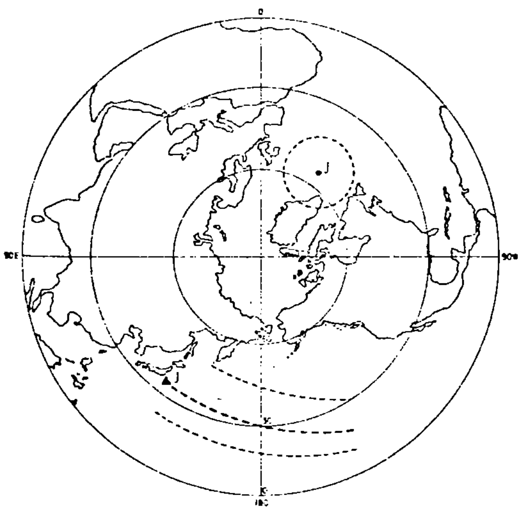

Fig. 7—Paleomagnetic pole and equator for Japanese seamounts (from Francheteau *et al.*, 1970). Triangle, Japanese seamounts; dot in circle, virtual geomagnetic pole, with confidence limits; heavy dashed line, paleoequator; light dashed lines, confidence limits.

age-versus-depth (rate-of-accumulation) curves for sediments in the range of ages between 40 and 70 m.y. The point on the east end of the 75-m.y. paleoequator is believed to be reasonably good, but its trend toward the west is very uncertain. At JOIDES Site 163 (11°N, 150°W) drilled on Leg 16 (van Andel *et al.*, 1971), the Upper Cretaceous (65-75 m.y.) sediments beneath the prominent seismic reflector (Horizon A) in the Eocene are about 125 m thick and are calcareous, but seismic-reflection records in the region show that this large thickness of "pre-Horizon A" sediments is confined to a narrow band only a few degrees wide on either side of Site 163 (J. Ewing, personal commun.). At Site 164, only 1° farther north but 10° farther west, sediments of equivalent age are probably only half as thick as at Site 163 and are mainly zeolitic clays (Winterer *et al.*, 1971b).

The width and productivity of the equatorial belt during Cretaceous time are matters of conjecture. The zone may have been very broad and weakly developed. Keeping this possibility in mind, we can look at the remaining evidence from sediments that gives clues to the locations of the equator during Cretaceous time. One line of evidence comes from comparisons of the thickness of pelagic sediments on the Magellan rise (7°N, 177°W), and Shatsky rise (32°N, 159°E).

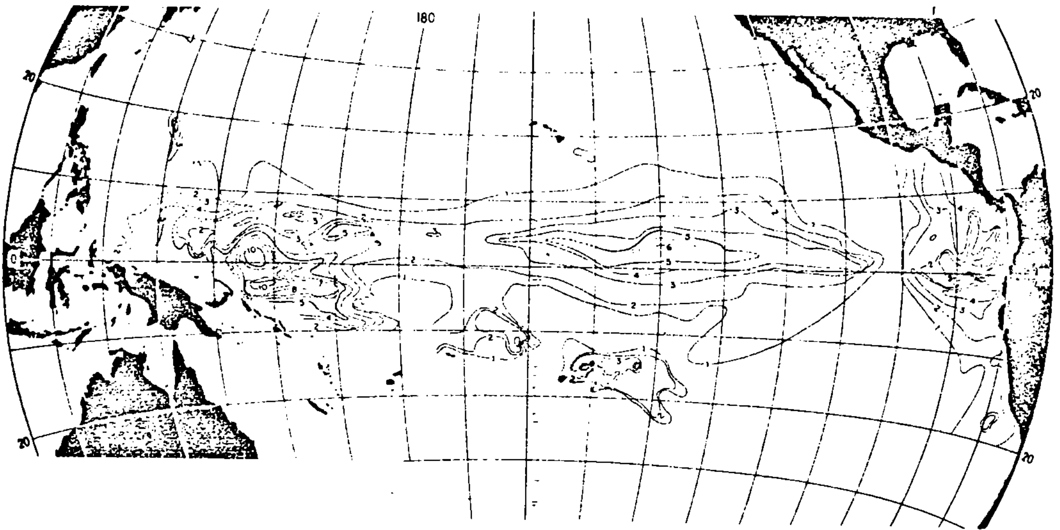

FIG. 8—Thickness of acoustically transparent sediment layer in equatorial Pacific (after Ewing *et al.*, 1968). Numbers on contours are round-trip reflection times of sound waves, in seconds.

The Cretaceous is about 500 m thick on Magellan (Winterer *et al.*, 1971b), and must be at least as thick on Shatsky (Fischer *et al.*, 1971, p. 68), where the oldest sediments are probably Early Cretaceous rather than Jurassic in age (R. G. Douglas and H. Thierstein, personal commun., 1972), suggesting that both plateaus may have been within the equatorial zone of Early and middle Cretaceous times.

Another piece of evidence is the prevalence of rudistid reef faunas of mid-Cretaceous age on guyots in the Mid-Pacific mountains, at 20°N (Berremian—Aptian, according to unpublished notes of the late E. C. Allison), and off Japan, near 30°N. No shallow-water faunas of mid-Cretaceous age have been dredged or cored elsewhere on the Pacific plate (excluding the sliver of North America now attached to the plate) and, therefore, we cannot evaluate yet the latitudinal limits of mid-Cretaceous reef development in the Pacific. Because the pattern of sea-floor spreading in the western Pacific during mid-Cretaceous time (and earlier) may have been substantially different from the patterns of later Cretaceous and Cenozoic times (Fig. 4), possibly paleoequatorial traces on the pre-mid-Cretaceous sea floor have been too much rearranged for us to reconstruct them with any confidence.

To sum up the plate versus spin axis data: paleomagnetic data suggests a 30°-northward shift of the Pacific plate since about 100 m.y. ago, and the locus of the equatorial biogenous sediments shows a northward shift of about 7° in the past 30 m.y. There are feeble indications that points in the western Pacific moved north faster than points in the central Pacific, at least during Cretaceous time. It is clearly too soon to define a detailed polar-wandering curve for the Pacific plate, at least for pre-Oligocene times.

