in the eastern Pacific has furnished strong evidence in support of the hypothesis of the spreading of the ocean floor. Many additional cores are needed from this area, however, to determine whether the spreading movement has been continuous or intermittent (7).

LLOYD H. BURCKLE
JOHN EWING
TSUNEMASA SAITO
ROBERT LEYDEN

*Lamont Geological Observatory, Columbia University, Palisades, New York*

#### References and Notes

1. W. Pitman III and J. R. Heirtzler, *Science* **154**, 1164 (1966).
2. F. Vine, *ibid.*, p. 1405.
3. R. S. Dietz, *Nature* **190**, 854 (1961).
4. H. H. Hess, in *Petrologic Studies: A Volume in Honor of A. F. Buddington* (Geological Society of America, New York, 1962), p. 260.
5. We define the limits of the East Pacific Rise after H. W. Menard [*Science* **155**, 72 (1967)].
6. Our Lower Miocene includes Zone N2 to N8; Middle Miocene, N9 to lower half of N15; and Upper Miocene, from upper half of N15 to N18 of Banner and Blow [*Nature* **208**, 1164 (1965)].
7. J. Ewing and M. Ewing [*Science* **156**, 1590 (1967)] observed an abrupt change in sediment thickness between the crest and flanks of the mid-ocean ridge system. They consider this as evidence of a major discontinuity either in the rate of spreading of the sea floor or in the rate of accumulation of sediment. Based on the spreading rate determined by the magnetic anomaly pattern they postulate that the present cycle of spreading of the sea floor began about 10 million years ago.
8. Paleomagnetic determinations were made by N. Opdyke.
9. W. R. Riedel and B. M. Funnell, *Quart. J. Geol. Soc. London* **120**, 362 (1964); L. H. Burckle and T. Saito, *Deep-Sea Res.* **13**, 1207 (1966); T. Saito, J. D. Hays, L. H. Burckle, in *Proc. Pacific Sci. Congr. 11th Tokyo* (1966), p. 39.
10. B. C. Heezen, B. Glass, H. W. Menard, *Deep-Sea Res.* **13**, 453 (1966).
11. E. L. Hamilton, *Geol. Soc. Amer. Mem. No. 64* (1956), p. 22.
12. M. Ewing, T. Saito, J. Ewing, L. H. Burckle, *Science* **152**, 751 (1966).
13. "Geological society phanerozoic time scale 1964," *Quart. J. Geol. Soc. London* **120**, suppl., 260 (1964).
14. Age determination of the basement rocks on the basis of the magnetic pattern was made by W. Pitman III.
15. W. H. Blow, *Micropaleontology* **2**, 57, (1956); O. L. Bandy, *ibid.* **10**, 11 (1964).
16. F. T. Banner and W. H. Blow, *Nature* **208**, 1164 (1965).
17. Recently, Budinger and Enbysk [*J. Geophys. Res.* **72**, 2271 (1967)] reported the occurence of a basalt boulder from a seamount near the crest of the northern extension of the East Pacific Rise which dated at $27 \pm 6$ million years. Although this occurrence is in direct conflict with spreading rates based upon magnetic anomaly patterns (2), it might be explained by assuming that the addition of new crust occurred in such a way that patches of older crust were left behind in the crestal area rather than being swept away from the axis [T. Saito, M. Ewing, L. H. Burckle, *Science* **151**, 1075 (1966)].
18. We thank J. R. Heirtzler, X. LePichon, W. Pitman III, and W. R. Riedel for review and discussion of the manuscript. Supported by NSF grant GA 558 and Nonr 266(48). Lamont Geological Observatory contribution No. 1080.

11 May 1967

## Radiolarian Evidence Consistent with Spreading of the Pacific Floor

Abstract. *In sediments west of the East Pacific Rise between the equator and 20°N, Eocene microfossils are recorded no farther east than 134°W; Oligocene, no farther east than 125°W; while Miocene and Pliocene occurrences extend closer to the crest of the rise. This distribution may result from post-Eocene spreading of the sea floor here averaging about 8 centimeters per year.*

It is an inevitable consequence of the hypothesized spreading of the sea floor (*1*) that the sediment immediately above the igneous basement should be progressively younger toward the crest of the ridge at which the spreading originates. Burckle *et al.* (*2*) have indicated that the ages of the oldest cores (Pliocene and Miocene) that they have obtained in the eastern South Pacific increase with increasing distance from the crest of the East Pacific Rise. Evidence extending this type of observation as far back in time as Eocene has now been culled from the numerous cores collected (*3*) in the area bounded by latitude 0° and 20°N and longitudes 115° and 150°W (Fig. 1).

