AGE AND TECTONIC RELATIONSHIPS
AMONG VOLCANIC CHAINS ON THE PACIFIC PLATE

A DISSERTATION SUBMITTED TO THE GRADUATE DIVISION OF THE UNIVERSITY OF HAWAII IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY IN GEOLOGY AND GEOPHYSICS DECEMBER 1978

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ABSTRACT

The Hawaiian-Emperor volcanic chain is used as a model to predict the ages of other volcanic chains on the Pacific plate. The Hawaiian-Emperor chain is assumed to have been formed at a hot spot, and is thus used to approximate the direction of motion of the Pacific plate relative to the hot spot coordinate system. The rate of motion of the plate relative to the Hawaiian hot spot is determined from the age data along the Hawaiian-Emperor chain. As a first approximation, hot spots are considered fixed relative to each other, and consequentially, coeval volcanic chains formed at hot spots follow small circles about a common pole. Poles of rotation for motion of the Pacific plate relative to the Hawaiian hot spot from about 68 m.y.b.p. to present were determined from the Hawaiian-Emperor chain. No assumptions were made about the relative ages of other volcanic chains. Three small volcanic chains north of the Hawaiian ridge were used to determine a plate to hot spot coordinate system pole applicable from about 125 m.y.b.p. to 68 m.y.b.p. Oblique latitude-longitude systems about these poles were plotted on a normal Mercator projection and compared to bathymetric charts of the Pacific ocean. Volcanic chains parallel to oblique lines of latitude about the same pole are taken to be coeval.

Using the preceding technique, most of the volcanic chains on the Pacific plate can be attributed with confidence to a hot spot origin; thus age predictions on volcanic chains formed since 68 m.y.b.p. are straightforward. There is some uncertainty about the direction and rate of plate to mantle motion prior to 68 m.y.b.p., and, consequentially, the ages of volcanic chains older than 68 m.y. are less certain. The number of hot spots active at any given time and the life span of hot
spots is variable; however, hot spots in the Pacific move very little relative to each other.

Once the relative ages of volcanic chains are established, chains formed during the same time interval are used to determine poles representing the average motion of the Pacific plate relative to the underlying mantle. Seven poles are required to describe plate motion back to 125 m.y.b.p.

In the Pacific there is a geometric relationship between linear volcanic chains and old plate boundaries. The Emperor chain is related to a transform fault between the Mesozoic and Cenozoic magnetic lineations in the northwest Pacific, and the Tuvalu-Gilbert-Radak (Ellice-Gilbert-Marshall) chain is related to a transform in the Phoenix lineations. These transforms may have had some influence on the structure of the volcanic chains. The three volcanic chains north of the Hawaiian ridge are very nearly parallel to the Mesozoic and Cenozoic magnetic lineations between the Mendocino and Murray fracture zones. This relationship suggests that these chains may be related to ridge jumps. Thus between 42 and 68 m.y.b.p. plate to mantle motion was parallel to the direction of spreading on the older Pacific-Phoenix and Pacific-Kula spreading ridges, and prior to 68 m.y.b.p., plate to mantle motion was parallel to the Pacific-Farallon ridge between the Mendocino and Murray fracture zones.
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1. INTRODUCTION

The primary objective of this investigation is to predict the ages of volcanic chains on the Pacific plate. The Hawaiian-Emperor volcanic chain is assumed to have been formed as the Pacific plate moved over a melting anomaly in the asthenosphere, and is thus used to approximate the direction of motion of the Pacific plate relative to the mantle. The age data on the Hawaiian-Emperor chain are used to determine the rate of motion of the Pacific plate over the Hawaiian melting anomaly, and as a model to predict the ages of other volcanic chains on the plate. Age predictions are based on the assumption that coeval volcanic chains formed as the plate moved over different melting anomalies will follow small circles about a common pole or poles. Poles of rotation for motion of the Pacific plate relative to the mantle from ~125 m.y.b.p. to present are determined from the Hawaiian-Emperor chain and from three short chains north of the Hawaiian ridge. Oblique latitude-longitude systems about these poles are plotted on normal Mercator projections. Coeval volcanic chains will be parallel to oblique lines of latitude about the same pole. The data necessary for this investigation are the age data along the Hawaiian-Emperor chain and the bathymetric charts of Chase et. al. (1971) and Mummerickx et al. (1975). Ages of other volcanoes on the Pacific plate are used as a check on the age predictions.

The linearity of volcanic groups in the Pacific Ocean has been noted since the work of C. Darwin and J. D. Dana in the mid-nineteenth century. After these initial exploratory expeditions and resulting publications, a major paper speculating on the origin of linear volcanic chains appeared about every ten years. Most of these early papers suggested that some sort of fracturing was responsible for the origin of volcanic chains. The hot
spot hypothesis of Wilson (1963a, b, c) was the first of a series of 
hypotheses related to plate tectonics.

