What *Really* Happened in the Pacific?

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The proper way to consider seamount volcanism on the Pacific plate is to examine all seamounts at once, as if the ocean were entirely drained away. This can be done by considering the modern chart of bathymetry derived from satellite-based altimetry (Smith and Sandwell, 1997), which was not available to Jason Morgan when he proposed mantle plumes (Morgan, 1971, 1972a, 1972b). This chart, based on a uniform remotely-sensed sampling of the entire plate, reveals thousands of seamounts in the Pacific arranged in bewildering arrays of alignments, non-alignments and orientations, and they are far from being regularly distributed. The Pacific plate contains huge plateaus without trailing seamounts; trains of seamounts that have no affiliated plateaus; trains that changed volume and rates of propagation through time; trains that contain curving, splayed, imbricate and cross-trend ridges; and trains that terminate at transform faults. It contains huge clusters of seamounts that are not trains at all. Only a few of them are grouped in the linear, concentric island chains so central to the plume hypothesis. The idea that linear island chains alone provide an adequate picture of mantle geodynamics beneath the plate thus must be seen as a misapprehension.

Extensive dredging of seamounts by many workers demonstrates that the geochemical category of "ocean-island basalt (OIB)" is misleading. Varieties of alkalic basalt or related differentiates occupy the summit of almost all seamounts that rise more than about 2-km above the seafloor, and islands themselves account only for the very small percentage of them that actually erupted in entire edifices. Even so-called E-MORB that erupt directly on ridge axes are merely alkalic olivine basalts very much like those of tall seamounts both near and away from spreading ridges (e.g., Engel et al., 1965; Batiza et al., 1989, 1990; Natland, 1989; Davis et al., 1995; Cousens, 1996; Niu et al., 2002; Niu and O'Hara, 2003). Mixing between depleted and enriched magma strains may explain much of the geochemical diversity of abyssal tholeiites. Islands are actually only the tips of the tallest of seamounts, thus if our interest were in deciphering the origins of "tall-seamount basalts" we would be nearer the mark than if we restrict our attention to the compositions, temporal sequences, and geometrical relationships of basalts that can be sampled only on foot. We should include all petrologically similar basalts in our purview, whether they erupted on islands or below sea level, young, old, tall or small seamounts, *or* spreading ridges. Since OIB-like lavas occur on so many features that are not age-progressive linear island chain, why should such geochemistry *require* a deep mantle plume anywhere else? What can we imagine the typical internal structure of plumes to be when some volcanoes within chains have no geochemical consistency from one to the next and the chains themselves have opposite geochemical trends through comparable stages of volcanism?

The Pacific plate, the largest on Earth, spans a history of more than 165 million years (e.g., Pringle, 1992), from an infancy when it was very small and entirely surrounded by spreading ridges (Nakanishi, 1993). Beginning in the Jurassic, it grew in all directions until some of its edges necessarily intersected subduction boundaries during mid- and later Cretaceous times. Today this giant among plates is more than half bounded by subduction boundaries and linking transform faults. The current trend of the plate's motion is to the WNW relative to those subduction boundaries, as it has been for at least 47 Ma (Sharp and Clague, 1999).

The modern concept and acceptance of mantle plumes depends strongly on assumptions of parallelism (concentricity) of the traces of linear volcanic chains on the Pacific plate and their apparent fixity with respect to each other since 47 Ma, but only since that time. Prior to that, the picture is much more complicated. For example, a substantial body of radiometric-age data extending back to the mid-Cretaceous exists for the Line Islands seamounts, which Morgan (1971;1972a, b) proposed to be coeval and concentrically age-progressive with the Emperors portion of the Hawaiian-Emperor chain. However, radiometric-age data summarized by Davis et al (2002) show NO age progression within the Line Islands seamounts (Figure 1). The northern end of the chain is also several times wider than the track of the Emperors, and has ridges and seamounts arranged in two principal orientations, NNW and WNW. Nearly synchronous volcanism occurred along much of the length of the chain at about 90 Ma and occurred again at about 70 Ma. The most recent volcanism was in the middle of the chain at about 37 Ma. The WNW Crosstrend ridges date from about 70 Ma (Davis et al., 2002), and are parallel to the much younger, non-hot spot Puka Puka Ridges west of the present-day East Pacific Rise (Sandwell et al., 1996; Lynch, 1999, Janney et al., 2000), and to the current direction of Pacific plate motion. Samples from these ridges include varieties of amphibole-bearing potassic mafic lava not found on emergent Pacific linear chains, but which are well known from, e.g., African rift valleys (Natland, 1976; Davis et al., 2002).