Plate Versus Asthenosphere

Morgan (1971, in press) has elaborated the hypothesis that the sequence of ages of volcanoes along the chains of Pacific seamounts, from younger at the southeast to older toward the northwest (Dana, 1849, 1890; Chubb, 1927, 1957; Wilson, 1963a, b; McDougall, 1964; Jackson *et al.*, 1972), is due to the motion of the Pacific plate over hot spots in the mantle beneath the plate. Three major parallel chains are recognized: the Hawaiian Island-Emperor seamount chain, the Tuamotu-Line Island ridge chain, and the Austral-Gilbert-Marshall Islands chain, each chain containing a bend about halfway along its length. The corresponding segments of each chain form small circles on a sphere, and the three chains can be generated by rotating the Pacific plate,

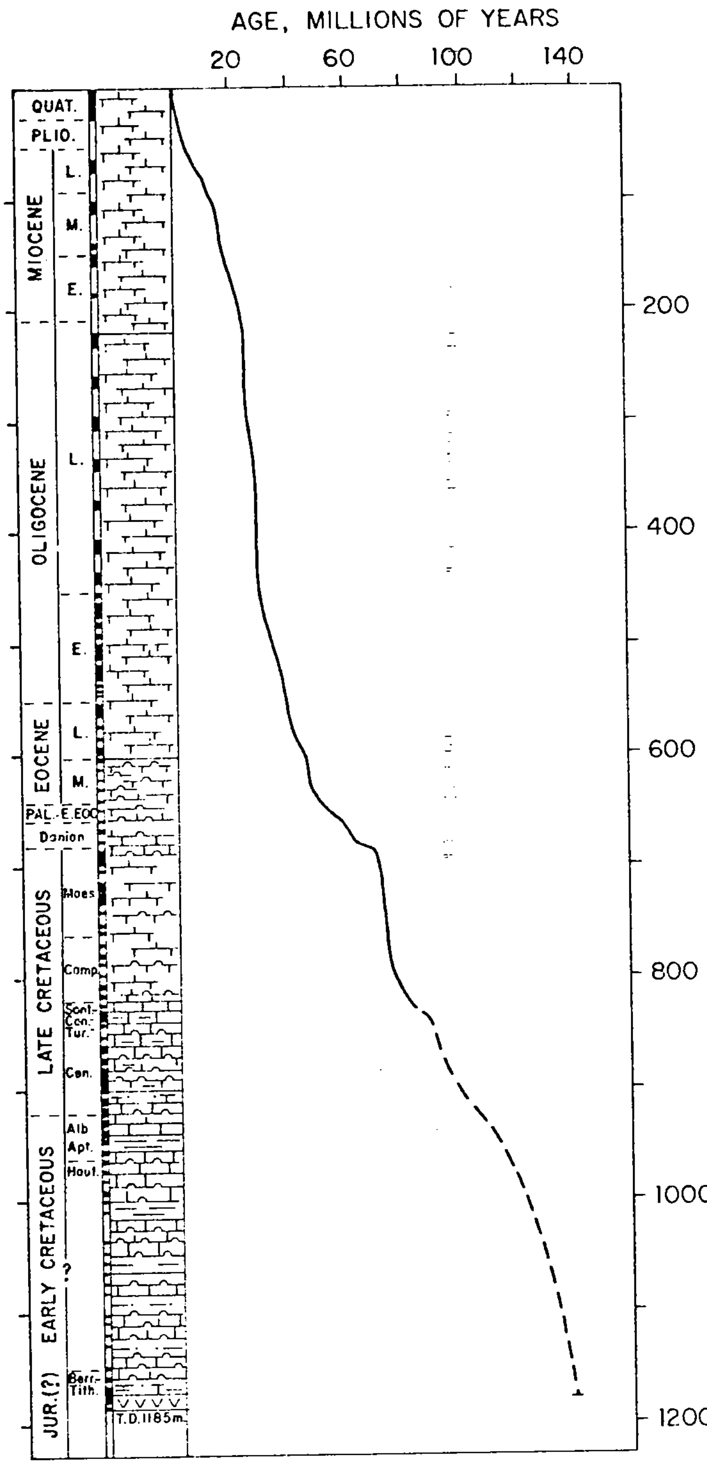

Fig. 9—Sediment age *versus* depth at JOIDES Site 167 on Magellan rise, at 7° 04′ N, 176° 50′ E. Water depth 3,176 m (after Winterer *et al.*, 1971b). Filled and open intervals to left of lithologic column indicate cored and uncored intervals, respectively.

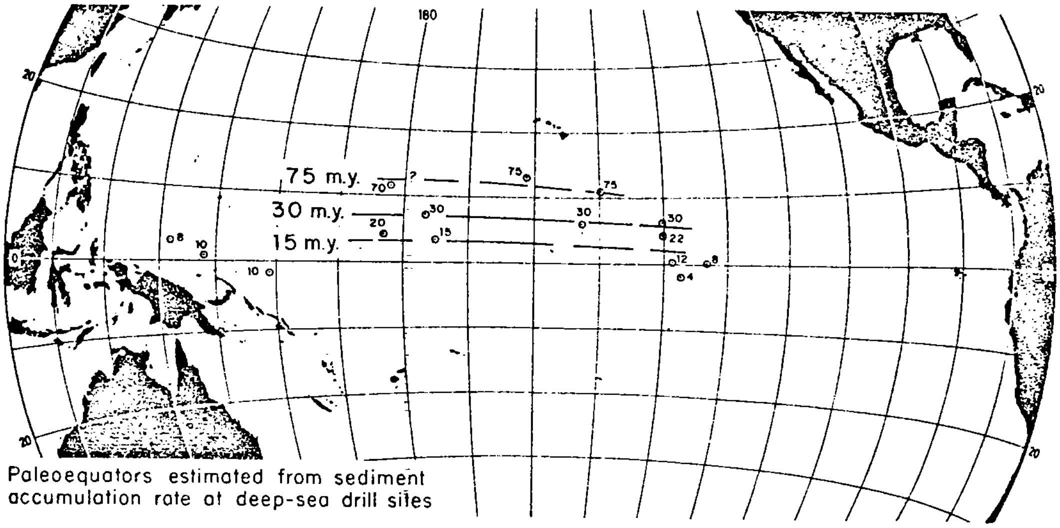

FIG. 10—Paleoequators estimated from deep-sea drilling data.

first around a pole at 67°N, 73°W through 34°, and then around a second pole at 23°N, 110°W, through a further 45°.

Morgan's hypothesis provides a powerful tool, because it can give in a very direct and detailed way the motion of the plate with respect to the top of the asthenosphere. If the hot spots in the asthenosphere are fixed with respect to the spin axis of the earth, then we can derive detailed polar-wandering curves for the Pacific plate and even solve, with the appropriate vector triangles, for the plate-versus-spin-axis motion of other adjacent plates. Alternatively, if the asthenosphere, with its hot spots, is moving with respect to the spin axis, then we may be able to detect and specify these motions by comparisons of plate-versus-spin-axis and plate-versus-asthenosphere motions.