Appendix A gives a summary of the hypotheses on the origin of vol-
canic chains. These hypotheses fall into five major categories: (1) hot 
spot-mantle plume, (2) propagating fracture, (3) thermal feedback, (4) old 
plate boundary, and (5) regional fracture system. A sixth possibility is 
a fracture propagating at some angle to the direction of plate motion. 
Plate reconstructions and geometric constraints, such as those used in 
this study, cannot distinguish between the hot spot, propagating fracture, 
or thermal feedback mechanisms since the surface manifestations of these 
mechanisms may have the same characteristics; e.g., the surface manifes-
tations may be fixed with respect to plate motion. Therefore, for the 
purposes of this study, the hypotheses are divided into two classes. 
Class I includes the hot spot, propagating fracture, and thermal feedback 
hypotheses. These hypotheses are characterized by melting anomalies that 
are located in the astenosphere or below, and are relatively fixed with 
respect to each other. In this paper the surface manifestation of a melt-
ing anomaly will be referred to as a hot spot, without reference to the 
origin of the melting anomaly; i.e., hot spot will be used as a general 
term for Class I mechanisms. Class II hypotheses include: (1) old plate 
boundary, (2) regional fracture system, and (3) fracture propagating at 
an angle to plate motion. The old plate boundary hypothesis actually only 
considers ridges and transform faults. Convergent boundaries generate a 
different type of volcanic chain. Individual volcanoes and small chains 
of volcanoes are occasionally associated with ridge crests and transform 
faults; however, this is not a common occurrence. Chains formed by a 
Class II mechanism need not be related to a plate to mantle pole and may
trend at an arbitrary angle to small circles about such a pole. However, these chains may be detected by their relationship to other linear features on the plate; e.g., magnetic anomalies.

Section 2 discusses the methods and assumptions used in this study, and the criteria for selecting poles of rotation which represent the motion of the Pacific plate relative to the Hawaiian melting anomaly.

Section 3 summarizes the data on the size of the Hawaiian melting anomaly and certain of its petrologic and geochemical characteristics.

In section 4, it is pointed out that pre-existing structure may locally influence the size and trend of a volcanic chain. These local influences suggest that small scale curvature of volcanic chains and volume of extrusion versus age relationships must be interpreted with caution.

Section 5 gives the predicted age relationships of the volcanic chains. The majority of the volcanic chains on the Pacific plate can be attributed confidentially to a Class I mechanism.

Section 6 discusses three volcanic chains which may have been formed by a Class II mechanism. These are the Wentworth, North Gardner, and Musicians chains located north of the Hawaiian ridge. These chains may have been formed by ridge jumps between the Mendocino and Murray fracture zones.

Once the relative ages of the volcanic changes have been established, chains formed in the same age range can be used to determine the average motion of the Pacific plate relative to the underlying mantle. Poles and rates of rotation for this motion are given in Section 7.

In addition to volcanic chains, other linear features on the Pacific plate include the Emperor and Nova-Canton troughs, present plate
boundaries, and past plate boundaries, as expressed by transform fault
traces and magnetic lineations. The technique used in this study has re-
vealed some previously unobserved relationships among these linear fea-
tures. The most puzzling is the relationship between volcanic chains and
pre-existing plate boundaries. These relationships are discussed in sec-
tion 8.

Section 9 is a summary and discussion of this investigation.
2. ASSUMPTIONS AND METHOD

2.1. Assumptions

In this investigation the following is assumed:

(1) The Pacific plate is rigid.

(2) The Hawaiian-Emperor chain was formed at a hot spot, and therefore, provides an estimate of the direction of motion of the Pacific plate relative to the mantle for the past 70 to 80 m.y.

(3) The age data along the Hawaiian-Emperor chain can be used to determine the rate of motion of the Pacific plate relative to the Hawaiian hot spot.

(4) As a first approximation, hot spots can be considered fixed relative to each other, and, therefore, coeval volcanic chains formed by hot spots will follow small circles about the same plate to mantle pole.

2.2. Oblique grid systems

The best available bathymetric charts of the Pacific are those of Chase et al. (1971) and Mannerickx et al. (1975) which are plotted on Mercator projections. Assuming that volcanic chains follow small circles about a pole of rotation, it is convenient to plot small circles about this pole superimposed on a normal Mercator projection. Thus the bathymetric data do not have to be transferred to another projection as was done in earlier studies (e.g., Clague and Jarrard, 1973; Jarrard and Clague, 1977). Figure 2.1 shows an oblique grid system superimposed on a standard latitude-longitude system and on a normal Mercator projection (Wong et al., 1975). Lines of latitude and longitude for the oblique grid system are shown as curved lines on the normal Mercator projection. The spacing between the oblique grid lines is distorted by the Mercator
Figure 2.1. Oblique grid system about poles $P_1$ and $P_2$ superimposed on the normal latitude-longitude coordinate system (left) and on a normal Mercator projection (right). From Wong et al. (1975).
projection just as other areas are distorted; thus areas on the Mercator projection can be compared directly with the oblique grid system. If the correct pole has been determined for a volcanic chain, then the volcanic chain should be parallel to an oblique line of latitude on the oblique projection constructed about that pole. This provides, among other things, a mechanism for testing how well a given pole represents the motion of the plate across the melting anomaly, and is a convenient way to check on the accuracy of both plate to mantle and plate to plate pole positions.