Early Cretaceous and Jurassic ocean crust, which extends from the Mid-Pacific Mountains to the western Pacific trenches, is so covered with large seamounts and their aprons (Menard, 1959) that an actual sample of ridge-related basalt has been difficult to obtain by drilling. Among these are hundreds of Mesozoic guyots capped with drowned reef platforms (e.g., Hamilton, 1956; Winterer et al., 1993; Haggerty and Premoli Silva, 1995). Based on isotope geochemistry, Koppers et al (in press) group these into several short seamount trains, but these are not age-progressive, and coeval trains dating from 130-90 Ma have sharply different trends. Lavas from these seamounts are mainly variably enriched alkalic basalts and related differentiates that are similar isotopically to lavas from the modern Polynesian linear island chains (Winterer et al., 1993; Koppers et al., in press).

The Mid-Pacific Mountains number several widely spread, very large, and elongate Mesozoic ridges that *splay* from ENE to E (Figure 1), thus which are not parallel. Such large, splayed ridges have no counterparts among the active linear chains of the Pacific, although less accentuated splaying occurs in the Tuamotus. Toward the west, seamount groups from the Wake to the Magellan seamounts have no clear or geographically persistent alignments. Instead, most are collections of large individual seamounts, guyots, and seamount-guyot clusters (Vogt and Smoot, 1986) that erupted throughout the same large region from 130-90 Ma (Winterer et al., 1993; Pringle et al., 1995; Koppers et al., in press). No similar congregation of large, isolated, and scattered volcanoes has formed anywhere else on the Pacific plate since that time.

We infer that orientations and distributions of seamount ridges on the Pacific plate are to first order controlled by tectonic stresses acting across the plate (Jackson and Shaw, 1975; Favela and Anderson, 2000; Smith, in press), and that volcanic alignments occur along fractures that are generally orthogonal to the direction of least principal stress (e.g., Fiske and Jackson, 1972; Nakamura, 1978). Since spreading ridges change orientation and geometry in response to consumption of ridge axes at trenches by migration of triple junctions along continental margins (e.g., Lonsdale, 1991), we assume that the stress field within a plate must change in complementary fashion, and that changes in directions of least principal stress will guide changes in patterns of lithospheric fracture that allow seamount volcanism to occur (Hieronymus and Bercovici, 2000, 2001). Major bends in linear volcanic chains reflect changes in the balance of stress orientations, not wholesale changes in plate motion, and splaying of ridges indicates either a non-uniform stress regime, or one that rotated through time (cf. Carey, 1958).

We thus construe three general periods with different stress regimes in the history of the Pacific plate.

1) When, during its earliest days in the Jurassic and Early Cretaceous, the Pacific plate was surrounded by ridge segments and was near the center of the huge world ocean, there were no major stress alignments within it. In this respect, it was much like that of the present-day Antarctic and African plates (Hamilton, 2002). Within-plate volcanism thus assumed the scattered arrangement predicted by the models of Hieronymus and Bercovici (2000) for the condition of *no tectonic stress*, and the large Magellan and Wake seamount clusters formed. Nonetheless, near the eastern boundaries of the plate, which were marked by migrating triple junctions, and which adjoined plates that were probably disappearing into subduction zones, complex and shifting patterns of ridge reorganization dictated formation of long, splayed, near-axis seamount ridges.

2) By about 90 Ma, the growing middle-aged Pacific plate achieved its first persistent stress regime with the formation of subduction boundaries along its western or northwestern margin. The plate was no longer static but began to move over the asthenosphere and into the mantle. The precise arrangement of those subduction boundaries and the overall direction of subduction are uncertain, but this imparted a general yet not fully stable component of tension across the plate. This stress combined with others produced the initial NNW Gilbert-Marshall, Musician, Line and Emperor Seamount ridges, orthogonal to the overall direction of least principal stress, and which still could vary somewhat from place to place. The Line Island seamount chain, being near ridge axes, thence to plates subducting into trenches in the eastern Pacific, sustained a more variable stress regime, thus its great width and dual orientations of ridges.