The many seamount chains on the Pacific plate can be grouped into two main sets (Fig. 11), and these two sets form small circles about two Euler poles of rotation. The set of chains parallel with the Hawaiian Island chain can be generated by moving the plate around a pole of rotation at 67° N, 45°W, and the other chain, parallel with the Line Island chain, can be derived by rotation about a pole at 23°N, 108°W. The position of this second pole is very sensitive to the trend of the Emperor seamounts and the pole position ignores both the chain of seamounts extending northwest at an angle to the Hawaiian chain at about 170°W, and the Musician seamounts, neither of which has a well-defined trend. It has been suggested that the Emperor chain marks the location of an important fracture zone (Erickson *et al.,* 1970). In this paper the assumptions are made (1) that the Emperor chain is part of the same set of chains containing the Line Islands, and (2) that the "elbow" between the Emperor and Hawaiian chains marks a change in direction of plate motion over a single hot spot.

We now need to consider rates of rotation around the Euler poles, *i.e.,* the rates of plate motion over the hot spots. This is given by the age progression of seamounts in the chains, and comes from both radiometric and paleontologic data.

Chains parallel with Hawaiian chain—Let us first consider the set of chains parallel with the Hawaiian chain. The Hawaiian chain has itself been the subject of a recent study by Jackson *et al.* (1972) who summarized all the radiometric data on volcanic rocks, especially tholeiitic rocks, along the chain from Hawaii to Midway. Their data yield a motion rate of about 15 cm/year along the chain with respect to a hot spot beneath. In terms of rotation around the Euler pole

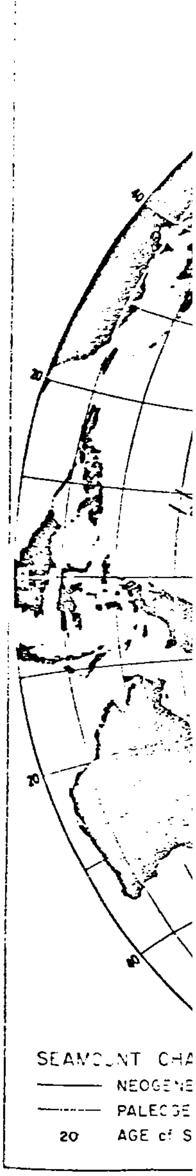

FIG. 11—Seamoun

Fig. 11—Seamount chains on Pacific plate. Solid lines, Neogene; dotted lines, Paleogene and Cretaceous. Figures give ages in millions of years.

at 67°N, 45°W, this amounts to about 1.1°/m.y. They estimate an age of about 25 m.y. for the elbow junction between the Hawaiian and Emperor chains. Uncertainties attach to these estimates of rate and age, but I accept the estimates as the best that can be made from the data now at hand. A reliable date for a seamount close to the elbow is needed.

Data on other chains of this set are scanty. In the Caroline Islands, the easternmost island of Kusaie (5°N, 163°E) is geomorphically very young, but no radiometric dates are available on Kusaie rocks. At Truk, about midway along the chain, larger Foraminifera in limestone xenoliths in volcanic breccias (Stark *et al.*, 1958, p. 78) are of middle or early Miocene age (Cole, 1960, p. 12) or between 9 and 22.5 m.y. old (Page and McDougall, 1970). Still farther west along the island chain, at JOIDES Drilling Sites 57 and 58, Fischer *et al.* (1971) reported basement on the Caroline ridge to be late Oligocene (22.5-30 m.y.). The total length of the Caroline chain is only about 24° (rotation around the "Hawaiian" Euler pole), but part of the western end of the chain may have been consumed in the Mariana and Yap trenches, and the eastern end lacks a modern volcano. Applying the Hawaii rate of rotation to the Carolines, and using the age at the drill sites, the predicted age for Kusaie is in the range 3-12 m.y.

In the Austral Islands, Johnson and Malahoff (1971) reported an active volcano at the southeastern end of the chain at 31°S, 140°W. Using the radiometric dates of Krummenacher and Noetzlin (1966), Johnson and Malahoff deduced an age gradient along the Austral chain of about 9 cm/year. Near the northwest end of the chain, on Mangaia (22°S, 158°W), there are uplifted reefs older than middle Miocene (15 m.y.; Marshall, 1927, p. 33).

In the other chains of the Hawaiian set, only a few radiometric or paleontologic dates are available. Krummenacher and Noetzlin (1966) reported K/A dates between 1 and 4 m.y. in the Society Islands, but no age trend is discernible except on geomorphic grounds. Krummenacher and Noetzlin (1966) and Krummenacher *et al.* (1972) also reported some very old K/A dates—up to 833 m.y.—from xenolith-like rocks and melanocratic differentiates in nepheline syenites and gabbros on Tahiti. All Tahiti samples giving concordant ages are less than 4 m.y. old, except for one sample of less than 11 m.y. and another of less than 30 m.y. All other sample pairs give discordant older ages. Krummenacher *et al.* (1972) explained the old ages by calling on "variable amounts of inherited argon in exotic rocks (probably from the mantle) incorporated into the magma close to its source." I accept this hypothesis, and therefore regard the "true" age of the Tahiti volcanism as being less than about 4 m.y. A radiometric date of about 8 m.y. has been obtained by Krummenacher (personal commun., 1971) from samples of basalt from drillholes on Mururoa atoll, at 22°S, 149°W at the northwest end of the Gambier trend (Deneufbourg, 1969). Several sets of island chains overlap in this area, and much more sampling will be needed before any good age trends can be established. In the northeast Pacific, the active volcano of San Benedicto (20°N, 110°W) lies at the southeast end of an ill-defined chain of seamounts, and fossils from Erben guyot (33°N, 132°W), at the northwest end of another nearby chain (Carsola and Dietz, 1952), suggested an age of early Miocene or older. A radiometric date of about 3 m.y. was reported by Ozima *et al.* (1968) for basalt from a small seamount about 250 km northwest of San Benedicto.