Oblique grid systems plotted on a normal Mercator projection are the principal analytical tool used in this study. Oblique grids are plotted about plate to mantle pole positions, as determined from the Hawaiian ridge, Emperor seamount chain, and three chains north of the Hawaiian ridge, for different age ranges. Coeval volcanic chains will be parallel to lines of latitude about the same pole. Some uncertainty may arise because oblique grid lines about different poles may be parallel in some regions, thus preventing a discrimination of the age bounds of volcanic chains in that region. This problem will be discussed as it arises.

2.3. Poles of rotation

Bullard et al. (1965) were the first to point out that the fixed point theorem, or Euler's theorem, is applicable to movements on the surface of the earth. McKenzie and Parker (1967) and Morgan (1968) showed that the relative motion of two plates on the surface of the earth could be defined as a rigid rotation about a vertical axis through some point on the surface of the earth. For instantaneous motions this point is termed a pole of rotation; for total movement during some time interval, as in the case of Bullard et al.'s (1965) application, this point is termed a center of rotation. Morgan (1968) demonstrated that a pole of
rotation can be located by constructing great circles normal to a small circle; two or more great circles intersect at the pole of rotation. The relative motion of two plates is thus defined by the pole and the relative angular velocity of the plates about that pole. Linear volcanic chains formed at a hot spot should describe small circles about a pole of rotation which, together with the angular velocity, defines the motion of the plate relative to the mantle or hot spot coordinate system. It should be noted that a third type of pole of rotation is also commonly used. Paleomagnetic and sediment distribution studies make use of poles which define the motion of a plate with respect to the earth's spin axis. The relationships and implications of plate to mantle and plate to spin axis motion are discussed in Appendix B.

This investigation will use linear volcanic chains to determine plate to mantle poles, and will refer to these poles unless otherwise stated. Since linear volcanic chains define finite rotations as opposed to instantaneous rotations, these are, strictly speaking, centers of rotation; however, following Morgan (1972b) the term pole of rotation will be used.

Table 2.1 gives the location of poles of rotation determined by other investigators from linear volcanic chains on the Pacific plate (see also Figure 2.14). With the exception of the Minster et al. (1974) pole (for the last 10 m.y. of the Hawaiian ridge) all of these investigators used more than one volcanic chain to determine each pole. This is an implicit assumption that the volcanic chains used to determine a given pole were formed during the same time interval.

2.4. Motion of the Pacific plate over the Hawaiian hot spot

In this investigation only the Hawaiian ridge and the Emperor seamount chain are used to determine poles representing the past 68 m.y. of
Table 2.1. Plate to mantle poles of rotation from volcanic chains on the Pacific plate

<table>
<thead>
<tr>
<th>Latitude (°N)</th>
<th>Longitude (°W)</th>
<th>Reference</th>
<th>Rate of Rotation (°/m.y.)</th>
<th>Volcanic Chains Used</th>
</tr>
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<tr>
<td>Hawaiian Ridge</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>67</td>
<td>73</td>
<td>1</td>
<td>0.85**</td>
<td>Hawaiian, Tuamotu, Austral</td>
</tr>
<tr>
<td>72</td>
<td>83</td>
<td>2</td>
<td>1.3-0.5*</td>
<td>Hawaiian, Cook-Austral, Guadalupe, Line cross</td>
</tr>
<tr>
<td>69</td>
<td>68</td>
<td>2</td>
<td>-</td>
<td>Hawaiian, Cook-Austral, Guadalupe</td>
</tr>
<tr>
<td>67</td>
<td>45</td>
<td>3</td>
<td>1.1*</td>
<td>Several chains parallel to Hawaiian</td>
</tr>
<tr>
<td>67.3</td>
<td>59.4</td>
<td>4</td>
<td>0.83</td>
<td>Inversion of all plate motion with respect to the hot spot coordinate system</td>
</tr>
<tr>
<td>Emperor Seamount Chain</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>110</td>
<td>1</td>
<td>0.75***</td>
<td>Emperor, Line, Gilbert-Marshall</td>
</tr>
<tr>
<td>17</td>
<td>107</td>
<td>2</td>
<td>0.8</td>
<td>Emperor, Tuamotu, northern Louisville, plus several short chains</td>
</tr>
<tr>
<td>23</td>
<td>108</td>
<td>3</td>
<td>0.5-0.7</td>
<td>Emperor, Line, plus other lines</td>
</tr>
</tbody>
</table>

1 Morgan (1972b)
2 Clague and Jarrard (1973)
3 Winterer (1973)
4 Minster et al. (1974)

* Relied on incorrect age for Midway
** 34° total rotation in 40 m.y.
*** 45° total rotation in 60 m.y.
Pacific plate motion. Thus, in determining these poles no assumptions are made about the relative ages of any other volcanic chains. Estimates of pole positions were obtained by drawing a curved line through the majority of the volcanoes in the Hawaiian and Emperor chains (Figures 2.2 and 2.3) and constructing several great circles normal to this line. Figure 2.4 shows the great circles constructed normal to the Hawaiian ridge. These great circles intersect all over the northwest quadrant and do not yield a well determined pole. This suggests that either (1) the curved fit in Figure 2.2 is not a good approximation to the small circle, or (2) there have been changes in the direction of plate motion relative to the Hawaiian hot spot in the past 42 m.y. If the great circles from different segments of the Hawaiian ridge are considered separately, it appears that the great circles fall into three groups. The great circles constructed along the older portion of the ridge, from the Hawaiian-Emperor bend to near Lisianski, fall into one group; those from near Lisianski to near Maui fall into a second group; and those constructed along the eastern end of the ridge form a third group. Figure 2.5 shows the great circles constructed along the Emperor chain. Again the pole position is not well determined, and the great circles can be separated into three groups.