At some of the sampling localities in this region, Tertiary sediments outcrop on the sea floor or are disconformably overlaid by a layer of Quaternary sediment thin enough to be penetrated by commonly used corers capable of penetrating 1.5 to 10 m. Comparison of the distribution of these *in situ* samples representing the various Tertiary epochs (Fig. 2) reveals that some Oligocene occurrences are farther east than the easternmost Eocene occurrence, and that some Miocene occurrences are farther east than the easternmost Oligocene occurrence, as would be expected in accordance with the hypothesized spreading of the sea floor and if the techniques now in use sampled the oldest sediments occurring in an area.

This latter condition is unlikely to be fulfilled, but some information on the nature of generally deeply buried sediments can be obtained by investigation of older microfossils reworked into younger sediments. Over a large proportion of the sea floor in the area under consideration the sediments deposited throughout the Cenozoic contain radiolarians, and at many localities microfossils as old as Eocene are reworked into Quaternary sediments (*4*). These siliceous microfossils are especially useful as tracers of the presence of Tertiary sediments, since they do not dissolve as readily as calcareous skeletons and therefore can probably survive several cycles of erosion and redeposition. At least over the area of the Pacific floor that is now considered, the discrete pattern of microfossil assemblages, and the fact that some Quaternary sediments scattered throughout the area do not contain reworked Tertiary microfossils, indicate that sediment components are not transported great lateral distances by reworking processes; therefore the occurrence of Oligocene radiolarians in a Quaternary sediment, for example, may be taken as evidence of the occurrence of Oligocene sediments in that vicinity. The information available from such reworked microfossils

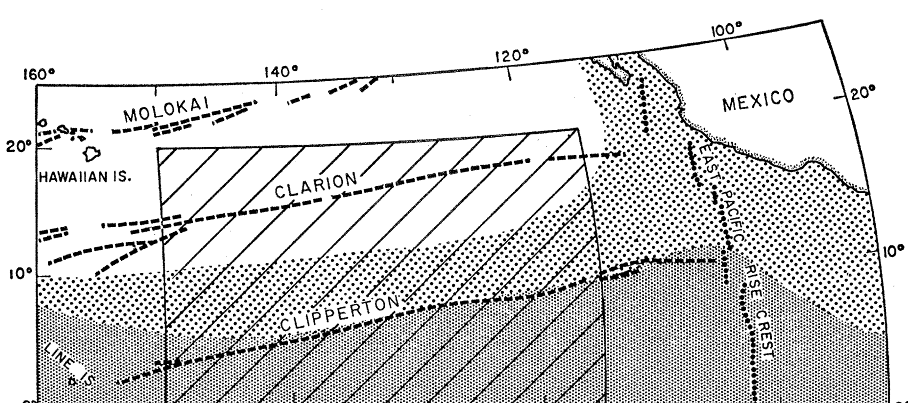


Fig. 1. The area investigated (hatched); equal-area projection. Positions of East Pacific Rise (dotted line) and fracture zones (broken lines) after Menard (*11*). General distribution of Quaternary types of sediment indicated by finer stippling (calcareous-siliceous ooze), coarser stippling (siliceous ooze and highly radiolarian clay), and no stippling (clay with few or no microfossils). Latitude, N; longitude, W.

thus provides a voluminous supplement to the relatively few samples of *in situ* Tertiary sediments.

In a compilation of data on reworked microfossils published in 1963 (*5*), mid-Tertiary occurrences were found to extend much farther east than the easternmost early-Tertiary occurrences between the equator and 20°N in the Pacific. However, in a later paper (*4*) this relation was not evident because that investigation was restricted to cores sampling *in situ* Tertiary sediments and Quaternary samples containing a high proportion of Tertiary admixture. I have examined microfossils from all available samples from the area bounded by the equator, 20°N, the crest of the East Pacific Rise, and 150°W and have plotted occurrences of Tertiary radiolarians (Fig. 2). The occurrences of reworked microfossils extend somewhat the areas in which sediments of the various Tertiary epochs are known to occur on the basis of *in situ* samples.

