36. TECTONIC, VOLCANIC, AND PALEOGEOGRAPHIC IMPLICATIONS OF REDEPOSITED REEF FAUNAS OF LATE CRETACEOUS AND TERTIARY AGE FROM THE NAURU BASIN AND THE LINE ISLANDS[1, 2]

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ABSTRACT

The age of the Pacific Plate at Deep Sea Drilling Project Site 462 is taken to be 148 m.y., based on the location of the site on Magnetic Anomaly M-26. Drilling at Site 462 however, revealed the presence of a thick volcanic complex made up of a lower sheet-flow unit and an upper sill unit which engulfed and intruded Cretaceous sediments. The igneous complex is entirely normally magnetized, indicating that it probably was emplaced during the Cretaceous long normal magnetic event which spans the period 80 to 112 m.y. ago. A $^{40}Ar-^{39}Ar$ date from a sill is 110 ± 3 m.y. However, the lower flow unit is probably Barremian. A displaced reef fauna containing a Campanian–Maestrichtian pseudorbitoidid assemblage was found in a volcaniclastic section that represents the final episode of Cretaceous volcanism in the Nauru Basin–Marshall Islands area. The probable sequence of volcanic events at Site 462 appears to be (1) formation of the underlying Pacific Plate 148 m.y. ago, (2) extrusive volcanism in Barremian time, about 115 m.y. ago, (3) sill and flow volcanism accompanied by edifice-building in late Aptian time, about 110 m.y. ago, and (4) a further episode of edifice-building and deep-water volcanism beginning in the Campanian and ceasing by the middle Maestrichtian, about 70 m.y. ago. Application of models relating lithospheric uplift and subsidence to volcanism developed by Crough (1978) and Detrick and Crough (1978), combined with sedimentological and paleontological evidence from Site 462, allows a semi-quantitative reconstruction of the vertical tectonic history of the Nauru Basin. The basin did not subside "normally" since its formation at a ridge crest 148 m.y. ago, but instead was uplifted in Barremian–Aptian time, about 115 to 110 m.y. ago, and it remained relatively shallow until Maestrichtian time, about 70 m.y. ago. Reefs grew in the Marshall Islands area during Campanian–Maestrichtian time; prior to DSDP Leg 61, the oldest reefs in the Marshall Islands were dated as Eocene at Enewetak. Analysis of the stratigraphic distribution of mid-plate volcanism and reef faunas from the Nauru Basin–Marshall Islands area, the mid-Pacific Mountains, the Line Islands, and the central Pacific Basin indicates that this entire area underwent thermally induced uplift between about 115 to 110 and 70 m.y. ago. The region has been subsiding since about 70 m.y. ago. This history of vertical tectonics associated with volcanism is reminiscent of the Darwin Rise, described by Menard (1964). The chronology and areal extent of Cretaceous mid-plate volcanism in the central Pacific is difficult to reconcile with the Wilson-Morgan hot-spot theory. We suggest that the mechanism proposed by Liu (1980), involving convection-generated stress in the lithosphere, which results in fractures allowing magma access to the surface, is an attractive alternative.

Correlation of central Pacific mid-plate volcanism with volcanic events in the Caribbean and South Atlantic indicates that uplift associated with mid-plate volcanism was a major factor in causing the global Cretaceous transgression heretofore ascribed to increases in spreading rates at mid-ocean ridges.

The Late Cretaceous reef faunas from the Marshall-Line Islands and the Caribbean have strong affinities, suggesting that these areas were closer together in Late Cretaceous time and that there were shallow-water "stepping stones" between them. This interpretation supports the contention of earlier workers that the present Caribbean Plate was part of the Farallon Plate in Cretaceous time.

Redeposited reef faunas found in Oligocene and Miocene turbidite sequences are related to accelerated reef erosion during glacially induced sea-level falls. The Cenozoic reef assemblages, in contrast to the Cretaceous ones, have Indo-Pacific affinities.

INTRODUCTION

Menard (1964) postulated the existence of a broad rise in the central Pacific, the Darwin Rise (Fig. 1), which owed its origin to an upward bulge of the mantle accompanied by "volcanism on an enormous scale in late Mesozoic time" (Menard, 1964, p. 144). Hsü and Schlanger (1968) attempted to relate the life cycles and vertical tectonic histories of oceanic rises such as the Darwin Rise to major changes in the geothermal gradient within the upper mantle that would be associated with widespread volcanism. With the appearance of the plate-tectonics model for the development of the Pacific Basin, attention was concentrated on horizontal movements of the lithosphere that formed at ridge crests, and on the subsequent subsidence of this lithosphere as it moved away from the ridge and cooled (Sclater et al., 1971). In recent years, the geologic history of the Pacific plate has been interpreted largely in terms of crustal generation at ridge crests, regular cooling subsidence, and, following the appearance of the "hot spot" hypothesis (Wilson, 1963; Morgan, 1972), mid-plate volcanism. With the accumulation of data collected by dredging and DSDP drilling during the past decade—indicating that the Central Pacific was the scene of widespread volcanic activity, seamount and island formation, and reef growth during Barremian—Aptian to

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[2] Hawaii Institute of Geophysics Contribution No. 1067.