The Hawaiian and Emperor chains are not a simple single line of volcanoes, but in places are several volcanoes wide. Therefore, the oblique grip system that confined the volcanic chain to the narrowest band along an oblique latitude was assumed to best represents the motion of the plate over the hot spot. Most of the Hawaiian ridge and Emperor seamount chain can be confined within a band on the order of 100-120 km wide. The oblique grid systems obtained from the curved line approximations to the Hawaiian and Emperor chains did not provide a satisfactory fit to the chains.
Figure 2.2. Curved fit to volcanoes in the Hawaiian ridge.
Figure 2.3. Curved fit to the Emperor seamount chain.
Figure 2.4. Great circles from curved fit (Figure 2.2) to the Hawaiian ridge.
Figure 2.5. Great circles from curved fit (Figure 2.3) to the Emperor seamount chain.
Fortunately, given one or more oblique grid systems it is easy to see how the pole must be moved to improve the fit. The poles which best represent motion of the Pacific plate over the Hawaiian hot spot were obtained by this extrapolation technique. Oblique grid systems were plotted for extrapolated pole positions until satisfactory fits were obtained.

Deciding which oblique grid system fits best is somewhat subjective inasmuch as no oblique grid system fits exactly. In the case of the Hawaiian ridge, part of the island of Hawaii, part of Gardner Pinnacles, and some of the volcanoes around Midway could not be confined with the rest of the ridge within one degree of latitude. These exceptions are significant and will be discussed later. In addition, oblique grid lines with slightly different pole positions may be parallel in the region of interest. Thus to obtain confidence limits on the pole positions oblique grid systems were plotted for a number of poles surrounding the best fit pole; those that fit the volcanic chain were included within the confidence limits. Figures 2.6 and 2.7 show the location of the poles of the oblique grid systems used to determine the best fitting poles and their estimated error ellipses for the 0-23 m.y., 23-42 m.y., and 42-68 m.y. age ranges. These figures also show the pole positions of oblique grid systems used to determine the 14-23 m.y. and 42-68 m.y. average motion poles; section 7.

The bathymetric chart of Chase et al. (1971) and also an unpublished Hawaii Institute of Geophysics bathymetric chart show that the Hawaiian ridge changes trend west of Lisianski. This is consistent with the change suggested by the great circle intersections in Figure 2.4. In addition, it is not possible to fit the entire length of the Hawaiian ridge in a one degree wide band. Two oblique grid systems about different pole
Figure 2.6. Pole positions of oblique grid systems used to determine the location of the best fitting pole and approximate error ellipses for the 0-23 m.y. and 23-42 m.y. age ranges fit to the Hawaiian ridge. The pole positions numbered are those of 1-Morgan (1972b), 2-Clague and Jarrard (1973), 3-Winterer (1973) and Lancelot and Larson (1975), 4-Minster et al. (1975). See Table 2.1. Also shown are the pole positions used to determine the 14-23 m.y. average motion pole (section 7) fit to the Hawaiian ridge, Gulf of Alaska chains, Austral chain, and Louisville chain. Polar projection.
Figure 2.7. Pole positions of oblique grid systems used to determine the location of the best fitting pole and approximate error ellipse for the Emperor seamount chain (42-68 m.y.), and for the average motion pole (section 7) fit to the Emperor, Tuvalu-Gilbert-Radak (TGR), and Louisville chains. The numbers are from the investigators listed in Figure 2.6 and Table 2.1 in addition to 5-Lancelot and Larson (1975). Mercator projection.
positions are necessary. The best fitting oblique grid systems are shown in Figure 2.8. The poles for these projections are located at $65^\circ N 40^\circ W$ for the eastern end of the ridge, and $59^\circ N 54^\circ W$ for the western end. These grid systems confine the change in trend to between Lisianski island and Pearl and Hermes reef.

The Emperor seamount chain has an obvious change in trend at about $50^\circ N$. South of this change the chain can be fit by one oblique grid system with a pole at $10^\circ N 98^\circ W$ (Figure 2.9). The bathymetry suggests a slight change in trend near $44^\circ N$. The great circle intersections in Figure 2.5 also suggest that the Emperor chain might be fit by two poles, one for the section south of $\sim 44^\circ N$, and the other for the section from $\sim 44^\circ N$ to $\sim 50^\circ N$. However, oblique grid systems with poles at $7^\circ N 98^\circ W$ (for the section south of $\sim 44^\circ N$) and $23^\circ N 102^\circ W$ (for the section from $\sim 44^\circ N$ to $\sim 50^\circ N$) do not fit the chain conclusively better than the oblique grid system with a pole at $10^\circ N 98^\circ W$. Thus, although there is a suggestion of a change in plate motion at $\sim 44^\circ N$, this change cannot be confirmed by the criteria used in this study.

