

Characteristics of the Hawaiian-Emperor Chain

The Hawaiian Ridge and Emperor seamounts lie along two parallel lines that appear to be the result of extensional fissures in the crust and upper mantle. Though the order of eruption appears to have progressed from northwest to southeast there are regions that seem to have erupted simultaneously. The large bend in the chain is thought to be the result of drastic change in Pacific plate motion and most likely occurred 24.6 ± 2.5 million years ago. The Hawaiian Ridge and the Emperor seamounts are both composed of shield volcanoes that erupted in the Tertiary or Quaternary periods.

“The Hawaiian Archipelago consists of a broadly linear chain of islands and seamounts extending more than 3,500 km across the central Pacific Ocean, from about Colahan Seamount on the northwest to the Island of Hawaii on the southeast (see Fig. 1). These islands and seamounts cap the Hawaiian Ridge, a pronounced topographic high on the ocean floor. The ridge crest is bordered by a symmetrical moat, or deep, which is as much as 0.7 km deeper than the surrounding ocean floor (Hamilton, 1957). The topographic highs on the ridge, for the most part, mark the central vent areas of shield volcanoes that are sub-merged and capped by coral in the northwest, deeply eroded in the central part, and active in the southeast.

Since the early work of Dana (1849, 1890), it has been known, largely from geomorphic evidence, that the extinction of the volcanoes that form the Hawaiian Archipelago generally progressed from northwest to southeast (see also Stearns, 1946, 1966). Only recently, however, was this order of extinction quantitatively confirmed by McDougall (1964), who determined K-Ar ages on lava from Kauai, Oahu, Molokai, Maui, and Hawaii. McDougall found that the volcanoes decreased systematically in age from Kauai (5.6 m.y. to 3.8 m.y.) to Hawaii (< 1 m.y.), and that the eruption of the tholeiitic lava during the shield-building stage of a single volcano proceeded rapidly. From these data he concluded that the order of commencement of eruption probably is reflected in the order of extinction, and he calculated a rate of migration of volcanism of about 10 to 15 cm/yr from northwest to southeast.”

The volcanoes that make up the Hawaiian ridge are about 75 km apart from one another. There is a visible pattern of eruption style in the upper parts of each shield. Tholeiitic eruptions dominate in the beginning giving way to much lesser amounts of alkalic and ending, in some instances,

with nephelinitic basalts. Eruptions during the Tholeiitic stage have some of the highest known eruptions rates on the planet. The Emperor seamount chain is much older and the submerged part of the Hawaiian- Emperor chain.

“The Emperor chain of seamounts extends nearly 2,500 km from the northwest end of the Hawaiian Ridge almost due north to the Aleutian Trench (see Figs. 1 and 2). The junction of the ridge with the seamount chain occurs at a sharp bend, and neither chain appears to extend beyond the intersection. Morgan (1972) suggests that the Emperor Seamounts are an older, completely submerged portion of the Hawaiian Ridge, and that the Hawaiian-Emperor bend represents an abrupt Tertiary change in the motion of the Pacific plate with respect to the underlying mantle. He estimates the age of this bend to be about 40 m.y. We have examined the available bathymetry in the vicinity of the bend and of the seamounts and concur with Morgan that the Emperor Seamounts are continuous with the Hawaiian Ridge. The seamounts form a submerged ridge similar to the Hawaiian one, and many segments of a symmetrical moat are preserved along both sides of the Emperor axis. Individual seamounts along both chains have characteristically smooth shield shapes, clearly distinctive from the rougher and steeper topography of older Cretaceous seamounts. The bathymetry in the region near the bend gives no indication of a projected continuation of either chain; rather the transition appears continuous (Fig. 1). The Emperor shields are about the same sizes as those of the Hawaiian group, and the bathymetry is detailed enough in places to show the probable rift zone configurations. The Emperor shields, however, are somewhat more widely spaced than the Hawaiian; the number of shields per linear 1,000 km of trend is about 13 for the former and 18 for the latter.”

The Hawaiian-Emperor ridge is located in the North-central part of the Pacific plate. The Hawaiian chain lies on middle Cretaceous period oceanic crust, the Hawaiian-Emperor bend lies on early Cretaceous period oceanic crust and the Emperor chain lies on Middle to late Cretaceous crust with a small amount of Eocene crust at the junction with the Aleutian Trench.