Figure 2 shows that in the samples I have studied the easternmost occurrence of Eocene microfossils is at 134°W; of Oligocene microfossils, at 125°W; while Miocene and probable Pliocene microfossils extend farther eastward. Also consistent with this west-east succession is the fact that the eastern occurrences of Oligocene are late Oligocene, and the eastern occurrences of Miocene are late and perhaps middle Miocene. This geographical pattern (apart from the approximate coincidence of the Miocene and Pliocene limits, which may be due to sampling deficiencies) would be expected on the basis of the hypothesis of spreading of the sea floor, if the occurrences of *in situ* and reworked microfossils are assumed to reflect the entire sediment column in any area. This assumption is perhaps tenable, since seismic-reflection records indicate that the sediments are generally less than 500 m thick in this area (*6*), and the topographic relief (abyssal hills commonly about 300 m high) may assist exposure of the oldest sediments at some localities.

In evaluating the micropaleontological data one must take into account the possibility that blocks of the sea floor may have been displaced laterally, relative to one another, along major fracture zones (*7*). If relative movement occurred during the Cenozoic along the Clarion and Clipperton fracture zones, it may not be meaningful to compare Miocene and Pliocene occurrences, north and south of the area bounded by these two fracture zones, with the Eocene and Oligocene occurrences between them. The Eocene and Oligocene occurrences between the fracture zones should not be affected by such movements, and in fact they show the relations expected on the basis of the hypothesized spreading of the sea floor.

An eastward thickening of the Cenozoic sediment column, in the area under consideration, would probably produce a pattern of Tertiary microfossil occurrences similar to that observed here and render this evidence inapplicable to the problem of sea-floor spreading. In this region, variations in the rate of accumulation of sediment depend principally upon the rate at which biogenous skeletal material is deposited. Siliceous oozes probably accumulate about five