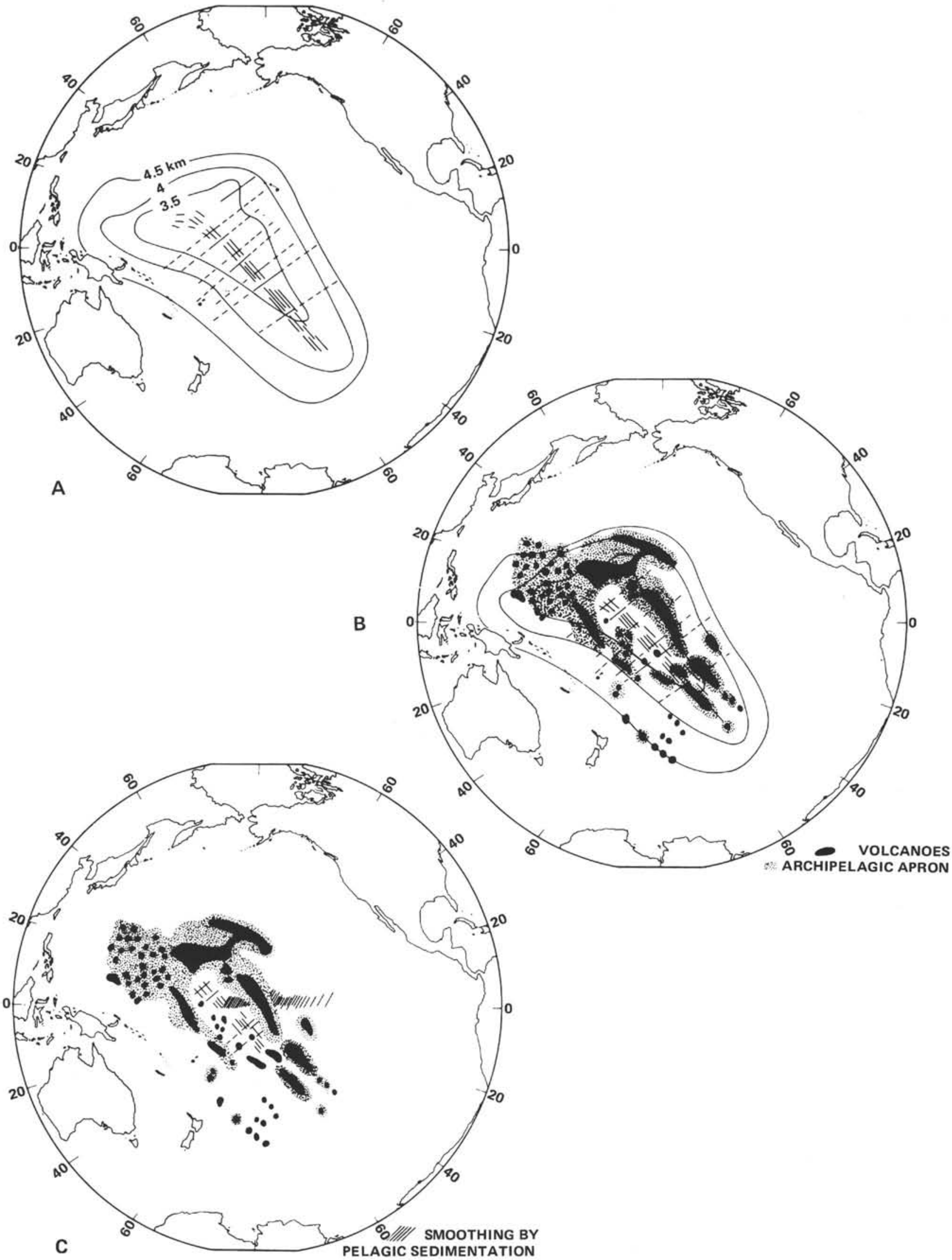

Figure 1. Evolution of the Darwin Rise: A. elevation of a broad rise. B. Late Mesozoic volcanism. C. Cenozoic subsidence. (From Menard, 1964, Figure 6.18 and caption.)

Late Cretaceous time (Figs. 2 and 3)— attention is once again focusing on the timing and mechanisms of mid-plate volcanism as a major factor in the vertical tectonic history of the Central Pacific (see Detrick and Crough, 1978, Crough, 1978).

Displaced reef faunas of Campanian-Maestrichtian age were recovered at DSDP drill sites in the Nauru Basin west of the Marshall Islands and adjacent to the Line Islands (Fig. 4). During Leg 17, Site 165 was drilled on a large fan just west of Kingman Reef, in the northern Line Islands. At this site, an integrated reef fauna of large benthic foraminifers (including *Pseudorbitoides*) and broken and abraded skeletal fragments of mollusks, echinoids, and bryozoans were found within volcaniclastic strata of Campanian-Maestrichtian age. These strata were interpreted to be turbidites containing calcareous skeletal debris which was eroded from reefs growing on edifices of Late Cretaceous age and redeposited in the surrounding deep water (Winterer, Ewing, et al., 1973). On Leg 33, two more sites were drilled adjacent to the Line Islands in geologic settings similar to 165; Sites 315 and 316 (Schlanger, Jackson, et al., 1976). At both sites, Cretaceous faunas virtually identical to those found at Site 165 were encountered in similar stratigraphic units. The Leg 33 sites yielded a diverse fauna that included *Pseudorbitoides, Asterorbis*, and *Sulcoperculina;* coralline algae and rudist fragments were also noted (Beckmann, 1976). These occurrences of coeval reef faunas of Campanian-Maestrichtian age in volcaniclastic sections along the Line Islands from Site 165 to Site 316 led Jackson and Schlanger (1976) to postulate that an uplift of some magnitude had accompanied volcanic activity in the Line Islands 80 to 85 m.y. ago, raising the edifices of the area into the photic zone, and allowing Late Cretaceous reef growth. At Site 462, drilled in the Nauru Basin during Leg 61, Campanian-Maestrichtian reef faunas were again found in strati-

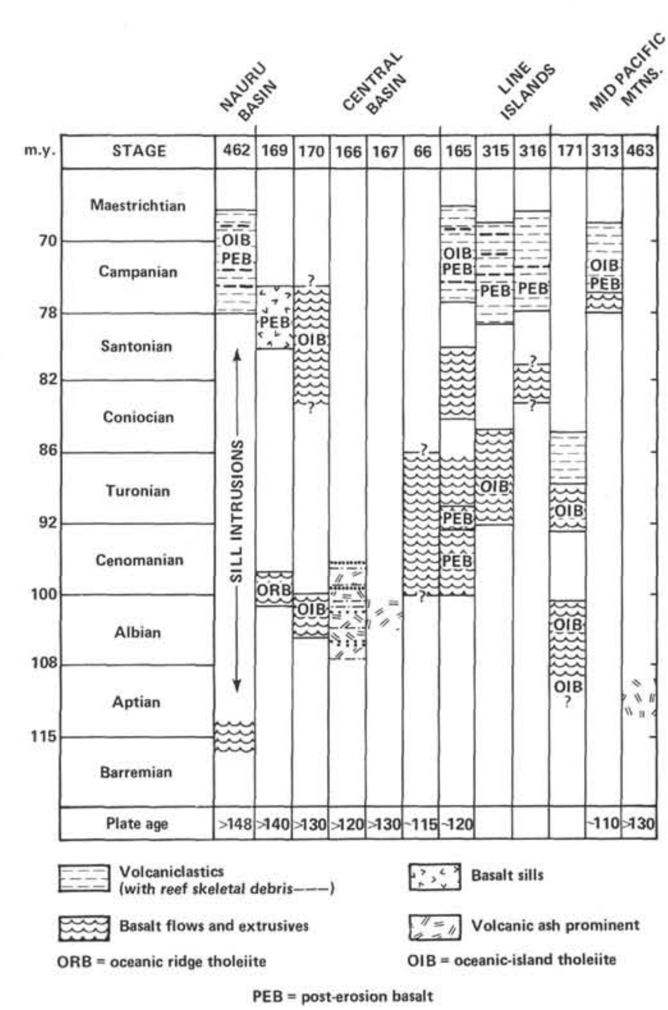

Figure 3. Stratigraphic distribution of Cretaceous mid-plate volcanic rocks at DSDP Sites in the central Pacific. (Compiled from *Initial Reports of the Deep Sea Drilling Project.*)