“Three major fracture zones cross the chain (Fig. 2). The Molokai fracture zone (Smith and Menard, 1965; Malahoff and others, 1966) passes between Oahu and Molokai (long 157.0° W., lat 21.2° N.) at an angle to the chain of about 30°. The Murray fracture zone (Raff, 1962; Menard, 1967; Malahoff and Woollard, 1968; Furumoto and others, 1971) probably crosses south of Pearl and Hermes Reef (long 175.8° W., lat 27.9° N.) at an angle of about 40°, and the Mendocino fracture zone (Menard, 1967) crosses the

Emperor chain just south of Ojin Seamount at an angle of about 75° to 80°. None of these fracture zones detectably affects the chain of shields, although they offset older magnetic anomalies by as much as 800 km (Vaquier and others, 1961; Smith and Menard, 1965; Heirtzler and others, 1968). Menard and Atwater (1968) consider these fracture zones to be fossil transform faults developed near mid-oceanic ridges during ocean-floor spreading, and note that the trend of the fracture zones marks the direction of spreading at the time of their formation. All three fracture zones are of Cretaceous age where they cross the Hawaiian-Emperor chain; it can be concluded that the Cretaceous spreading directions were 30° to 75° counterclockwise from the present trend of the chain.

Projected linear magnetic anomalies (Uyeda and others, 1967; Malahoff and Woollard, 1968; Flayes and Pitman, 1971) cross the chain at angles of 60° near Hawaii and 30° near Midway (177° W.), and show no change in trend across the Hawaiian-Emperor bend (Fig. 2). Anomalies projected from west of the Emperor Sea-mounts trend at 80° to 100° to that portion of the chain. Thus, the available evidence suggests that the alignment of the Hawaiian-Emperor chain of shield volcanoes was not influenced in any major way by the structure of the older Cretaceous sea floor on which the chain developed.

It has been apparent to us for some time that the individual volcanic shields, from Molokai south, lie along two curved lines that comprise the loci of shield centers (see inset, Fig. 1). The East Molokai, West Maui, Haleakala, Kohala, Mauna Kea, and Kilauea-shields lie on a northern locus, while the West Molokai, Lanai, Kahoolawe, Hualalai, and Mauna Loa shields lie on a southern locus. These loci correspond quite closely to the Kea and Loa series of Dana (1849). The shields are fairly evenly spaced on both lines. A large gap occurs in the southern locus between Kahoolawe and Hualalai, but a small bathymetric high lies near the middle of the gap, and might mark the position of a submarine shield. Furthermore, the order of eruption of the tholeiitic lava of these shields zigzags back and forth between the north and south lines. Radiometric ages, where available, and geomorphic and petrologic data elsewhere, allow us to deduce that over the last 1.8 m.y. the order of theoleiitic eruption was West Molokai, East Molokai, Lanai, West Maui, Kahoolawe, Haleakala, Kohala, Hualalai, Mauna Kea, Mauna Loa, and Kilauea, respectively. It would appear that the shields of the two loci have been advancing simultaneously, but somewhat out of phase, over the entire period. The southern locus may be reasonably extended northwestward, through both Oahuan shields and Kauai, which are progressively older. Beyond Kauai, no simple extension is possible. The position of Niihau is definitely offset, and, moreover, age data reported below suggest that Niihau is much younger than Kauai.”

The loci on the Hawaiian part of the chain is clockwise where as the loci on the Emperor part of the chain is counterclockwise.

“Looking at the chain as a whole, there are several features that should be emphasized: (1) the loci are sigmoidal; (2) the loci are parallel or sub parallel where they overlap; (3) loci in the Hawaiian portion tend to start 25 to 75 km north or east of the average linear centerline of the trend of the chain, and they swing south or west for about the same distance; loci in the Emperor portion start west and swing east; (4) for much of its length the chain is characterized by single loci, with only minor overlap where lines begin or end, but in several areas multiple (adjacent) loci are present; and (5) in the latter regions, many more shields and a much greater volume of basalt per linear kilometer of chain have been added to the sea floor than in the former regions.”

The age of the volcanoes and seamounts can be estimated by the oldest date provided since the shield formation was so rapid (the main mass formed in 0.5 million year or less). The oldest aged tholeiitic flows on the volcanoes and seamounts are only slightly younger than the date of origination of the volcano. Volcanisms from Kauai to Hawaii seems to have occurred in an accelerating manner in a sub parallel pattern.