Chains parallel with Line Islands—Age determinations on volcanoes in the older set of seamount chains, parallel with the Line Island chain, are very few. In the Emperor chain, Ozima *et al.* (1970) reported a K/A date of 41 m.y. for altered andesite and basalt dredged from Suiko seamount, at 45°N, but the roundness of the rocks, their composition, and their association with sedimentary rocks suggest ice rafting. At the north end of the chain and slightly west of the main trend is a plateau at a depth of 3,000 m. At JOIDES Site 192, on this plateau, lower Maestrichtian (70 m.y.) calcareous sediments lie depositionally on basalt (Scholl *et al.*, 1971). If we accept the plateau at Site 192 as being a part of the Emperor chain, and if we use the extrapolated age of 25 m.y. for the south end of the chain (Jackson *et al.*, 1972), the rate of formation of the chain is about 5 cm/year, or about 0.5°/m.y. around the "Emperor" Euler pole.

Within the long arc of seamounts (Fig. 11) that sweeps for about 50° from Johnston Island (17° N, 170°W), at the north end of the Line Island chain, through Christmas Island (2°N, 158°W) to the south end of the Tuamotu chain (20°S, 140° W), only two dates are available. At JOIDES Site 165 (8°N, 165°W), only 50 km from a guyot in the Line Island chain, the drill recovered alkaline basalt depositionally overlain by Upper Cretaceous (85 m.y.) volcanic and biogenous turbidites, derived from nearby guyots (Winterer *et al.*, 1971b). Farther south along the trend, on the north slopes of the Tuamotu chain, displaced

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fossils of early Eocene age (about 50 m.y.) are present in a Pliocene turbidite at JOIDES Site 76 (14°N, 146°W) (Hays *et al.*, 1972). From dredge hauls on the west side of the Tuamotus are reported shallow-water Foraminifera of middle Eocene age (43-49 m.y.) from the north end of the chain (14°S, 150°W; Burckle and Saito, 1966), and of late Eocene age (38-43 m.y.) from a site about 500 km farther southeast (17°S, 146°W; Cole, 1959).

At the northernmost end of the chain, at Horizon Guyot (19°N, 169°W), the drill and dredge data suggest an age of at least 110 m.y. for this feature (Winterer *et al.*, 1971b; Lonsdale *et al.*, 1972), but because the guyot lies along the general trend of the Mid-Pacific mountains, which include bathymetric trends both at right angles to and parallel with the Line Island trend, the guyot may not belong to the Line Island sequence. The Mid-Pacific mountains may be entirely older than the Line Island chain and possibly are part of some set of west-trending seamount chains generated around a third, "Mid-Pac" Euler pole, as suggested by Morgan (in press). Rudistid reef faunas of Barremian to Aptian age (110 m.y.) cap many of the guyots in the Mid-Pacific mountains (E. C. Allison, personal commun.).

If we apply the rate of rotation of the plate versus hot spots derived from the Emperor chain (0.5°/m.y.) to the Line Island chain we get mixed results. Using the 85-m.y. date at JOIDES Site 165 as a starting point and moving north, we deduce an age of 110 m.y. for the north end of the chain, an age permitted by the data from Horizon Guyot. South from Site 165, we deduce an age of about 35 m.y. for the north end of the Tuamotus—an age a little too young to account for the Eocene fossils there. If we assume a minimum age of 50 m.y. for the north end of the Tuamotus, the deduced rate of rotation between there and Site 165 is about 0.7°/m.y., and the extrapolated age to the north end of the Line Island chain, close to Horizon Guyot and Johnston Island, becomes about 100 m.y. The extrapolated age to the south end of the Tuamotus at about 20°S., where the chains show a pronounced bend congruent with the bend in the Emperor-Hawaiian chain, is 30 m.y. According to the hypothesis proposed herein, the age should be the same at both bends, or about 25 m.y., using the Hawaiian estimate of Jackson *et al.* (1972). On the other hand, Mururoa atoll, which lies very close to this bend, has a K/A age of only 8 m.y. Manifestly, much more work must be done before we shall have satisfactory control over the rate of rotation around this older Euler pole.

In the Marshall Islands, drillholes at Bikini (12°N, 165°E; Emery *et al.*, 1954) and Eniwetok (12°N, 162°E; Schlanger, 1963) found upper Eocene shallow-water sediments; at Eniwetok, these overlie basalt. The age of the volcano at Eniwetok is thus at least 40 m.y. A K/A age of 59 m.y. has been reported (Kulp, 1963) for the basalt.

Still farther west, among a group of seamounts on the Pacific edge of the Mariana Trench, at JOIDES Site 61 (12°N, 147°E), basalt was drilled below Upper Cretaceous sediments (Winterer *et al.*, 1971a), but this group of seamounts has no obvious trend. The rest of the reported pre-Oligocene dates from the Pacific similarly are all from seamounts in groups without apparent trend (Ozima *et al.*, 1968, 1970; Dymond and Windom, 1968).

To summarize the motion of points on the Pacific plate with respect to hot spots in the asthenosphere beneath, as deduced from trends and age distributions along seamount chains: (1) 0-30 m.y.—Euler pole at 67°N, 45°W, rate, 1.1°/m.y., clockwise; and (2) 30-100 m.y.—Euler pole at 23°N, 108°W, rate, 0.5 to 0.7°/m.y., clockwise.

MOTION OF ASTHENOSPHERE

We are now in a position to compare, at least over the past 30-40 m.y., the motions of the Pacific plate in one frame of reference versus another frame. The types of motion of interest are depicted in a diagrammatic way in Figure 1, and as a set of vector triangles in Figure 2. In the diagram the motion of the asthenosphere with respect to the spin axis has been made uniform over the whole area of the diagram and is unaffected by plate boundaries. If there is indeed motion in the asthenosphere in the real earth, it may well be more complicated than shown in this simple diagram.

ASTHENOSPHERE VERSUS SPIN AXIS

The elements we need to know in order to test for asthenosphere-versus-spin-axis motions are: (1) plate versus asthenosphere; (2) plate versus spin axis. We have an estimate of (1), at least for the past 30 m.y., from the Hawaiian seamount-chain data. For (2), we have only the paleoequators derived from the distribution of equatorial sediments over the past 30 m.y., plus a virtual geomagnetic pole for a time about 100 m.y. ago. The paleoequators give us only the north component of the plate-versus-spin-axis motion with any confidence, and we should, therefore, com-

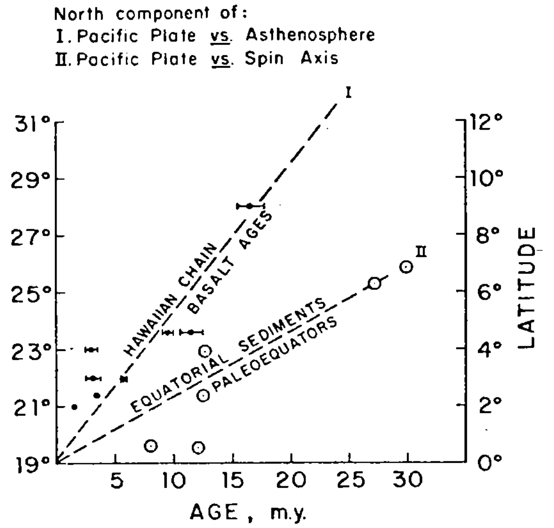

FIG. 12—Age *versus* latitude for: *I*, Hawaiian seamount chain basalts (after McDougall, 1964), and *II*, paleoequators deduced from pelagic biogenous sediment accumulation rates at JOIDES drill sites.

pare this value with the north component of plate-versus-asthenosphere motion.