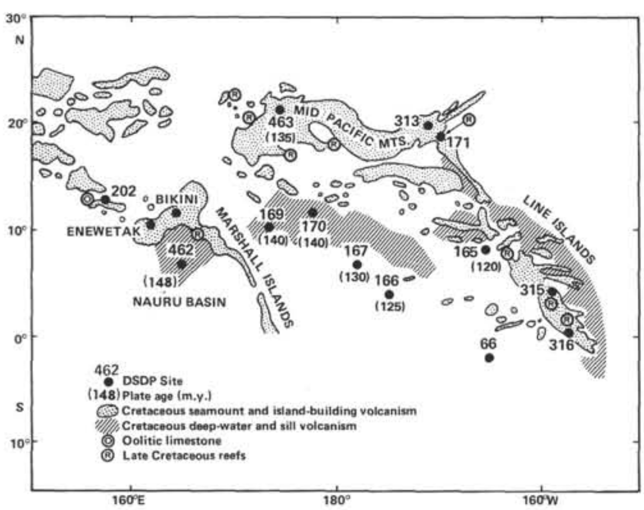

Figure 2. Areal distribution of Cretaceous mid-plate volcanism in the central Pacific and Late Cretaceous reefs and oolitic limestone (modified from Winterer, 1976; Late Cretaceous reefs from various sources; oolitic limestone locality from Heezen, MacGregor, et al., 1972).

graphic contexts identical to those found along the Line Islands (see Site Summary, this volume; Premoli-Silva and Brusa this volume). This discovery showed that Campanian-Maestrichtian reefs grew simultaneously along both the Line and Marshall Islands—the latter being the presumed source of the Nauru Basin reef debris. The thick section of Cretaceous sills and extrusive basalt units emplaced atop the 148-m.y.-old lithospheric plate at Site 462 suggested to us that uplift and edifice-building—permitting reef growth on a Cretaceous Marshall Island chain—accompanied this volcanism. Heretofore, the only evidence for the age of the Marshall edifices came from drilling on Enewetak (Schlanger, 1963), where the basalt basement was dated as Eocene; middle Eocene reefs are the oldest shallow-water sediments atop the edifice.

Based on the areal and stratigraphic distribution of volcanic rocks and reefs, we propose a genetic link between the Late Cretaceous period of reef growth in the central Pacific and the widespread mid-plate volcanism in this region. We argue that this volcanism caused regional shallowing from about 115 or 110 to about 70

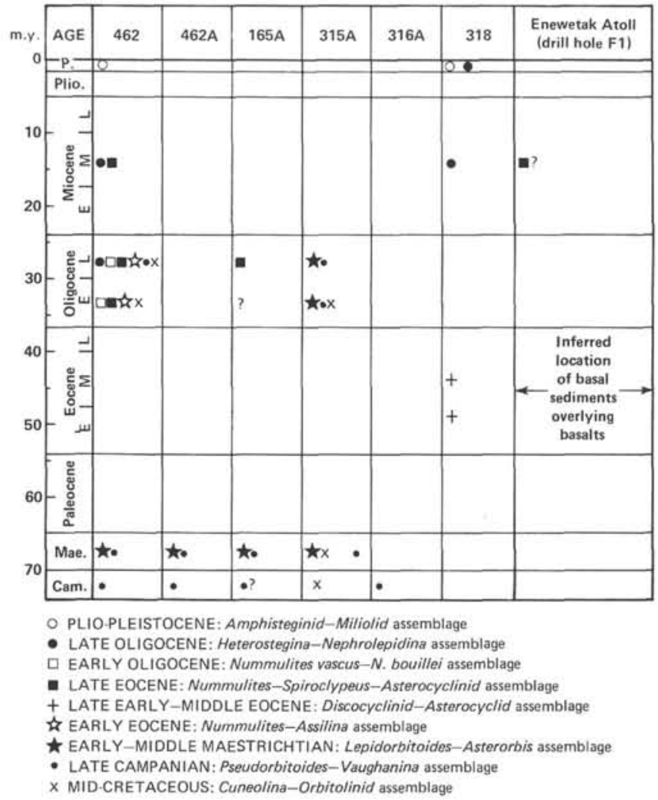

Figure 4. Stratigraphic distribution of reef faunas found at DSDP drill sites in the Nauru Basin, the Line Islands, and the Tuamotu Islands (from Premoli Silva and Brusa, this volume).

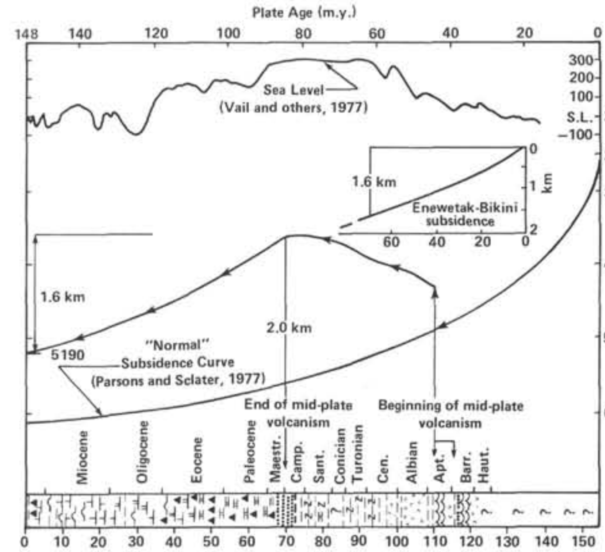

Figure 5. Vertical tectonic trajectory of Site 462. Actual path of Site 462 from ridge crest elevation to present depth of Nauru Basin at 5190 m is shown by line marked by arrowheads. Enewetak-Bikini subsidence curve from Detrick and Crough, 1978.

m.y. ago, because of changes in the thermal regime in the lithosphere and/or the upper mantle (Menard, 1964; Hsü and Schlanger, 1968; Detrick and Crough, 1978; Crough, 1978), and that reef growth was initiated on seamounts that built up or were raised into the euphotic zone; regional sudsidence has dominated since about 70 m.y. ago (Fig. 5).