“Wilson (1963) proposed that the Hawaiian chain owed its origin to the Pacific plate moving over a fixed hot spot in the mantle. Jackson and Wright (1970) pointed out that if only heat were supplied, the spreading plate must carry the source material for the volcanoes, and must extend therefore to depths of at least 100 km. They thought it equally likely that the south-eastward extension of the Hawaiian chain is due to a slowly propagating fracture that repeatedly taps fresh mantle, an old idea perhaps first phrased in modern form by Betz and Hess (1942). McDougall (1971) and Green (1971) share this idea, although they prefer a model involving diapiric intrusion of "high temperature" peridotite along lines of structural weakness. Morgan (1971, 1972) attributed both heat and magma to a continually rising plume of mantle material that originates far below the asthenosphere. He suggested that three island chains in the Pacific — the Hawaiian-Emperor, Fuamoto-Line Islands, and the Austral-Marshalls were generated by the motion of the rigid Pacific plate over three such hot spots in the mantle that are fixed with respect to each other. Morgan showed that the Emperor Seamount chain, the Line Islands, and the Marshall Islands all lie on small circles about a pole of rotation at 23° N. lat, 110° W. long. These island chains all bend eastward to become the Hawaiian Archipelago, the Tuamotos, and the Austral Islands, respectively, all of which lie on small circles about a pole at lat 67° N., long 73° W. McDougall (1971) considers the melting spot to be part of a region of return flow in the asthenosphere moving in a direction opposite to that of the lithosphere and at approximately the same speed. Thus, he suggests that the spot is not

fixed with respect to the lower mantle. In either case, the abrupt bend in the island chains represents a significant change in the motion of the Pacific plate with respect to the melting spot.”

The presence of a melting spot is commonly agreed upon however questions arise as to the temperature of the melting spot. The melting spot is defined as finite in size, located within the mantle where tholeiitic magma is generated and capable of eruptions to earth’s surface.

“Genesis aside, we can estimate the size of the Hawaiian-Emperor melting spot. From the data in Figures 1 and 3 it appears that volcanoes that occur on the same or on different loci in a given region may erupt simultaneously. For example, Waianae, Niihau, and perhaps Nihoa were in their tholeiitic eruptive phases at roughly the same time. The length of the melting spot along the chain, therefore, may be 200 to 400 km. The width between adjacent multiple loci in the southeastern part of the chain is presently only about 50 km. The multiples at Midway, however, give cross-chain distances of about 300 km. On the basis of present information, the vertical projection of the melting spot is most likely a circle about 300 km in diameter, whose previous path across the Pacific has been wide enough to include all of the volcanoes of the chain. We do not think the spot is currently centered on Kilauea, but rather northeast of there, because the curvature of the loci at Kilauea and Mauna Loa has carried the volcanic centers far south of the median line of the chain. We predict that a new locus of centers will begin about 40 to 50 km north or east of Kilauea, perhaps coincidentally on its currently active east rift, in the near future.”

Due to the fact that the source area is many times larger than the diameter of the shield it is possible and probable for simultaneous eruptions to occur which would create sigmoidal lines of loci.

“In order to estimate the age of the Hawaiian-Emperor bend and the rate of motion of the Pacific plate with respect to the melting spot, it is necessary to choose between three possible assumptions about the constancy of this rate through time. The first two of these assumptions are: (1) the rate has been constant during the formation of the Hawaiian segment and constant but different during the formation of the Emperor segment, and (2) the rate has been constant during the formation of the entire Hawaiian-Emperor chain. For each of these assumptions, it is possible to calculate a least-squares straight-line fit to all of the available data and then to calculate an age for the bend from the equation of the line

(Table 2). The only difference between these two fits is that the data for Suiko Seamount are excluded to meet the requirements of assumption (1). It seems reasonable to suppose that the inferred change in the direction of motion of the Pacific plate represented by the Hawaiian-Emperor bend was also accompanied by a change in rate, and, in our opinion, assumption (1) gives the best possible estimates for the rate motion of the Hawaiian segment (14.8 cm/yr) and for the age of the bend (24.6 ± 2.5 m.y.). Using these data and the age and position of Suiko Seamount, we calculate a rate of motion of 7.9 cm/yr for the Emperor segment (Table 2)."

The best age estimates of the Hawaiian-Emperor bend are 24.6 ± 2.5 m.y and the rate of motion is 14.8 cm/yr. These estimates are based on least-squares fit to the Hawaiian segment. A fixed hotspot hypothesis implies that all volcanic centers were formed in the present day location of Kilauea. However, paleomagnetic data suggests that Midway was formed as much as 15° south of Kilauea's latitude. Though this seems to imply hotspot motion there is not enough data at this time to support this theory.