3) By 47 Ma, the Pacific plate was huge, and the Gondwanan dispersal of southern continents was shifting into a pattern of major continental collision. Plates east of the East Pacific Rise axis were growing smaller as the approaching Americas rolled them back at trenches. Nearly half of the boundaries of the Pacific plate now were also trenches spanning from the Aleutians to New Zealand. In addition, northward migration of the Indian plate and Australia caught a major portion of the westerly moving Pacific plate between the northeast corner of the Tonga Trench and the Aleutians. The plate could no longer shift laterally in response to whatever was occurring along its eastern spreading boundaries. A very consistent and possibly stronger stress regime therefore

developed across the Pacific plate with a NNE direction of least principal stress. The change in stress orientation may have taken up to 10 million years, during an interval marked by little or no volcanic productivity at the western end of the Hawaiian chain. Since that time, the predominant alignment of both linear island chains and Puka Puka-type ridges, from the Kodiak-Bowie chain in the Gulf of Alaska to the Louisville Ridge south of the Antarctic convergence, has been orthogonal to this direction. The expression of this stress regime nearest the Tonga Trench is the voluminous, elongate, WNW-trending, post-erosional volcanic sequence in the Samoan Islands, which is along the tensional crest of a bend in the plate dipping toward the transform portion of the trench (Natland, 1980).

Three additional hypotheses seem necessary to explain seamount volcanism on the Pacific plate. The first is that enriched mantle sources of variable geochemical provenance are distributed in a shallow layer at the base of the lithosphere. This geometry is required wherever volcanism has occurred simultaneously along very long ridges, as, e.g., the Samoan post-erosional volcanic rift zone (Natland, 1980), or the Puka Puka ridges in the eastern Pacific (Janney et al., 1999). Perhaps dispersed veins, schlieren, or blobs of enriched material, such as have been invoked to explain alkalic basaltic summits of near-ridge seamounts in the northeastern Pacific (Cousens, 1996), and that are readily subject to partial melting, produce melts that migrate and accrue at the base of aging and thickening lithosphere (e.g., Anderson, 1989, 1995; Niu et al., 2002). They may concentrate there because of shear dilatancy (Holtzman et al., 2003) at the base of the nearly impermeable lithosphere. The magmas are later tapped when regional stresses cause that lithosphere to fracture. The geometry of a zoned plume may instead be represented by lateral or vertical heterogeneity within a layered mantle. Enriched material attached to the base of the lithosphere may later become involved with volcanism a great distance away. This hypothesis says nothing about the ultimate depth of origin of the enriched material, the ages of its diverse isotopic components, or how they were transported vertically, only that it accrues through time at the base of the lithosphere. Isotopic similarities between Mesozoic seamounts of the far western Pacific to their likely backtracked locations near the modern chains of the Southwest Pacific (Staudigel et al., 1991; Koppers et al., in press) suggest persistence of this process in the same part of the upper mantle for more than 130 million years.

The second hypothesis is that some concatenation of stresses is likely required to localize the modern linear island chains, as for example plate-bending near the Samoan Islands. Although the general pattern of stresses acting across the Pacific plate appears to have a consistent orientation, the stresses sum from all boundaries of the plate, thus their magnitude within the plate cannot be uniform. The underlying asthenosphere itself could also bulge locally in response to plate-tectonic stresses, and develop concentrations of partial melt at the base of the lithosphere, where most basalts erupted on island chains appear to originate. The lithosphere may contain internal zones of weakness inherited from prior stress fields or local concentrations of more readily fusible and thus weaker materials. These will act to concentrate stress and initiate fractures (Lawn, 1993). The lithosphere will contain regions of great thickness and strength that will stop propagating fractures in their track or deflect them. Local hydraulic overpressure resulting from inequities in the distribution of ponded magma and magma buoyancy may drive fractures from underneath. Transfer of material from the base to the top of the lithosphere will modify the stress field and produce new stress concentrations that will become preferred locations of new volcanism (e.g., Hieronymus and Bercovici, 2001). Nevertheless, the general effect of a strongly directional stress field, one that developed through time on the Pacific plate, will be an equilibrium tendency (not always ideally satisfied) for parallel fractures to develop and to propagate in tandem at the rate of plate motion over the asthenosphere. On the other hand, once the lithosphere is fractured, the resulting lines of weakness should easily be reactivated by shifts in the stress regime, as in the Line Island seamounts (Davis et al., 2002) and the younger Cook-Austral chain (McNutt et al., 1997).

Finally, the large sizes of Pacific plateaus and some seamounts, seamount ridges, and linear island chains, require one or more of three things: 1) concentrations of mantle with high fertility, which is fundamentally an aspect of heterogeneity of the bulk composition of the mantle (e.g., presence of fertile peridotite, garnet pyroxenite, and/or eclogite); 2) differences in the size of master fractures through the lithosphere, effectively determining the ease or efficiency with which melt can rise through it – a valve effect; or 3) locally more vigorous convective turnover of mantle beneath the plate; the basalt-releasing conveyor belt moves faster. The latter, of course, is presumed in the plume hypothesis, but usually without consideration of whether 1 or 2 might be important. Even so, any such turnover in the upper mantle need not involve deep-mantle material (Sandwell et al., 1996).