The term "central Pacific" in this paper denotes that area included by the Mid-Pacific Mountains on the north, the Marshall Islands on the west, the Line Islands on the east, and the Manihiki Plateau on the south.

The Cretaceous geologic time scale used in this paper is that of van Hinte (1976).

VOLCANISM AND TECTONICS IN AND AROUND THE CENTRAL PACIFIC

Nauru Basin and Marshall Islands

The chronology of volcanism at Site 462 can be deciphered from considerations of basalt–sediment relations in the flow-and-sill complex, geochemical, paleomagnetic, and paleontological evidence. The history of vertical tectonics in the area can be developed by applying the models of Crough and Thompson (1976), Detrick and Crough (1978), and Crough (1978) for determining the vertical component of the trajectory of a plate subjected to reheating after its formation at a mid-ocean ridge crest. Details of the evidence summarized below can be found in the Site Summary; Steiner; Batiza et al.; Moberly and Jenkyns; Premoli Silva and Brusa; Ozima et al; and Thomson et al. (all this volume). See also Larson and Schlanger (this volume).

Site 462 was drilled on Anomaly M-26, which dates the Pacific Plate below the Nauru Basin at 148 m.y. (see Larson and Schlanger, this volume). Based on this evidence, a Parsons–Sclater (1977) normal-subsidence curve can be drawn as shown on Figure 5. The curve used is not corrected for sediment load. If the Nauru Basin had subsided normally, without any vertical perturbations, it would now be about 6.0 km deep. The present depth, 5190 meters, suggests that its subsidence path deviated from a Parsons–Sclater curve. Based on the agglutinated foraminifer assemblage in Core 80 (Sliter, this volume), indicative of bathyal depths, Site 462 had passed well below the CCD by Barremian time, about 115 to 120 m.y. ago. Hyaloclastite–sediment relations indicate that some volcanic activity in the form of sheet-flows had taken place in the area in Barremian time. Paleomagnetic data (Steiner, this volume) indicates a short reversed interval in the Late Cretaceous volcaniclastic section overlying the sill-and-flow complex, which can be considered correlative with the reversed interval that separates Magnetic Anomalies 33 and 34. The sill-and-flow complex itself is entirely normally magnetized, suggesting that much of it probably was emplaced during the Cretaceous long normal event, the boundaries of which are 80 m.y. and 112 m.y. according to Larson (pers. comm.), i.e. from the Campanian–Santonian boundary to Aptian time. Steiner (this volume) interprets the inclination data as indicating two periods of volcanism subsequent to the formation of the underlying plate 148 m.y. ago. Therefore, the Barremian sheet-flow unit, assuming the 115-m.y. age is correct, would have to have been erupted during normal magnetic epochs within the Barremian, between M-2 and M-3 or M-4 and M-5. Ozima et al. (this volume) report that a sill from the complex yielded a ^{40}Ar–^{39}Ar age of 110 m.y. This date is used here because they consider it reliable, and we consider it reasonable in the light of the paleomagnetic evidence. Therefore, at least one sill intrusion took place in Aptian time. Further evidence on the timing of volcanism in the Nauru Basin–Marshalls area is the reef-derived fauna of Campanian–Maestrichtian age found in the volcaniclastic section of the same age. This fauna indicates that shallow-water edifice-building volcanism continued until early Maestrichtian time (see Rea and Thiede, this volume). As reported by Premoli Silva (this volume), two larger-foraminifer assemblages recovered at Site 462 can be distinguished: (1) an older one (Cores 52 and 51) associated with late Campanian planktonic foraminifers attributed to the *Globotruncana subspinosa* and *Globotruncana calcarata* Zones respectively, dominated by *Vaughanina* and *Pseudorbitoides* and attributed to the Campanian, and (2) a younger one (Core 48) associated with planktonic foraminifers attributed to the *Globotruncana gansseri* Zone of middle Maestrichtian age, which contains besides the above-mentioned forms representatives of the genera *Asterorbis* and *Lepidorbitoides*. *Lepidorbitoides bisambergensis* is characteristic of the early Maestrichtian, whereas *L. socialis* characterizes the late Maestrichtian.

Although the two assemblages are separated by some 15 meters of sediments which contain only pelagic foraminifers, it appears that they could represent the entire late Campanian–early late Maestrichtian interval during which the reefs were continously growing. Moberly and Jenkyns (this volume) have examined the relationships between flows, sills, and intercalated sediments in the sill-and-flow complex and point out that some sills baked strata of Barremian–Aptian–Albian age, but that some flows lie under these strata. They propose that two periods of post-plate volcanism occurred, at 118 ± 6 m.y., and 74 ± 2 m.y.

Taking into account the above-described evidence, we propose a probable sequence of volcanic events at Site 462 as follows:

1) Formation of the underlying Pacific plate 148 m.y. ago at a ridge crest;

2) Mid-plate volcanism in the form of flows in Barremian time, about 115 m.y. ago;

3) A period of sill emplacement in Aptian time, about 110 m.y. ago, near the lower boundary of the Cretaceous long normal event.

4) A final episode of edifice-building deep-water volcanism beginning during Campanian time and ceasing by middle Maestrichtian time, about 70 m.y. ago.

According to Thomson et al. (this volume), thermally matured hydrocarbons in strata of Albian, Campanian, and Maestrichtian age are evidence of a Late Cretaceous volcano-thermal event.