The result (Fig. 12) is a factor-of-two difference (3 versus 6 cm/year) in the rate of northward motion of the plate, suggesting that the hot spot in the asthenosphere beneath the Hawaiian chain has been moving southward with respect to the earth's spin axis at about the same rate at which the Pacific plate has been moving north. Whether there is also an easterly component in the motion of the hot spot cannot be detected by this method.

Models

Another approach is to look more closely at the consequences, in terms of the detailed shape of the equatorial sediment mass, of contrasting models of asthenosphere-versus-spin-axis motion, for example: (1) no motion; or (2) a motion with a north component equal and opposite to the north component of the Pacific-plate-versus-spin-axis motion, as implied by the discrepancy in the slope of the lines shown in Figure 12. To test these possibilities, we have the actual shape of the "acoustically transparent" sediment layer (Ewing *et al.*, 1968) in the equatorial Pacific (Fig. 9), which has been confirmed and refined by the results of JOIDES drilling.

Accumulation rate model—First we need a model for accumulation rates along the equatorial belt of high productivity, but because the East Pacific Rise crosses the equator—and has done so for at least the past 40 m.y. (Fig. 5)—we need to include the effects of depth in the rate-of-accumulation model. Points on the rise crest move into deeper water as they move away from the spreading center. The model adopted (Fig. 13) uses the half-spreading rate of 10 cm/year derived from drilling data (Fig. 4), and the empirical curve of Sclater *et al.* (1971) for crustal age versus depth (Fig. 2). The accumulation rates in the model are derived from averaging data from many JOIDES drill sites and from piston and gravity cores at various depths in the equatorial Pacific. While recognizing that many other models are possible, I believe this one to be representative of Neogene pelagic rates. The 2 m/m.y. rate is typical for brown clays, and 5 m/m.y. is typical for siliceous oozes near the equator in water depths greater than the compensation depth for calcium carbonate. The change from 5 to 10 m/m.y. at a water depth of 4,500 m corresponds to the change from siliceous to calcareous sediments at the calcium carbonate compensation depth. In the model this depth will be held fixed, as will the other depth-controlled changes

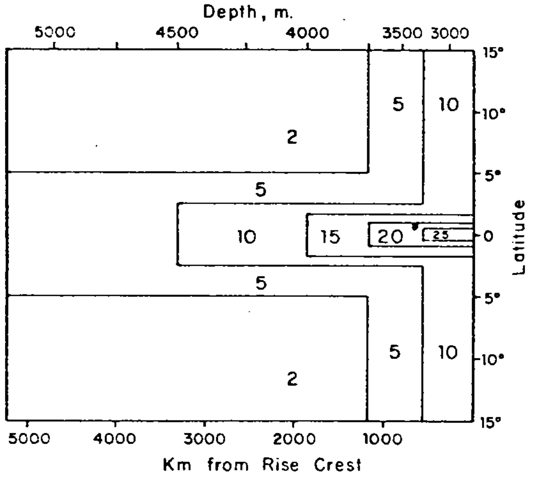

FIG. 13—Model rate of pelagic sediment accumulation (in meters/million years) near equator on west slope of East Pacific Rise. The east-west scales are for a 10 cm/yr half-spreading rate.

in accumulation rates, together with the width of the belt of high productivity and the rate of shell production in the surface layers. All these quantities are subject to change and doubtless they have changed over the past 40 m.y. (Heath, 1969; Berger, in press), but the changes are not considered to have been so drastic in this region as to effect the gross differences in accumulation rates between the equator and regions 5 or 10° away. We are dealing with a tripling of rates along the model equator.

If we were to allow the model (Fig. 13) to run for 10 m.y. while spreading proceeded from the rise crest at 10 cm/year (half rate) in a due west direction, with no other plate motions, the result would be the creation of an asymmetric lens of sediment with its thickest part (250 m) located 1,000 km west of the rise crest (Fig. 14).

Motion models—The next step is to apply the accumulation-rate model to the two contrasting plate-motion models. If the asthenosphere has been stationary, then we can generate, from the seamount trend and age data, a set of theoretical paleoequators (Fig. 15), using the Euler poles and rates of rotation previously specified. The paleoequators must be fitted on the map of crustal ages (Fig. 5); the eastern end of each paleoequator trace is its intersection with the corresponding crustal-age isochron. The result of applying the accumulation-rate model to this set of paleoequators for the period 0-40 m.y. is shown in Figure 16. The lens of sediment slants away from the present rise crest and reaches maximum thickness of about 400 m at about 10°N, 140°W. Although it bears a gross resemblance to the "real" isopach map (Fig. 8), this model has its locus of thickest sediments too far north of the equator by a factor of two.

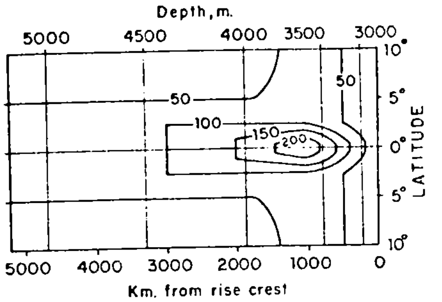

FIG. 14—Isopachs of sediment accumulated during 10 m.y., using model rates of Figure 13. A 10 cm/yr half-spreading rate is used.