For comparison, Figures 2.10 and 2.11 show oblique grid systems obtained in this investigation, and, in addition, those obtained using the poles given in Table 2.1 fit to the Hawaiian and Emperor chains.

In section 7, I show that the average motion of the Pacific plate relative to the mantle for the past 68 m.y. requires six poles; however, to predict the ages of other volcanic chains during this time interval (section 5), only three poles are necessary.

2.5. Motion of the Pacific plate prior to 68 m.y.b.p.

There are three roughly parallel chains of volcanoes north of the Hawaiian ridge (see Figure 6.1). The western chain trends northwest
Figure 2.8. Oblique grid systems about poles (65°N 40°W and 59°N 54°W) which best fit the Hawaiian ridge in the age ranges 0-23 m.y. and 23-42 m.y. Oblique latitude spacing is 1° and oblique longitude spacing is 5°.
Figure 2.9. Best fitting oblique grid system about 10°N 98°W for the Emperor seamount chain. The two lines north of 50°N show the fit of the oblique latitude lines about 36°N 76°W to the northern end of the chain. Oblique latitude spacing is 1° and oblique longitude spacing is 5°.
Figure 2.10. Comparison of the oblique grid systems superimposed on the Hawaiian ridge. A-this investigation, B and C-Clague and Jarrard (1973), D-Morgan (1972b), E-Winterer (1973), F-Minster et al. (1974). Oblique latitude spacing is 1° and oblique longitude spacing is 5°.
A-65°N 40°W (0-23 M.Y.)
59°N 54°W (23-42 M.Y.)
B-72°N 83°W
C-69°N 68°W

D-67°N 73°W
E-67°N 45°W
F-67.3°N 59.4°W
Figure 2.11. Comparison of oblique grid systems superimposed on the Emperor seamount chain. 10°N 98°W—this investigation, 17°N 107°W—Clague and Jarrard (1973), 23°N 110°W—Morgan (1972b), 23°N 108°W—Winterer (1973), 11°N 89°W—Lancelot and Larson (1976). Oblique latitude spacing is 1° and oblique longitude spacing is 5°.
from near Midway. Wentworth seamount, located just northwest of Midway, has been dated at 71.0±0.3 m.y. (Clague and Dalrymple, 1975). This volcano is probably a part of the northwest trending chain and not a part of the Hawaiian ridge. This chain of volcanoes will be called the Wentworth chain. The central chain will be called the North Gardner chain because the southward extension of this chain intersects the Hawaiian ridge at Gardner Pinnacles. The eastern chain forms the western boundary of the Musicians seamounts between the Mendocino and Murray fracture zones.

It was first assumed that these chains were formed at three hot spots and could be used to determine a plate to mantle pole. (This assumption will be reconsidered later.) Oblique grid systems were obtained for each chain, and the final pole position was obtained by extrapolating to the pole position which best fit all three chains (Figure 2.12). Small circles about this pole are parallel to the Emperor chain north of 50°N, the Line islands, and several other volcanic chains (section 5). Assuming that the Emperor chain was formed by a hot spot, this pole represents plate to mantle motion for some period prior to 68 m.y.b.p. If the Line islands were formed by a hot spot, an old age limit (~125 m.y.; see section 2.7) for plate to mantle motion about this pole can be determined.

2.6. Ages along the Hawaiian-Emperor chain

Jarrard and Clague (1977) summarized the available age data for Pacific volcanoes. Since their summary, Dalrymple et al. (1977) have published a revised age for Midway (27.0±0.6 m.y.) and Bonhomme et al. (1977) have published an age for Lanai (1.25±0.04 m.y.). Preliminary dates for Northampton, Layson, and Jingu (B. Dalrymple, personal communication to M. Garcia), and for Ojin, Nintoku, and Suiko (J. Morgan,
Figure 2.12. Oblique grid system about 36°N 76°W superimposed on the Wentworth, North Gardner, and Musicians chains. Oblique latitude spacing is 1° and oblique longitude spacing is 5°.
personal communication) are close to the ages predicted by a linear propagation of volcanism.

In interpreting this age data the following problems must be considered. First, the location of the sample within the eruptive sequence of the volcano must be known. The age of the main shield building lavas may vary considerably. Late stage tholeiitic and alkalic eruptions are relatively short lived and dates on these lavas are best for inter-volcano age comparison. The eruption of post-erosional undersaturated lavas may occur at more or less random times after the main shield building and late stage eruptions. (See section 3 for further discussion of this problem.) Thus, when compared to shield building and late stage ages, post-erosional lavas will be young by some undetermined amount. The second problem is that alteration of the sample tends to produce young ages. In view of these problems, age data should be interpreted to give the least significance to ages which appear too young. Because of the greater number of samples, and probably because the samples are from above sea level and are, therefore, relatively unaltered, the errors in dating the Hawaiian islands are small compared to the errors in dating volcanoes along the western part of the chain.