In developing their model for thermally induced uplift and the origin of mid-plate swells, Detrick and Crough (1978) and Crough (1978) postulated that as normally thickening and cooling lithosphere moves away from its site of formation at a ridge crest it may pass over a hot spot. As it does, the lithosphere would be reheated, thinned, and uplifted. In their analysis of mid-plate swells, Detrick and Crough (1978) pointed out that Bikini and Enewetak in the northern Marshalls have subsided 1.4 km in the past 60 m.y. (see inset on Fig. 5). According to Heezen, MacGregor, et al. (1972), drilling at Site 202 on Ita Maitai Guyot (Fig. 2) penetrated an oolitic limestone that overlies lagoon carbonates of Paleocene age. Ita Maitai Guyot built up as a volcanic edifice with eruptions culminating in Campanian–Maestrichtian time, and then subsided to its present depth of 1500 meters. The oolitic limestone has subsided 1600 meters since Paleocene time; the volcanic basement may have subsided more. We take 1600 meters then as the amount of subsidence at Site 462 since 70 m.y. ago. If we accept this model, we can plot a possible trajectory of Site 462 as shown on Figure 5 by the line marked by arrows. At the initiation of major mid-plate volcanism during late Aptian time, the lithosphere around the Nauru Basin was uplifted. Lithospheric thinning and uplift began immediately after initiation of the heating of the base of the lithosphere (Crough and Thompson, 1976). Prior to Aptian time, some volcanism occurred, and uplift may have begun. However, during Barremian time the Nauru Basin was at bathyal depths. Volcanism continued, perhaps intermittently, until about 70 m.y. ago, when edifices in the area reached into the euphotic zone, and Campanian–Maestrichtian reefs grew. The abundance of macroscopic terrestrial-plant debris in cores of late Aptian age (Jenkyns and Schlanger, this volume) indicates that islands formed as a result of the Aptian volcanic event. The area stayed anomalously high with respect to a "normal" subsidence curve from about 110 to 70 m.y. ago. Taking 1.6 km as the amount of subsidence in the Nauru Basin over the last 70 m.y., and plotting a curve parallel to the Enewetak–Bikini subsidence curve so that the curve intersects the 0-m.y. stratigraphic-age point at the present depth of the Nauru Basin (5190 m), we obtain 2.0 km as the difference between the depth of the Nauru Basin 70 m.y. ago and the approximate depth at which the Nauru would have been if mid-plate volcanism had not occurred (see Larson and Schlanger, this volume, for a discussion of the trajectory problem). Following cessation of volcanism about 70 m.y. ago, as evidenced by the peak in the accumulation rate of volcaniclastic debris during late Campanian to middle Maestrichtian time, the Nauru Basin subsided, as did Enewetak, Bikini, and Ita Maitai Guyot. Present-day heat flow in the Nauru Basin is 1.1 HFU, as determined from shipboard measurements of down-hole temperature gradients and rock conductivity (Site Summary, this volume; Boyce, this volume). This value indicates that heat flow has returned to normal for 70-m.y.-old lithosphere (Parsons and Sclater, 1977).

Line Islands

The geological history of the Line Islands has been discussed extensively by Jackson and Schlanger (1976), citing data gathered on DSDP Legs 33 and 17 (Winterer, Ewing, et al., 1973), and the petrologic studies of Natland (1976) and Jackson et al. (1976). These authors showed that mid-plate volcanic rocks are present over a wide area of the central Pacific, from the seamounts northeast of Wake Island, through the mid-Pacific Mountains, to the Line Islands (Figs. 2 and 3). As Jackson and Schlanger (1976) concluded: "From available age data, we might suggest a period of epeirogeny in the area from the Wake Guyots to as far east as Site 170, occurred at some time ≥100–103 m.y. The upper basalts at Sites 169 and 170 may then record a second epeirogenic event that occurred as far east as the Line Islands at 80–85 m.y." At all three DSDP sites along the Line Islands—165, 315, and 316 (Fig. 4)—reef faunas made up of large benthic foraminifers, coralline algae, and, locally, rudist fragments of Campanian–Maestrichtian age have been described (Premoli Silva and Brusa, this volume; Winterer, Ewing, et al., 1973; Schlanger, Jackson, et al., 1976; Beckmann, 1976). It was the discovery of these late Cretaceous reef faunas in volcaniclastic sections that led Jackson and Schlanger to postulate that a Late Cretaceous epeirogenic pulse caused by mid-plate volcanism raised the Line Islands into the euphotic zone, allowing reefs to develop simultaneously along the entire Line Islands chain.

Rea and Thiede (this volume), in a study of mass accumulation rates of volcaniclastic debris, point out that a marked increase in the accumulation rate of such debris took place over a wide area of the central Pacific from the Caroline Islands to the Line Islands. They date this maximum rate of accumulation between the late Coniacian and early Maestrichtian (68 to 85 m.y. ago). During this time, there was an especially marked peak during the Campanian and Maestrichtian. Volcaniclastic sediments of this age in the Line Islands at Site 165 and at Sites 315 and 316 are largely reworked and resedimented breccias, sandstones, and siltstones displaying graded bedding, lamination, and cross-lamination. Such sediments were probably formed by erosion of volcaniclastic and hyaloclastic highs (Winterer, Ewing, et al., 1973), with consequent redeposition in deeper water by turbidity currents. At Site 462, similar volcaniclastic sediments of the same age occur with large benthic foraminifers, echinoids, rudist fragments, and bryozoans. The striking similarity in lithology and age of the volcaniclastic sections at Site 462 and Sites 165, 315, and 316 along the Line Islands lends weight to our argument that the Line Islands and the Marshall Islands may have had very similar Late Cretaceous histories. Moberly and Jenkyns (this volume) point out that some of the volcaniclastic material at Site 462 is hyaloclastic and vesicular, the latter feature indicating eruption in shallow water. We suggest that over this wide area of the central Pacific these islands were the product of a Late Cretaceous volcanic episode, and that the widespread epeirogenic pulse postulated by Jackson and Schlanger (1976) was caused by a volcano-thermal event which had its beginning approximately 115 to 110 m.y. ago.

Lanphere and Dalrymple (1976) proposed that the deepest basalts drilled at Site 165 could be as old as 100 m.y. The Line Islands then may have undergone Albian thermal uplift that would correlate with the 100 to 103 m.y. event that took place from the Wake Guyots to as far east as Site 170. We would argue then that the history of the Line Islands is similar to that of the Nauru Basin–Marshalls area, and that Crough's (1978) thermal-uplift model is applicable to the Line Islands.

Mid-Pacific Mountains

Hamilton's (1956) classic work summarized the extant data for this region. His conclusions were that the Mid-Pacific Mountains, from Necker Ridge to near Wake Island, were a chain of basaltic islands during Cretaceous time. These islands supported rudist-coral reefs of Aptian–Cenomanian age. Hamilton's work left little doubt that edifices had built up into the euphotic zone by Aptian time over a wide area of the Mid-Pacific Mountains. Dean et al. (1979), reporting on Leg 62 results, state that organic-carbon-rich limestone in the Mid-Pacific Mountains is associated with volcanic ash of Aptian age, 110 to 115 m.y. old. They also point out that the organic carbon is rich in humic land-derived material from nearby islands. The late Aptian plant remains at Site 462 (Jenkyns and Schlanger, this volume) indicate islands in the Marshalls area. Matthews et al. (1974) reported Aptian–Cenomanian reef limestones from dredge hauls taken from the eastern Mid-Pacific Mountains, through the Marcus-Wake Seamounts, to the Japanese Seamounts as far west as 144°E. They confirmed Hamilton's picture of reef growth followed by subsidence in the Late Cretaceous, probably the Cenomanian. Ladd et al. (1974) showed that Darwin Guyot in the western Mid-Pacific Mountains was indeed a true atoll, with abundant rudists of Cretaceous age.