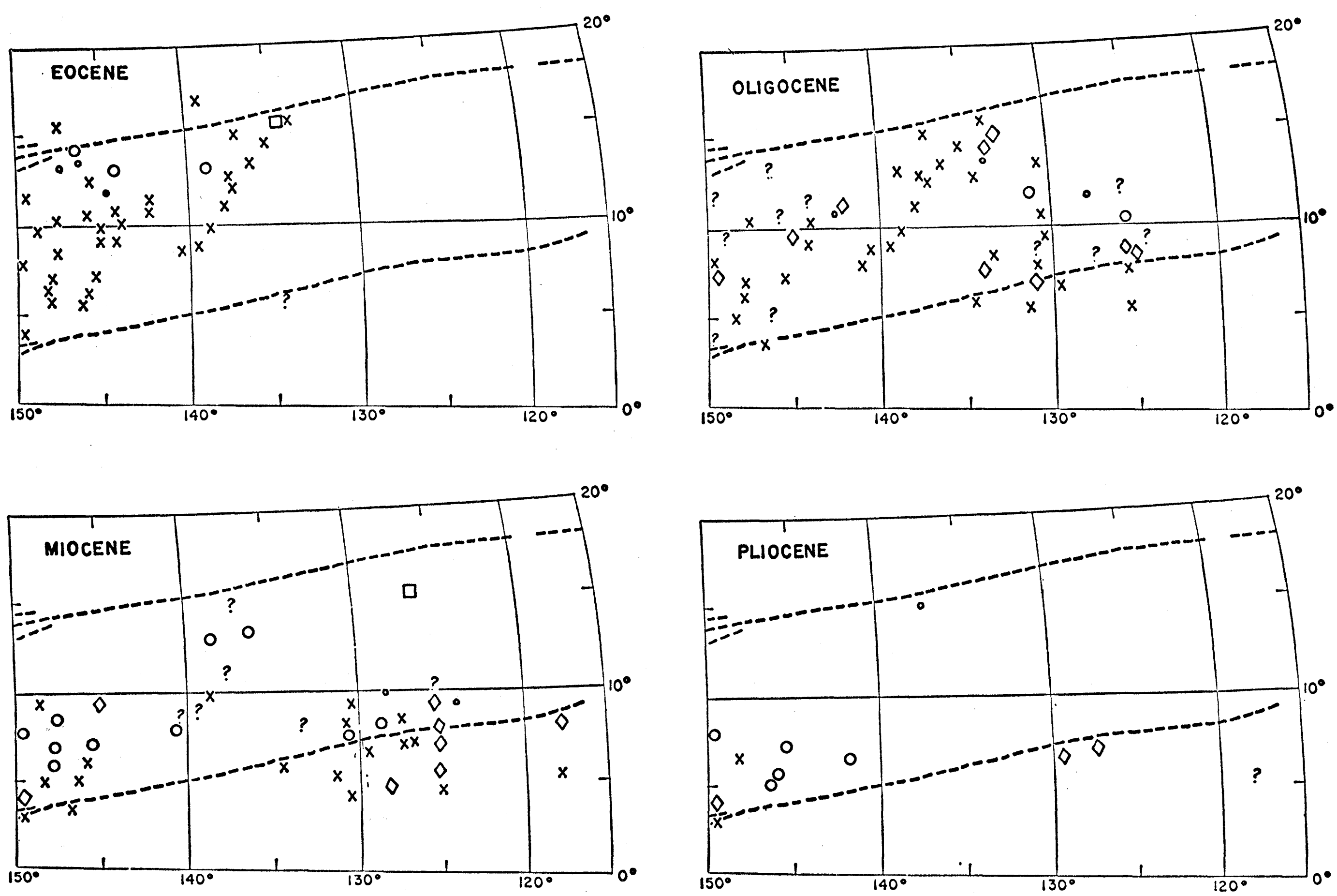


Fig. 2. Occurrences of *in situ* Tertiary sediments (diamonds, squares, and circles) and reworked Tertiary radiolarians (*X* and *?*). Diamonds represent calcareous-siliceous ooze; squares, calcareous ooze lacking siliceous microfossils; circles, siliceous ooze and radiolarian clay. Unquestioned occurrences of reworked radiolarians are indicated by *X*; doubtful occurrences, by *?*. Where microfossil occurrences are excessively crowded, some repetitious symbols are omitted. Broken lines represent the Clarion and Clipperton fracture zones. Latitude, N; longitude, W.

times as rapidly as do clays not bearing fossils, and calcareous-siliceous oozes probably accumulate about five times as rapidly as siliceous oozes. If mid- and late-Cenozoic sediments became progressively more calcareous, or even more siliceous, eastward, the older sediments might be so deeply buried as to be beyond the reach of erosional processes (as is apparently the case at the equator).

The information that is available on the nature of Tertiary sediments of various ages (Fig. 2) is insufficient to provide a conclusive answer to this question, but these data give no reason to suspect a pronounced thickening of the sediment column eastward. And even in the vicinity of 5° to 10°N, 145° to 150°W, where all post-Eocene sediments are apparently siliceous and calcareous-siliceous oozes, the resulting sediment column is not sufficiently thick to prevent the occurrence of Eocene microfossils at the sediment surface.

These considerations seem to justify interpretation of the micropaleontological evidence in relation to the hypothesis of spreading of the sea floor. If the easternmost observed occurrence of Eocene microfossils is taken to represent the part of the sea floor formed at the crest of the East Pacific Rise at the end of the Eocene, an average rate of spreading (from the ridge crest at about 105°W) of approximately 8 cm/year is indicated between the Eocene and Recent time—about twice the spreading rate calculated for the late Cenozoic far to the south on this rise (see *8*).

Rates for Oligocene and Miocene spreading also may be deduced from the evidence presented, but the data may be less satisfactory—partly because uncertainties in long-range correlation of the Oligocene-Miocene boundary (*9*) affect the necessary time-distance calculation, and partly because sampling localities are sparse east of 125°W.

Possible stumbling blocks to explanation of this micropaleontological evidence in terms of spreading of the sea floor are the occurrences of calcareous oozes lacking siliceous microfossils at 15°54′N, 133°57′W (late Eocene) and 15°34′N, 127°11′W (early Miocene) (*10*). These occurrences are readily explicable if their localities of deposition are assumed to be within the area covered by the Tertiary equivalent of the North Pacific Central Water, which is now underlaid by sediments containing little or no biogenous silica (*4*). However, the crest of the East Pacific Rise in these latitudes was probably within an area in which the accumulating sediments contained siliceous microfossils throughout the Tertiary; therefore the only explanation (consistent with spreading of the sea floor) of the absence of siliceous microfossils from these two calcareous oozes is that they were deposited well west of the crest of the rise, where sediments might be expected to contain few or no siliceous microfossils. Sediments deposited farther east during the portions of the Eocene and Miocene that are represented by these two cores presumably contain siliceous microfossils.