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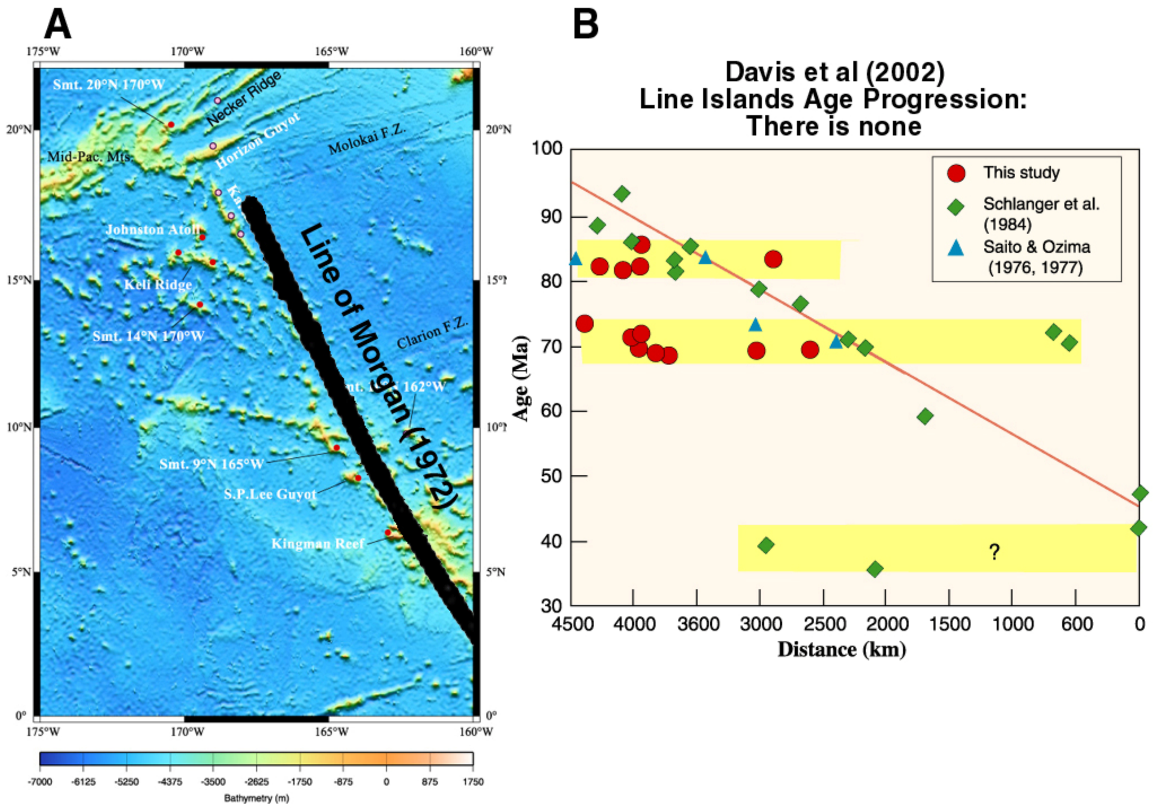

Figure 1

A. Bathymetry and B. age progression of the Line Islands seamounts, from Davis et al (2002). Bathymetry is taken from Smith and Sandwell (1997). Locations of 68-73 Ma volcanism are red dots; locations of 81-86 Ma activity are pink dots. The black line is the hypothetical age-progressive trend line of Morgan (1972a, b) paralleling the Emperor Seamounts. The line was selected from a scanned image of his figure, and is plotted here to the scale shown. The principal Line seamount trend and Line cross-trend ridges are evident in the bathymetry, as is the pattern of ridge splaying of the Mid-Pacific Mountains to the north. Ages in B, from sources cited in the figure, are plotted against distance from the Line-Tuamotu bend. "The diagonal red line represents rate of volcanic propagation (9.6±0.4 cm/yr) proposed by Schlanger et al (1984) as evidence for a hot spot trace. New ages indicate two major episodes of volcanism more than 10 million years apart. Ages of Schlanger et al (1984) from the southern Line Islands suggest another episode of volcanism ~ 40 Ma) in this region." (Davis et al., 2002, p. 17, caption to their Figure 8).