In the other motion model, the hot spots in the asthenosphere are moving southward with respect to the earth's spin axis with a velocity exactly opposite to the north component of the velocity of the plate. In terms of the Hawaiian

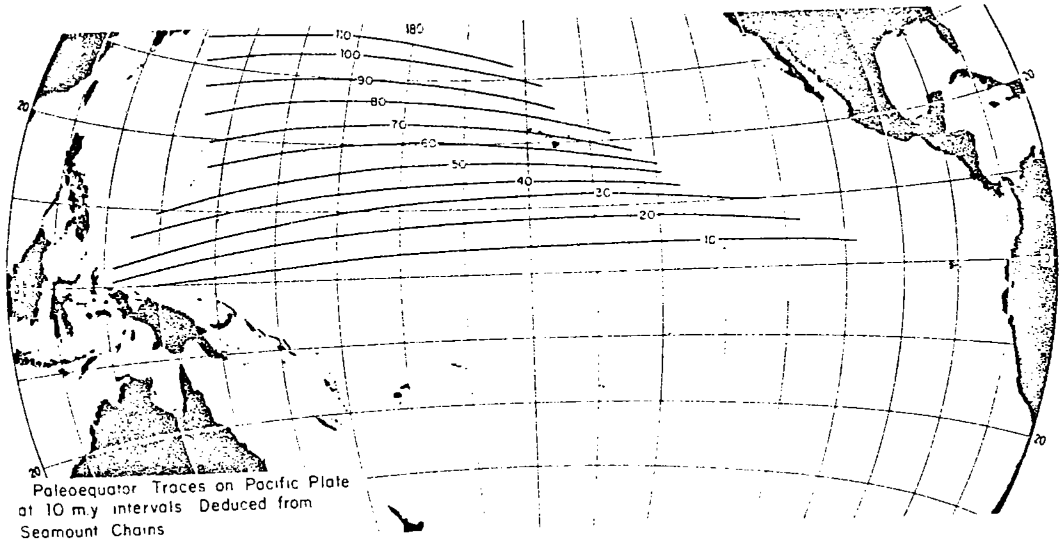

FIG. 15—Paleoequator traces on Pacific plate, deduced from seamount chains.

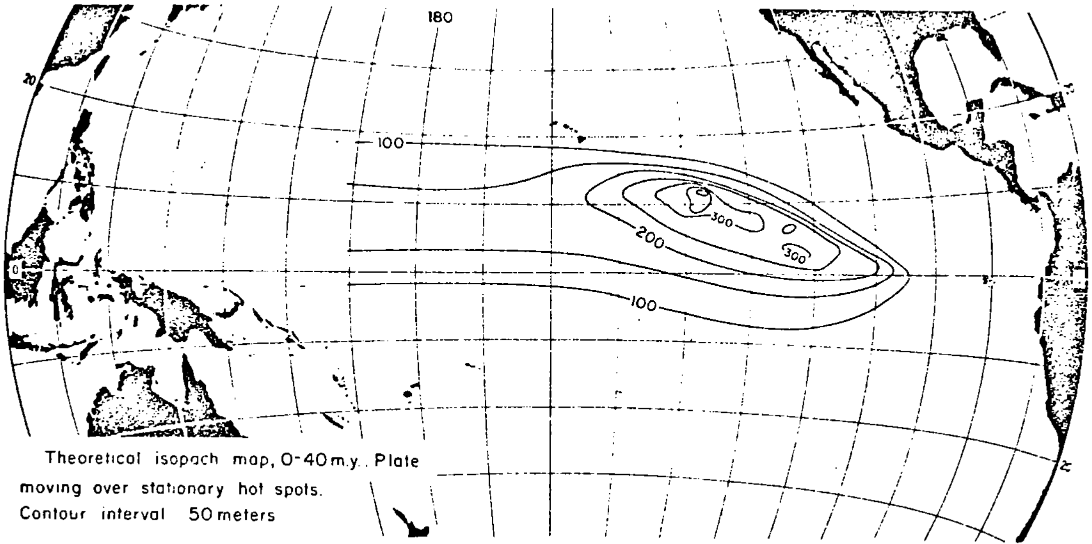

FIG. 16—Theoretical isopach map of pelagic equatorial sediments deposited over past 40 m.y. Plate moving over stationary hot spots.

chain, this would make it appear that the Hawaiian hot spot has been moving southeast along the trend of the chain at 7 cm/year while the Pacific plate has been moving northwest at the same rate. The resulting isopach map is shown in Figure 17. In this map the locus of thickest sediments is still a bit too far north, but only by about 2°. The fit to the isopachs of Figure 8 is substantially improved, and suggests that we may be on the right track. The differences between model and "reality" are of an order that might be accounted for by relaxing the restrictions on the calcium-carbonate compensation depth. The evidence from the drilled transect across the equator at 140°W (Tracey *et al.*, 1971; van Andel *et al.*, 1971) supports Heath's (1969) suggestion that the compensation depth may have lain somewhat deeper in the Oligocene than in the Eocene or later Miocene. A wider belt of high biological productivity and relatively higher rates of accumulation of calcareous sediments during the late Oligocene and early Miocene, when the paleoequator (at 140°W) was at about 5° north, would result in a slight southward shift in the locus of thickest sediments in the model.

SUMMARY AND DISCUSSION

Comparison over the past 30 m.y. of the northward component of motion of the Pacific plate with respect to earth's spin axis, as measured by the northward shift of equatorial pelagic sediments, with the northward component of motion of the plate with respect to hot spots in the asthenosphere beneath the plate, as measured by the northward increase of age of volcanoes in the Hawaiian seamount chain, suggests that the hot spots, while remaining fixed in relation to one another, are moving southward at a rate about equal to the northward motion of the plate with respect to the earth's spin axis.

What the motion history has been for times previous to 30 m.y. ago is quite uncertain. The Line Island set of seamount chains gives us a direction of motion for plate versus hot spots, but not a reliable rate. The Japanese seamount paleomagnetic pole—probably about 110 m.y. old—gives us a point to steer toward in constructing a polar-wandering curve, *i.e.*, a plate-versus-spin-axis path. The two model polar-wandering curves (1) plate versus stationary hot spot, with 0.5°/m.y. around the older Euler pole, and (2) plate versus spin axis, are shown in Figure 18, where it can be seen that the hot-spots-versus-spin-axis motion should be measured by any difference between the two curves. Measured at a time 30 m.y. ago, the difference is half the length of the Hawaiian segment of the curve. From this point.