On Leg 17 (Winterer, Ewing, et al., 1973) at Site 171 on Horizon Guyot, Eocene cherts were penetrated, and the drill bottomed in weathered vesicular basalt of probable Albian age. The overlying sediments are shallow-water skeletal clastic limestones that underwent vadose- or phreatic-zone diagenesis. These are capped by shallow-water or subaerial basalts erupted during Late Cenomanian and Turonian time. Above these are late Campanian to Miocene pelagic deposits. Wood fragments in Turonian and Coniacian volcanogenic sandstones were noted. Thus, Horizon Guyot records episodes of:

1) Albian or older volcanism, resulting in edifice formation;
2) A reef period followed by subaerial diagenesis;
3) Renewed volcanism in Late Cretaceous time; and
4) Final subsidence from late Campanian to present time.

On Leg 32, Site 313 was drilled in the eastern Mid-Pacific Mountains (Larson, Moberly, et al., 1975). Campanian–Maestrichtian volcaniclastic turbidites from this site are similar to the coeval volcaniclastic section drilled at Sites 462, 315, 165, and 316. Large reef benthic foraminifers were not reported. However, Moberly and Keene (1975) described rounded fragments of calcite spar that were transported to the site, presumably by the turbidity currents that deposited the enclosing volcaniclastic sandstones. We suggest that these spar fragments were derived from eroding reefs coeval with the reef skeletal debris from Sites 462, 165, 315, and 316. Therefore, we now have evidence for Campanian-Maestrichtian reef growth from the Nauru Basin-Marshalls area, the Line Islands, and the Mid-Pacific Mountains. It should be noted that the volcaniclastic section at Site 313 is described as Coniacian in the Leg 32 volume, but it is actually Campanian-Maestrichtian (Moberly, pers. comm., 1979).

Considering the evidence for the origin of the Mid-Pacific Mountains, Larson, Moberly, et al., (1975, p. 325) state: "However, the Mid-Pacific Mountains certainly are not a typical seamount chain. Their strike is not parallel to the other chains, and thereby does not fit easily into the "hot-spot" or other concepts of the origin of volcanic chain popular at this date."

Central Pacific Basin

The preceding sections demonstrate that both the Nauru Basin-Marshall Islands area and the Line Islands were affected by a series of volcano-thermal events associated with mid-plate volcanism that resulted in major uplift and edifice-building with concomitant exposure of local highs to the euphotic zone environments within which Campanian-Maestrichtian reefs developed. A similar history appears to be recorded in the Mid-Pacific Mountains. If we postulate that this Cretaceous uplift also affected the area between the Line and Marshall Island chains, we must find evidence for mid-plate volcanism and vertical uplift in the geologic record revealed at Sites 166, 167, 168, 169, and 170, drilled on Leg 17 (Winterer, Ewing, et al., 1973).

Following Leg 33 (Schlanger, Jackson, et al., 1976), Winterer (1976) attempted a synthesis of the development of the Central Pacific Basin. In one of his models he proposed two episodes of mid-plate volcanism younger than the 135 to 140 m.y. crust that underlies Sites 169 and 170. The first of these was early Albian (100-105 m.y. ago), and the second is represented by sills which he considered to be 87 to 95 m.y. old at Site 169 and 80 to 87 m.y. old at Site 170. He postulated a modest amount of general regional uplift associated with the Albian mid-plate volcanism, because of the presence of basal limestone at Sites 169 and 170, the implication being that these sites on 135 to 140 m.y. crust should have been below the CCD before Albian time.

If these volcanic events were associated with epeirogenic uplift of the Central Pacific Basin, as in the Nauru Basin and along the Line Islands, the sedimentary records of Central Pacific Basin DSDP sites should record some synchronous regional shallowing. At Site 166 (Winterer, Ewing, et al., 1973), the present water depth is 700 meters less than would be expected if the site had followed a normal-subsidence curve. We suggest that this depth anomaly is due to a thermally induced uplift of the area similar in timing to but of lesser magnitude than that shown in the Nauru Basin-Marshall Islands area, and that it is not inherited from an abnormally high original ridge elevation. There is no evidence however, that Site 166 was ever raised above the CCD following its original descent below it by Albian time. At Site 169, nannofossils in the various cores showed that the site was above the CCD in Albian and Cenomanian time, but sank below it during Turonian time (86-92 m.y. ago). By early Campanian to middle Maestrichtian time, it had risen above the CCD. Thus, Site 169 appears to have been uplifted at the same time as the Nauru Basin and the Line Islands. Winterer (1973) showed similarly that Site 170 passed below the CCD 80 m.y. ago for a very short period, but then rose above the CCD until at least 70 m.y. ago. Therefore, Site 170 also shows elevation above the CCD during Campanian time. Older foraminifers, reworked and sorted, are abundant in Campanian strata, suggesting accelerated erosion of nearby highs at that time.

One would expect that Site 167, drilled atop the Magellan Rise in the Central Pacific Basin, would contain the most compelling evidence for any major vertical uplift episode, inasmuch as the present depth of its upper surface is approximately 3200 meters. According to the gross lithologic character ($CaCO_3$-rich sediments throughout the entire section from Quaternary to Tithonian-Berriasian), the Rise has been above the CCD during all of that time. Late Albian mid-plate volcanism is recorded at Site 167 by dark-green, volcanic siltstones with abundant ash and zeolites. According to the Site Summary for Site 167 (Winterer, Ewing, et al., 1973, p. 148): "Recrystallized benthonic foraminifera similar to outer neritic and upper bathyal species in California, occur in the reddish marls of Cores 56 to 60." These cores span late Turonian to early Campanian time, 75 to 87 m.y. Thus the top of the Magellan Rise could have been at a depth of 600 meters or less at that time, taking the shallow limit of the outer neritic zone to be 100 meters, and the deeper limit of the upper bathyal zone to be 600 meters. If the Magellan Rise had been steadily subsiding since Tithonian time (the age of the oldest sediments above the basalt), it would have been at a depth of almost 3 km by Turonian-Campanian time (Thierstein, 1979). We propose that the Magellan Rise also underwent uplift at approximately the same time that Sites 169 and 170 rose above the CCD.