Figure 2.13 shows the published ages versus distance from Kilauea for the Hawaiian-Emperor chain. Distances were measured along oblique lines of latitude plotted for the poles given in the preceding section. These distances are slightly different from the straight (rhumb) line distances and those measured along the curved loci defined by Jackson et al. (1975). These data are given in Table 2.2. The ages versus distance along the Hawaiian-Emperor chain do not fall on one straight line. The lines in Figure 2.13 have been fit by eye and, to facilitate
Figure 2.13. Age of Hawaiian-Emperor volcanoes versus distance from Kilauea. Ages are from Jarrard and Clague (1977), Dalrymple et al. (1977), and Bonhommet et al. (1977). Distances were measured along oblique lines of latitude.
Table 2.2. Ages and distances along the Hawaiian-Emperor chain.*

<table>
<thead>
<tr>
<th>Volcano</th>
<th>Distance from Kilauea (km)</th>
<th>Age (m.y.)</th>
<th>Rock</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kilauea</td>
<td>0</td>
<td>0</td>
<td>Tholeiite</td>
</tr>
<tr>
<td>Kohala</td>
<td>67</td>
<td>0.45-0.33</td>
<td>Tholeiite</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.25-0.06</td>
<td>Alkaline basalt</td>
</tr>
<tr>
<td>Haleakala</td>
<td>122</td>
<td>0.84-0.45</td>
<td>Alkaline basalt</td>
</tr>
<tr>
<td>West Maui</td>
<td>178</td>
<td>1.30-1.16</td>
<td>Alkaline basalt</td>
</tr>
<tr>
<td>Lanai</td>
<td>211</td>
<td>1.25±0.04</td>
<td>Tholeiite</td>
</tr>
<tr>
<td>East Molokai</td>
<td>217</td>
<td>1.48-1.31</td>
<td>Alkaline basalt</td>
</tr>
<tr>
<td>West Molokai</td>
<td>244</td>
<td>1.84</td>
<td>Tholeiite</td>
</tr>
<tr>
<td>Koolau</td>
<td>311</td>
<td>2.6-1.84</td>
<td>Tholeiite</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.85-0.03</td>
<td>Post erosional Honolulu series</td>
</tr>
<tr>
<td>Waianae</td>
<td>356</td>
<td>3.8-3.0</td>
<td>Tholeiite</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.1-2.4</td>
<td>Alkaline basalt</td>
</tr>
<tr>
<td>Kauai</td>
<td>500</td>
<td>5.62-3.9</td>
<td>Tholeiite</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.84</td>
<td>Alkaline basalt</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.42</td>
<td>Post erosional Koloa series</td>
</tr>
<tr>
<td>Niihau</td>
<td>561</td>
<td>3.00±0.2</td>
<td>Tholeiite (one flow)</td>
</tr>
<tr>
<td>Nihoa</td>
<td>745</td>
<td>7.0±0.3</td>
<td>Tholeiite</td>
</tr>
<tr>
<td>Necker</td>
<td>1056</td>
<td>10.1±0.3</td>
<td>Rhyolite porphyry</td>
</tr>
<tr>
<td></td>
<td></td>
<td>77.6±0.17</td>
<td></td>
</tr>
<tr>
<td>LaPerouse</td>
<td>1222</td>
<td>11.7±0.4</td>
<td>Tholeiite</td>
</tr>
<tr>
<td>Pinnacles</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Northamton</td>
<td>1811</td>
<td>20-21**</td>
<td></td>
</tr>
<tr>
<td>Pearl and</td>
<td>2266</td>
<td>20.1±0.5</td>
<td>Alkaline basalt</td>
</tr>
<tr>
<td>Hermes Reef</td>
<td></td>
<td>18.4±0.6</td>
<td>Phonolite</td>
</tr>
<tr>
<td>Volcano</td>
<td>Distance from Kilauea (km)</td>
<td>Age (m.y.)</td>
<td>Rock</td>
</tr>
<tr>
<td>-----------------------</td>
<td>---------------------------</td>
<td>----------------------</td>
<td>-------------------------------------------</td>
</tr>
<tr>
<td>Midway</td>
<td>2417</td>
<td>27.0±0.6</td>
<td>Tholeiite</td>
</tr>
<tr>
<td>Wentworth</td>
<td>2484</td>
<td>71.0±0.3</td>
<td>Alkaline basalt</td>
</tr>
<tr>
<td>Unnamed Seamount</td>
<td>2567</td>
<td>27.3±0.4</td>
<td>Alkaline basalt</td>
</tr>
<tr>
<td>Unnamed Seamount</td>
<td>2800</td>
<td>26.7±0.5</td>
<td>Alkaline basalt and analcime tephrite</td>
</tr>
<tr>
<td>Kanmu</td>
<td>3467</td>
<td>37.5-43</td>
<td></td>
</tr>
<tr>
<td>Diakakuji</td>
<td>3511</td>
<td>41.3±2.2</td>
<td></td>
</tr>
<tr>
<td>Yuryaku</td>
<td>3567</td>
<td>42.3±1.6</td>
<td></td>
</tr>
<tr>
<td>Kinmei</td>
<td>3667</td>
<td>38.9±1.2</td>
<td></td>
</tr>
<tr>
<td>Koko</td>
<td>3834</td>
<td>46.4±1</td>
<td></td>
</tr>
<tr>
<td>Jingu</td>
<td>4226</td>
<td>47.49**</td>
<td></td>
</tr>
<tr>
<td>Suiko</td>
<td>4867</td>
<td>58.1±0.6</td>
<td></td>
</tr>
<tr>
<td>Meiji</td>
<td>5889</td>
<td>67-70</td>
<td></td>
</tr>
</tbody>
</table>