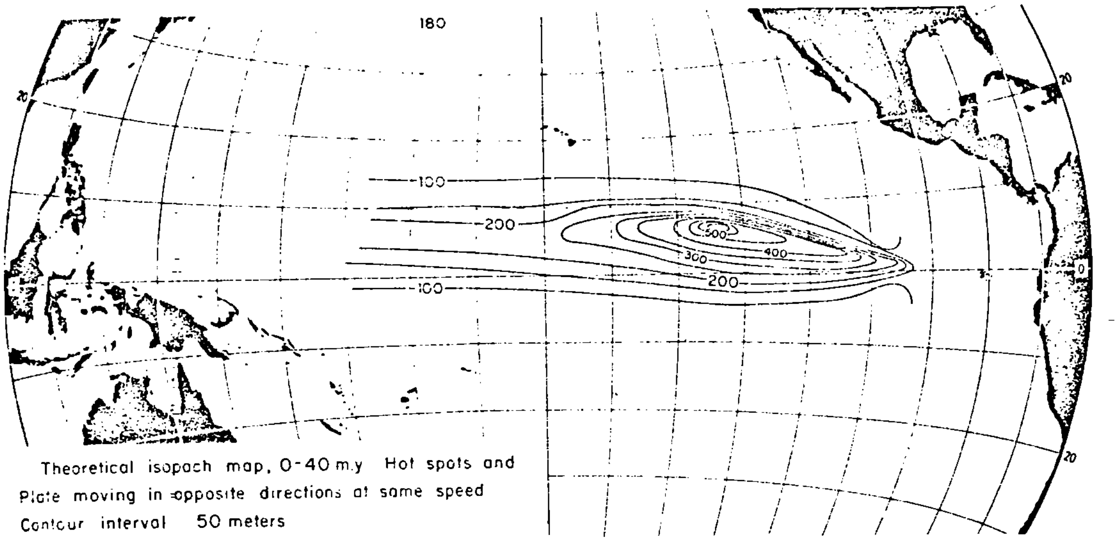

FIG. 17—Theoretical isopach map of pelagic equatorial sediments deposited over past 40 m.y. Plate and hot spots moving in opposite directions at same speed.

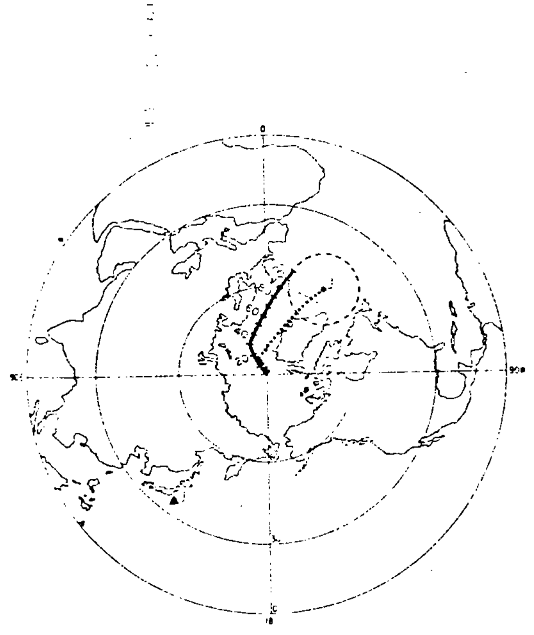

FIG. 18—Polar wandering curves for Pacific plate. Solid line: plate *versus* stationary hot spot; dotted line: plate *versus* spin axis; *J*: paleomagnetic pole for Japanese seamounts with confidence limits (Francheteau *et al.*, 1970). Figures are millions of years.

deciding whether the two paths are parallel and of the same length is beyond the limits of the data at hand, but the curves point up what needs to be done to solve the problem. First, dates are needed along the hot-spot curve, and next, paleomagnetic data (preferably from oriented cores of dated sediments) are required to bring more control to the spin-axis curve.

The possibility that at least the upper parts of the asthenosphere may be in motion and moving *toward* an active spreading center in the southeast Pacific raises many questions. Is the phenomenon confined to the Pacific plate? If not, is there a single worldwide flow pattern in the asthenosphere, or is there a different flow-direction beneath each plate? Is the movement related to upwelling of new crustal material at a spreading center? What happens when a hot spot reaches the rise crest, in terms of spreading rates, and mode of formation and petrology of new crust and volcanoes? And finally, what gives rise to and sustains motions in the mantle?

REFERENCES CITED

Atwater, T., and H. W. Menard, 1970, Magnetic lineations in the northeast Pacific: Earth and Planetary Sci. Letters, v. 7, p. 445-450.

Berger, W. H., in press, Deep-sea carbonates: solution facies and age-depth constancy: Nature.

Burckle, L. H., and T. Saito, 1966, An Eocene dredge haul from the Tuamotu ridge: Deep-Sea Research, v. 13, p. 1207-1208.

Carsola, A. J., and R. S. Dietz, 1952, Submarine geology of two flat-topped northeast Pacific seamounts: Am. Jour. Sci., v. 250, p. 481-497.

Chubb, L. J., 1927, The geology of the Austral or Tubuai Islands: Geol. Soc. London Quart. Jour., v. 8, p. 291-316.

——— 1957, The pattern of some Pacific island chains: Geol. Mag., v. 94, p. 22-228.

Cole, W. S., 1959, *Asterocyclina* from a Pacific seamount: Cushman Found. Foram. Research Contr., v. 10, p. 10-14.

——— 1960, Problems of the geographic and stratigraphic distribution of certain Tertiary larger Foraminifera: Tuhoku Univ. Sci. Repts., ser. 2 (Geol.). Spec. V., no. 4, p. 9-18.

Dana, J. D., 1849, Geology, v. 10 *in* U.S. exploring expedition, during the years 1838, 1839, 1840, 1841, 1842, under the command of Charles Wilkes, U.S.N.: Philadelphia, 756 p.

——— 1890, Characteristics of volcanoes: New York, Dodd, Mead, 399 p.

Deneufbourg, G., 1969, Les forages de Mururoa: Cahiers Pacifique, v. 13, p. 47-58.

Dymond, J., and H. L. Windom, 1968, Cretaceous K-Ar ages from Pacific ocean seamounts: Earth and Planetary Sci. Letters, v. 4, p. 47-52.

Emery, K. O., J. I. Tracey, Jr., and H. S. Ladd, 1954, Geology of Bikini and nearby atolls: U.S. Geol. Survey Prof. Paper 260-A, p. 1-265.

Erickson, B. H., F. P. Naugler, and W. H. Lucas, 1970, Emperor fracture zone: a newly discovered feature in the central north Pacific: Nature, v. 225, p. 53-54.

Ewing, J., M. Ewing, T. Aitken, and W. J. Ludwig, 1968, North Pacific sediment layers measured by seismic profiling, *in* The crust and upper mantle of the Pacific area: Am. Geophys. Union Geophys. Mon. 12, p. 147-173.