"A change in the trend of the Emperor Seamounts occurs at the northern end of the chain, but this change is difficult to interpret. A locus of several shields trends northeast to intersect the Aleutian Trench (Fig. 1). Also, a broad, smooth topographic high trends to the north-west. Using the data of Table 2 to extrapolate to a possible age for this northern bend, we find that all values, except for the Kilauea to Necker extrapolation, fall within a range of 47 to 53 m.y. Morgan (1972) has proposed that the northern Line Islands bend westward to join the Mid-Pacific Mountains, and that the Marshall Islands bend westward to join the Magellan Seamounts. If the three melting spots that generated the Hawaiian-Emperor, Tuamoto-Line Islands, and Austral-Marshall chains were fixed with respect to each other at the time of this second bend, then the apparent northeastward trend for the older bend at the northern end of the Emperor Seamounts conflicts with the directions proposed by Morgan for the other two island chains. The northwest-ward bend is more in accord with Morgan's (1972) suggestion for the bends of the other chains. For all three chains there are far too few data in the regions of these possible older bends and the age and directions of these bends will have to await further study.

The reason for these apparent abrupt and drastic changes in the motion of the Pacific plate are not well understood. It is possible that a sudden change in the location and activity of subduction resulted in changes in plate motion. Alternatively, a change in activity of convective processes in the mantle may have produced the change in plate motions directly. In this regard, Morgan (1971, 1972) suggests that plumes of deep mantle material

beneath the melting spots spread out horizontally below the lithosphere, driving the plates. On the other hand, if McDougall's (1971) hypotheses are correct, then the melting spot becomes a secondary disturbance in the asthenosphere, and cannot drive the lithospheric plate.”

The data presently available lead us to the following conclusions:

- The Hawaiian Ridge and Emperor Seamounts are part of a single chain of shield volcanoes erupted during Cenozoic time. The position of the chain and of individual volcanoes within the chain do not appear to have been influenced in any major way the structure of the older oceanic crust on which they rest.
- In detail the chain is not a simple linear feature. It appears to have operated on short, sigmoidal, en echelon segments that are nested with respect to each other, and that are locally adjacent and multiple. These segments are the loci of shield volcanoes and may be the result of extension in the Pacific plate.
- The ages of these shields, while generally older in the north and younger in the south-east, are not, in detail, systematic in the way previously supposed. It appears that simultaneous tholeiitic eruptions have occurred within circular areas having maximum diameters of roughly 300 km. Furthermore, even along individual loci, the rates of progression of volcanism are not linear where best studied.
- A melting spot roughly 300 km in diameter seems to have existed during the life of the chain and now appears to, be centered about 40 to 50 km north of the Island of Hawaii. We are unable to say whether this spot is abnormally hot or whether the volcanism is due to release of pressure.
- In general, the northwestward increase in the age of eruption of volcanoes in the Hawaiian-Emperor chain is consistent with a genesis related to the passage of the Pacific plate over a melting spot in the mantle. This hypothesis requires a change in motion of the Pacific plate at the time of formation of the Hawaiian-Emperor bend (Morgan, 1972). Our best estimate of the age of the bend is 24.6 ± 2.5 m.y. An age of about 30 ± 3 m.y. cannot be precluded, but a younger extreme of about 20 m.y. seems highly unlikely.

- The change in plate motion required to produce the Hawaiian-Emperor bend is about 12 cm/yr in a west-southwestward direction, if the melting spot is fixed. We suggest that this new motion resulted in strong compression on the western boundary of the Pacific plate. The age of about 25 m.y. for this event corresponds to a period of renewed tectonic activity in the western Pacific island arcs, and also to changing plate boundaries in the northern and eastern Pacific. If the melting spot is not fixed, no rigorous determination can be made for quantitative boundary effects, although McDougall's (1971) hypotheses give vectors of about one half the magnitude of those that we calculate using Morgan's (1972) hypothesis.
- In calling attention to the structural and temporal significance of the chain, we wish to emphasize the critical need for more data on the compositions, radiometric ages, and especially apparent paleomagnetic latitudes of the individual volcanic shields within the chain, particularly those of the Emperor segment and in the vicinity of the Hawaiian-Emperor bend. The age of what may be a second, older bend now near the Aleutian Trench should also be determined.

Though this paper was written over 20 years ago it introduces the possibility that the hotspot is not fixed and throughout history has had different latitudes. Work is still being done today to determine if in fact the hotspot has moved in the past.