**Preliminary value

*Distances were measured along small circles about poles at 65°N 40°W, 59°N 54°W, and 10°N 98°W; see section 2.1.

Ages are from Jarrard and Clague (1977), Bonhommat et al. (1977), Dalrymple et al. (1977), Saito and Ozima (1977), and Dalrymple (personal communication to M. Garcia).

Ages are as listed in these references and were calculated using the pre-1977 decay constants.
discussion have been labeled A through E. Line B was drawn to best fit the data on the eastern end of the chain. Lanai and East Molokai fall slightly below the line. Niihau falls significantly below and will be discussed below. Line B does not intersect Kilauea at the origin of the plot. With the exception of West Molokai, the dates from Kilauea to Koolau fit on line A. Line C was drawn to best fit the data on the eastern end of the chain, in addition to corresponding to the age of the bend between Lisianski and Pearl and Hermes (see above) determined by the age data west of the bend. There is some allowable variation in the slope of this line since the exact location of the bend is not known. In any case, this line does not fit the data east of Oahu. Neither line B nor C satisfactorily fit the data west of the Lisianski-Pearl and Hermes bend. The fit to the data northwest of Midway is less well constrained because there are fewer data. Lines D and E give the range of possible fits for this data. The Hawaiian-Emperor bend has been dated at 42.0±1.4 m.y. (Dalrymple and Clague, 1976), and both lines D and E are within 0.2 m.y. of this date.

The dates of six of the volcanoes in the Hawaiian-Emperor chain are younger than expected; i.e., they don't fit the assumed linear rate of propagation of volcanism. The date for Niihau is based on only one K-Ar age determination, and Jarrard and Clague list this date as a "concordant age, probably reliable." According to Macdonald (personal communication), however, the great amount of erosion on Niihau is consistent with Niihau being older than Kauai. Obviously more data from this island would be useful. As pointed out above, undersaturated basalts can yield dates that are too young. Such is apparently the case for Pearl and Hermes reef and the unnamed seamount ~380 km west of Midway. Clague et al. (1975) state
that the samples from Pearl and Hermes are nepheline phonolite and that
the samples from the seamount west of Midway are analcime tephrite, which
were probably derived from a post-erosional nephelinitic suite. The sam-
ples from the seamount ~160 km west of Midway are alkalic basalt and
Jarrard and Clague (1977) list the date from this seamount as reliable.
Of the three samples from this seamount which were dated, two are unal-
tered. The age for this seamount is, however, only ~1 m.y. younger than
predicted by a linear rate of propagation of volcanism. The sample from
Kinmei seamount is an altered alkali basalt (Darymple and Clague, 1976)
and the young date may be the result of alteration. The nannoplankton age
for Meiji seamount is about 5 m.y. too young and is listed as a minimum
age by Jarrard and Clague (1977). Thus the dates for these six volcanoes
may be due to sampling and dating problems.

2.7. Age ranges for pole positions, rates of motion and propagation
of volcanism

The age data in Figure 2.13 suggests that the rate of propagation of
volcanism has changed at 0.5-2.0 m.y.b.p. and at 20-25 m.y.b.p. There is
presently no evidence for a change in the rate of propagation of volcanism
at the Hawaiian-Emperor bend, at the suggested bend in the Emperor chain
near 44°N, or at the bend in the Emperor chain near 50°N. The rate of
propagation for the past 0.5-2.0 m.y. appears to be high, on the order
of 160 mm/yr. Between 0.5-2.0 and 20-25 m.y.b.p. the rate was on the
order of 76 mm/yr.

The southern part of the island of Hawaii falls south of the one
degree band which fits the eastern end of the Hawaiian ridge. This sug-
gests that there has been a change in the direction of plate to mantle
motion, which is supported by the change in the rate of propagation
0.5-2.0 m.y.b.p. However, this may also be an indication that the melting anomaly has a diameter somewhat greater than 100 km.