In other parts of the Pacific, available samples bearing Tertiary microfossils are still too few for attempts to relate them to spreading of the sea floor. Occurrences between 0° and 10°S in the eastern Pacific are sparse but not inconsistent with the pattern in the northern latitudes that I have considered.

W. R. RIEDEL

*Scripps Institution of Oceanography, University of California at San Diego, La Jolla 92037*

**References and Notes**

1. R. S. Dietz, *Nature* **190**, 854 (1961); H. H. Hess, in *Petrologic Studies: A Volume to Honor A. F. Buddington* (Geological Society of America New York, 1962), pp. 599–620.
2. L. H. Burckle *et al.*, *Geol. Soc. Amer. Ann. Meeting Program 1966*, p. 30.
3. Mostly by expeditions from Scripps Institution of Oceanography; some by the *Carnegie* and the Swedish Deep-Sea Expedition.
4. W. R. Riedel and B. M. Funnel, *Quart. J. Geol. Soc. London* **120**, 305 (1964).
5. W. R. Riedel, in *The Sea*, M. N. Hill, Ed. (Interscience, New York and London, 1963), vol. 3, pp. 866–87.
6. G. G. Shor, Jr., *Deep-Sea Res.* **5**, 283 (1959). J. Ewing (personal communication) believes it to be less than 100 m.
7. H. W. Menard, *Marine Geology of the Pacific* (McGraw-Hill, New York, 1964), pp. 46–9.
8. F. J. Vine, *Science* **154**, 1405 (1966).
9. I use Oligocene to include zones P. 17 to lower N. 4; Miocene, zones upper N. 4 to lowest N. 18; and Pliocene, most of Zone N. 18 to N. 21 of F. T. Banner and W. H. Blow, *Nature* **208**, 1164 (1965). This calibration was made possible by the generous cooperation of W. H. Blow. Thus I place the Oligocene-Miocene boundary near the base of the *Globorotalia kugleri* zone of H. M. Bolli, *U.S. Nat. Museum Bull.* **215**, 97 (1957).
10. Determinations of age, on the basis of calcareous nannoplankton, by M. N. Bramlette.
11. H. W. Menard, *Science* **155**, 72 (1967).
12. I thank H. W. Menard for stimulating discussions. Kathleen McCauley helped to organize the data, and J. R. Moriarty and Heidi Häusermann prepared the figures. Sampling was supported by NSF (grants GP-1235 and G-19239) and ONR (contract Nonr 2216-01), and this investigation was aided by NSF grant GA-658. Contribution from the Scripps Institution of Oceanography, University of California at San Diego.

17 April 1967

## Holocene Changes in Sea Level: Evidence in Micronesia

Abstract. *Investigation of 33 islands, scattered widely across the Caroline and Marshall Island groups in the Central Pacific revealed no emerged reefs in which corals had unquestionably formed* in situ, *or other direct evidence of postglacial high stands of sea level. Low unconsolidated rock terraces and ridges of reef-flat islands, mostly lying between tide levels, were composed of rubble conglomerates; carbon-14 dating of 11 samples from the conglomerates so far may suggest a former slightly higher sea level (nine samples range between 1890 and 3450 and one approaches 4500 years ago). However, recent hurricanes have produced ridges of comparable height and material, and in the same areas relics from World War II have been found cemented in place. Thus these datings do not in themselves necessarily indicate formerly higher sea levels. Rubble tracts are produced by storms under present conditions without any change in datum, and there seems to be no compelling evidence that they were not so developed during various periods in the past.*

Daly's (*1*) time-honored hypothesis of a postglacial stand of sea level higher than that of the present has had little support from many recent investigations made along many of the supposedly relatively stable coasts of the world (*2*). Most of these painstaking studies show the sea rising rapidly until 6000 or 7000 years ago, then rising at a decreasing rate, and possibly reaching a relatively steady state during the last 2 or 3 millennia. However, evidence of recent stands of the sea higher than today's has been reported from the Mediterranean Sea and South America (*3*), and many scientists have reported evidence of postglacial stands as much as 3 m higher than today's (*4*) in the Pacific islands. The best way to test the two hypotheses for a portion of the Pacific area seemed to be for advocates of both ideas to make a joint visit to the Marshall and Caroline islands, center of the disputed area; this we did, spending 2 months (*5*) visiting 33 islands between Guam and Kwajalein (Fig. 1). We worked on 22 atoll islands, including four on a par-