TERTIARY REDEPOSITED REEF DEBRIS

At Site 462, considerable amounts of reef-derived skeletal debris made up of larger benthic foraminifers, coralline algae, mollusks, bryozoans, and corals were found in deep-water pelagic sediments of Oligocene and middle Miocene age (see Premoli Silva and Brusa, this volume), as shown on Figure 4.

In particular, the larger foraminifers recovered from Cores 21 through 34 are characteristic of the following ages: early Eocene, middle and late(?) Eocene, early Oligocene, and late Oligocene.

The early Eocene assemblage is well dated by *Nummulites burdigalensis N. rotularius, N. pernotus*, and

Assilina leymeriei, possibly associated with other, less-diagnostic forms, such as discocyclinids, asterocyclinids, etc.

The middle Eocene assemblage is characterized by the presence of *Polylepidina antillea, Nummulites* sp. cf. *N. bagelensis*, and possibly *N.* sp. aff. *N. variolarios*, also associated with asterocyclinids.

The late Eocene assemblage is characterized by *Nummulites problematicus, Spiroclypeus* sp. cf. *S. vermicularis, S.* sp. cf. *S. albapustula, Asterocyclina penuria, A. matazensis*, and *Operculina eniwetokensis.*

The early Oligocene assemblage is dated by the presence of *Nummulites vascus* and *N. bouillei*, possibly associated with less-diagnostic forms such as heterosteginids, operculinids, etc.

Finally, a rich assemblage attributable to the late Oligocene contains *Miogyspinoides ubaghsi, M. grandipustula, Nephrolepidina sumatrensis*, and *Eulepidina* sp. cf. *E. eohippoides*, associated with heterosteginids, operculinids, and *Spiroclypeus.*

As discussed by Premoli Silva and Brusa (this volume), most of the reef debris was redeposited during late Oligocene time.

We do not interpret this redeposition of Eocene reef debris as indicating regional uplift. Instead, we believe that sea-level falls resulted in erosion of the Tertiary and Cretaceous reefs. The occurrence of Eocene fossils in deep-water Oligocene strata is probably the result of erosion of reefs during the major Late Oligocene sea-level fall approximately 28 m.y. ago described by Vail et al. (1977) (see Fig. 5). Schlanger and Douglas (1974) have pointed out that both Enewetak and Bikini atolls were emergent during Oligocene time. Savin et al. (1975) have documented a severe drop in sea-surface temperatures beginning in Eocene time and culminating in late Oligocene time, about 27 m.y. ago. This date corresponds to a major phase of glaciation in the southern hemisphere, which would account for the Oligocene sea-level fall and consequent erosion of Eocene reefs over much of the Pacific. This late Oligocene erosion caused redeposition of Late Cretaceous reef fossils into late Oligocene strata (Fig. 5), testifying to the intensity of erosion. Finally, in middle Miocene time, ~13 m.y. ago, a minor sea-level drop (Vail et al., 1977) resulted in some erosion of late Eocene assemblages (Fig. 5).

BIOPROVINCIAL AFFINITIES OF THE REEF FAUNAS

During Aptian–Albian time, Pacific reef faunas had Tethyan affinities, which is not surprising, since Cretaceous rudistid reefs and their associated faunas appear to have been cosmopolitan at low latitudes.

As already pointed out by Beckmann (1976), the Campanian–Maestrichtian shallow-water reef foraminifers from the Line Islands show Caribbean affinities. The identical fauna at Site 462 (Premoli Silva, this volume) extends the Caribbean bioprovince west to the Marshall Islands. Although the orbitoidid and similar faunas may have easily migrated where closely spaced, shallow "stepping stones" were available, it is doubtful that they could quickly migrate across a large, deep ocean such as the present eastern Pacific. The rapid colonization of the Line and Marshall Island areas by Caribbean shallow-water reef faunas may be explained by a Campanian–Maestrichtian paleogeographic reconstruction in which the eastern Pacific was entirely missing—not having been formed—and in which the present Caribbean Plate was close to those segments of the Pacific Plate on which the Line and Marshall Islands formed.

Previous workers have interpreted the Caribbean as originally having been part of the Farallon Plate (Malfait and Dinkelman, 1972; Edgar et al., 1971). Mattson (1969) argued that the Caribbean was a detached relic of the Darwin Rise. The similarities between the Caribbean and the Nauru Basin are striking. Both areas contain sill complexes of Cretaceous age (Burke et al., 1978), the magnetic character is similar (Donnely, 1973), and the geochemistry of the sill complexes is similar (Batiza et al., this volume). The affinities between the Caribbean and Line Islands–Nauru Basin Cretaceous faunas substantiate the idea that the Caribbean and Nauru Basin areas were closer together in Cretaceous time.

The Tertiary reef faunas from the Nauru Basin–Marshall Island area and the Line Islands (see Premoli Silva and Brusa, this volume) show strong affinities to the Indo-Pacific faunas, and also with regions farther away, such as the Tethys. *Nummulites burdigalensis, N. problematicus, N.* sp. aff. *N. variolarius*, and *Assilina leymeriei* are also described from the Mediterranean area. It appears that the main direction of the colonization of the Marshall and Line Islands area changed from east-towards-west during Late Cretaceous time to west-towards-east during the Tertiary, the latter dispersal direction prevailing at the present time. This shift can be explained by the growth, since late Cretaceous time, of a large, deep eastern Pacific basin which cut off colonization from the east, and by the formation of numerous stepping stones by early Tertiary volcanism in the western Pacific, such as the last phase of volcanic activity at Enewetak in Eocene time.

CONCLUSIONS

A large area of the central Pacific, extending from the Nauru Basin–Marshall Islands area on the west to the Line Islands on the east, and including the Mid-Pacific Mountains on the north, underwent thermally induced regional uplift associated with sill intrusions and the buildup of seamounts and large subaerial volcanic edifices as a mid-plate volcanic phenomenon. This regional volcano-thermal event began in Barremian–Aptian time, about 115 to 110 m.y. ago, and continued into Late Cretaceous time, ending approximately 70 m.y. ago. Our interpretation of the history of vertical tectonics of the area is similar to the evolution of the Darwin Rise described by Menard (1964) and incorporates elements of the model used by Hsü and Schlanger (1968), in which they related changing thermal regimes in the upper mantle to crustal uplift and subsidence history. Menard (1964) postulated the elevation of a broad swell, in late Mesozoic time, which he called the Darwin Rise, over an area which includes that discussed in the present paper. He further called on volcanism on an enormous scale in late Mesozoic time to form the Mid-Pacific Mountains, the Line Islands, and the Marshall Islands, as well as many other island chains. By applying the methods of Detrick and Crough (1978) and Crough (1978), we have been able to quantify this uplift somewhat and show that by Late Cretaceous time the area was perhaps 2 km shallower than it would have been had it subsided "normally" for the past 148 m.y.