Fischer, A. G., *et al.*, 1971, Initial reports of the Deep Sea Drilling Project, v. 6: Washington, U.S. Govt. Print. Off., 1329 p.

Francheteau, J., C. G. A. Harrison, J. G. Sclater, and M. L. Richards, 1970, Magnetization of Pacific seamounts: a preliminary polar curve for the northeastern Pacific: Jour. Geophys. Research, v. 75, p. 2035-2061.

Hayes, D. E., and W. C. Pitman, III, 1970, Magnetic lineations in the north Pacific, *in* J. D. Hayes, ed., Geological investigations of the north Pacific: Geol. Soc. America Mem. 126, p. 291-314.

Hays, J. D., *et al.*, 1972, Initial reports of the Deep Sea Drilling Project, v. 9: Washington, U.S. Govt. Print. Off., 1205 p.

Heath, G. R., 1969, Carbonate sedimentation in the abyssal equatorial Pacific during the past 50 million years: Geol. Soc. America Bull., v. 80, p. 689-694.

——— and R. Moberly, Jr., 1971, Noncalcareous pelagic sediments from the western Pacific, *in* E. L. Winterer, *et al.*, Initial reports of the deep-sea drilling project, v. 7: Washington, U.S. Govt. Printing Office, p. 987-990.

Herron, E. M., 1971, Crustal plates and sea-floor spreading in the southeastern Pacific, *in* Antarctic oceanology, I: Am. Geophys. Union, Antarctic Research Ser., v. 15, p. 229-237.

Jackson, E. D., E. A. Silver, and G. B. Dalrymple, 1972, The Hawaiian-Emperor chain and its relation to Cenozoic circumpacific tectonics: Geol. Soc. America Bull., v. 83, p. 601-618.

Johnson, R. H., and A. Malahoff, 1971, Relation of MacDonald volcano to migration of volcanism along the chain: Jour. Geophys. Research, v. 76, p. 3282-3290.

Krummenacher, D., and J. Noetzlin, 1966, Ages isotopiques K/A de roches prélevées dans les possessions françaises du Pacifique: Soc. Géol. France Bull., ser. 7, v. 8, p. 173-175.

——— D. H. Dowd, V. F. Duda, W. B. Cunningham, F. L. Kingery, and W. F. Speidel, 1972, Potassium-argon ages from xenoliths and differentiates in coarse-grained rocks from the center of the island of Tahiti (French Polynesia): Geol. Soc. America Abs. with Programs, v. 4, no. 3, p. 186.

Kulp, J. L., 1963, Potassium-argon dating of volcanic rocks: Bull. Volcanol., v. 26, p. 247-258.

Lonsdale, P., W. R. Normark, and W. A. Newman, 1972, Sedimentation and erosion on Horizon Guyot: Geol. Soc. America Bull., v. 83, p. 289-316.

Marshall, P., 1927, Geology of Mangaia: Bernice P. Bishop Mus. Bull., v. 36, p. 1-48.

McDougall, I., 1964, Potassium-argon ages from lavas of the Hawaiian Islands: Geol. Soc. America Bull., v. 75, p. 107-128.

McManus, D. A., *et al.*, 1970, Initial reports of the Deep Sea Drilling Project, v. 5: Washington, U.S. Govt. Printing Office, 827 p.

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

——— in press, Plate motions and deep mantle convection: Geol. Soc. America Hess Mem. Vol.

Ozima, M., I. Kaneoka, and S. Aramaki, 1970, K-Ar ages of submarine basalts dredged from seamounts in the western Pacific area and discussion of oceanic crust: Earth and Planetary Sci. Letters, v. 8, p. 237-249.

——— M. Ozima, and I. Kaneoka, 1968, Potassium-argon ages and magnetic properties of some dredged submarine basalts and their geophysical implications: Jour. Geophys. Research, v. 73, p. 711-723.

Page, R. W., and I. McDougall, 1970, Potassium-argon dating of the Tertiary f_{1-2} stage in New Guinea and its bearing on the geological time scale: Am. Jour. Sci., v. 269, p. 321-342.

Pitman, W. C., III, E. M. Herron, and J. R. Heirtzler, 1968, Magnetic anomalies in the Pacific and sea-floor spreading: Jour. Geophys. Research, v. 73, p. 2069-2085.

Schlanger, S. O., 1963, Subsurface geology of Eniwetok atoll: U.S. Geol. Survey Prof. Paper 260-BB, p. 991-1065.

Scholl, D. W., J. S. Creager, *et al.*, 1971, Deep Sea Drilling Project, Leg 19: Geotimes, v. 16, no. 11, p. 12-15.

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

——— and R. D. Jarrard, 1971, Preliminary paleomagnetic results, leg 7, *in* E. L. Winterer, *et al.*, 1971, Initial reports of the deep-sea drilling project, v. VII: Washington, U.S. Govt. Printing Office, p. 1227-1234.

Stark, J. T., J. E. Paseur, R. L. Hay, H. G. May, and E. D. Patterson, 1958, Military geology of Truk Islands, Caroline Islands: U.S. Army, Chief of Engineers, Intelligence Div., Headquarters U.S. Army Pacific, 205 p.

Tracey, J. I., Jr., *et al.*, 1971, Initial reports of the Deep Sea Drilling Project, v. 8: Washington, U.S. Govt. Printing Office, 1037 p.

van Andel, T. H., G. R. Heath, *et al.*, 1971, Deep Sea Drilling Project, leg 16: Geotimes, v. 16, no. 6, p. 12-14.

von Huene, R., L. D. Kulm, *et al.*, 1971, Deep Sea Drilling Project, leg 18: Geotimes, v. 16, no. 10, p. 12-15.

Wilson, J. T., 1963a, Evidence from islands on the spreading of ocean floors: Nature, v. 197, p. 536-538.

——— 1963b, A possible origin of the Hawaiian Islands: Canadian Jour. Physics, v. 41, p. 863-870.

Winterer, E. L., J. Ewing, *et al.*, 1971a, Deep Sea Drilling Project, leg 17: Geotimes, v. 16, no. 9, p. 12-14.

——— *et al.*, 1971b, Initial reports of the Deep Sea Drilling Project, v. 7: Washington, U.S. Govt. Printing Office, 1754 p.

——— *et al.*, 1971c, Site 66, *in* E. L. Winterer *et al.*, Initial reports of the Deep Sea Drilling Project, v. 7: Washington, U.S. Govt. Printing Office, p. 725-819.