This regional uplift was accompanied by the formation of numerous seamounts and large subaerial edifices, on and around which developed Aptian–Cenomamanian rudistid-coral reefs and later Campanian–Maestrichtian reefs. Turbidite debris from the latter has been found at Site 462 in the Nauru Basin, and at Sites 165, 315, and 316 along the Line Islands (Winterer, Ewing, et al., 1973; Schlanger, Jackson, et al., 1976); Cores from Site 313 in the Mid-Pacific Mountains also record this event. Thus, it appears that Late Cretaceous reef development was widespread. The presence of these reef faunas at Site 462 indicates that the Marshall Islands have a history of Cretaceous reef growth. Prior to drilling Site 462, these islands were presumed to have formed in Eocene time, as indicated by drilling on Enewetak (Schlanger, 1963).

The widespread Cretaceous mid-plate volcanism in the Central Pacific leads us to conclude that the concept of hot spots of Morgan (1972) does not account for this type of widespread, synchronous, and long-lived volcanism. One implication of the hot-spot concept is that mid-plate volcanic activity due to plate motion over a hot spot should be restricted within a circle on the surface of the earth perhaps 200 km in diameter at any given time. This restriction on the areal extent of surficial volcanism derives from the fact that the linear island chains in the Pacific, used to trace the path of hot-spots relative to the overriding plate, can be enclosed by a band 200 km wide. A further implication is that the temporal extent of volcanism at any given point is limited by the velocity of the plate relative to the hot spot. Considering an average plate velocity of about 10 cm/yr and a hot spot surface-manifestation diameter of 200 km, volcanism at one point in the plate should last on the order of 1 to 2 m.y.—e.g., the time span of Hawaiian shield-building volcanism is restricted to 1 to 2 m.y.

Our survey of central Pacific mid-plate volcanism shows that during Cretaceous time volcanism took place over an area covering millions of square kilometers and that volcanism such as took place in the Nauru Basin, and probably in the Line Islands and the eastern Mid-Pacific Mountains, persisted, albeit intermittently, for more than 40 m.y., from the Barremian–Aptian (115 to 110 m.y.) to the Campanian–Maestrichtian (~70 m.y.). Attempts to explain the areal and temporal distribution of Late Cretaceous volcanism can lead to difficulty in applying the Wilson-Morgan hot-spot model. For example, Winterer (1976), in trying to reconcile the sill age at Site 170 of 80 to 87 m.y. with the simultaneous cessation of volcanism at Site 165 at 80 to 85 m.y., pointed out that a very rapid progression of volcanism between these sites must be assumed. He suggests a more attractive hypothesis that "would allow nearly simultaneous eruption of basalt over a broad region by having numerous relatively short progressive chains operating in parallel" (Winterer, 1976, p. 742). Thus, to avoid very high progression rates, numerous hot spots are invoked, each making its own micro-chain. By avoiding the fast-progression difficulty, one then is led to a new difficulty involving the need for numerous hot spots, the surface expression of each being very short lived. This short-lived attribute then is in contradiction to the original hot-spot idea that Pacific hot spots are long lived and produce chains as long as the Hawaiian–Emperor chain. Larson, Moberly et al. (1975) also were unable to reconcile the history of the Mid-Pacific Mountains with a hot-spot origin. Jackson and Schlanger (1976) argued that the results of DSDP drilling along the Line Islands indicated that the hot-spot mechanism could not be applied to that large chain.

We proposed that thinking in terms of individual, areally restricted hot-spots leads only to greater difficulties and an ever more-complicated scheme as our data base expands. The way out of these difficulties is to eliminate the hot-spot mechanism as the only one that can account for mid-plate volcanism in the Central Pacific. We suggest that potential extrusive magmas underlay the lithospheric plate across the entire central Pacific from Aptian to Campanian–Maestrichtian time, and that the problem of Cretaceous mid-plate volcanism is one of finding a mechanism that would allow the magmas access to the surface. Liu (1980) has proposed that magmas can migrate through the lithosphere because of fracturing in response to stresses induced in the lithosphere by mantle convection currents. He applies his argument to the occurrence of Cenozoic intra-plate volcanism. We suggest that the Liu mechanism is an attractive alternative to hot-spot theory in explaining Pacific mid-plate regional volcanism in Cretaceous time.

The uplift of much of the central Pacific in Late Cretaceous time due to Barremian–Aptian mid-plate volcano-thermal events followed by volcanism ending in Campanian–Maestrichtian time contributed to the major Cretaceous sea-level rises (Vail et al., 1977) described as worldwide events. Therefore, changes in spreading rates along rise crests (Hays and Pitman, 1973; see Pitman, 1978, for a review) may not have been the only major factor that produced the great Cretaceous transgressions; epeirogenic, thermally-induced regional uplift may also have contributed. As shown on Figure 5, the sea-level curve of Vail et al. (1977) shows the global Cretaceous transgression correlating with widespread Barremian–Aptian to Maestrichtian volcanism. The Nauru Basin evidently had a history similar to that of the Caribbean Sea, whose shallow depth and thick underlying crust has been attributed to the large-scale intrusion of sills approximately 80 m.y. ago (Burke et al., 1978). Indeed, results of Leg 61 reinforce the argument of earlier workers that the Caribbean was originally part of the Farallon Plate in Late Cretaceous time. The recent work of Kumar (1979) in the Atlantic shows that "excessive" volcanism between 100 and 80 m.y. ago formed the Rio Grande-Walvis Ridge system of paired aseismic ridges. If the Caribbean and Atlantic volcanic events also resulted in uplift, then they also contributed to the Cretaceous transgressions.

The presence of reef debris of Cretaceous, Eocene, and Oligocene ages in deep-water sediments of Oligocene age at Sites 462 and also at Site 165 (Winterer, Ewing, et al., 1973) is due to a glacially induced sea-level drop in Oligocene time that led to emergence of atolls over wide areas of the Pacific (Schlanger and Douglas, 1974); climatic deterioration (Savin et al., 1975) accompanied by development of Antarctic glaciers caused this major regression. The sea-level curve of Vail et al. (1977) shows this dramatic Oligocene sea-level drop.

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