The change in rate of propagation of volcanism at 20-25 m.y.b.p. corresponds to the change in trend of the Hawaiian ridge between Lisianski and Pearl and Hermes reef. On the basis of the fit by oblique grid systems, this bend occurs between 1667 and 2445 km from Kilauea, with the center of the one degree oblique band bending near 2167 km from Kilauea. The range of possible ages at 2167 km is 21-24.5 m.y., so an age of 23 m.y. is assigned to this bend. The Hawaiian-Emperor bend occurs 3556 km from Kilauea and has been dated at 42.0±1.4 m.y. (Dalrymple and Clague, 1977). The bend in the Emperor chain near 50°N occurs between 5445 and 5612 km from Kilauea. The maximum range in the ages of these distances (from the data in Figure 2.13) is 65.8 to 70.2 m.y., with a mean of 68 m.y. The northern end of the Emperor chain is fit by the oblique grid system obtained for the Musicians, North Gardner, and Wentworth chains (Figure 2.9). This bend in the Emperor chain gives an approximation for the younger age limit for this pole. The older age limit is less certain. Two seamounts in the Musicians have been dated (Jarrard and Clague, 1977). Extrapolation of dates on Rachmaninoff and Khachaturian give an older limit of 150 m.y. However, a linear extrapolation of magnetic anomalies suggests that the lithosphere in this region of the Pacific may not be 150 m.y. old. As will be shown later, this oblique grid system also fits the Line islands. There is a reliable age of 126 m.y. (Saito and Ozima, 1977) in the northern Line islands, and on the basis of this date it is assumed that this pole is applicable from about 68 to approximately 125 m.y.b.p.
Thus, for the purposes of predicting the ages of other volcanic chains on the Pacific plate, pole positions were determined for four age ranges: 0-23 m.y., 23-42 m.y., 42-68 m.y., and 68-125 m.y. Pole positions for those intervals and rates of rotation about these poles are given in Table 2.3. Rates of motion of the Pacific plate over the hot spot are given in Table 2.4. Since different time intervals have been averaged, the rates of motion over the hot spot do not correspond exactly to the rates of propagation of volcanism. Figure 2.14 shows these pole positions together with the pole positions obtained by the investigators listed in Table 2.1.

2.8. Relative motion of hot spots

If hot spots move relative to one another, coeval volcanic chains may deviate from small circles about a plate to mantle pole. For example, if the Macdonald hot spot has moved relative to the Hawaiian hot spot, then the Austral chain may lie at an angle to the small circles about the pole of rotation found for the Hawaiian ridge. The angle between the small circle and the volcanic chain will depend on the rate of motion of the plate relative to the mantle, the rate of motion of the hot spot, and the angle of relative motion. Rates of motion of the plate over the Hawaiian hot spot vary from 73 to 94 mm/yr (Table 2.4). There is, however, considerable uncertainty about the relative rates of motion of hot spots. Morgan (1972b) noted that the Austral-Gilbert-Marshall volcanic chain did not exactly fit the pattern predicted by the motion of the Pacific plate over fixed hot spots. According to his analysis the Austral chain is 10% longer than predicted and the Ellice-Gilbert-Marshall chain (Tuvalu-Gilbert-Radak chain in this paper) is 25% shorter than predicted. In addition, the Ellice-Gilbert-Marshall chain did not fall
Table 2.3. Poles of rotation of the Pacific plate relative to the Hawaiian hot spot.

<table>
<thead>
<tr>
<th>Time Interval</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Rotation</th>
<th>Rate of Rotation</th>
</tr>
</thead>
<tbody>
<tr>
<td>(m.y.)</td>
<td>(°N)</td>
<td>(°W)</td>
<td>(degrees)</td>
<td>(°/m.y.)</td>
</tr>
<tr>
<td>0-23</td>
<td>65</td>
<td>40</td>
<td>19.7</td>
<td>0.86</td>
</tr>
<tr>
<td>23-42</td>
<td>59</td>
<td>54</td>
<td>12.7</td>
<td>0.67</td>
</tr>
<tr>
<td>42-68</td>
<td>10</td>
<td>98</td>
<td>17-18.5</td>
<td>0.68</td>
</tr>
<tr>
<td>68-125*</td>
<td>36</td>
<td>76</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

*Estimated maximum age
Table 2.4. Rate of propagation of volcanism along the Hawaiian-Emperor chain and the rate of motion of the Pacific plate over the Hawaiian hot spot.

<table>
<thead>
<tr>
<th>Age (m.y.)</th>
<th>Rate of Propagation of Volcanism (mm/yr)</th>
<th>Distance from Kilauea (km)</th>
<th>Rate of Motion over Hot Spot (mm/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>160</td>
<td>2167</td>
<td>94</td>
</tr>
<tr>
<td>2</td>
<td>75-100</td>
<td>3556</td>
<td>73</td>
</tr>
<tr>
<td>23</td>
<td>76</td>
<td>5556</td>
<td>76</td>
</tr>
</tbody>
</table>


Figure 2.14. Pole positions from this investigation and from the investigators listed in Table 2.1: 1 and 6-Morgan (1972b), 2-Minster et al. (1974), 3 and 4-Clague and Jarrard (1973), 5 and 7-Winterer (1973). Poles 5, 8, and 9 were determined by Lancelot and Larson (1976).
along the predicted trend. Morgan used these discrepancies as a measure of the rate of relative motion of hot spots, which he predicted could be 5 mm/yr. Minster et al. (1974) concluded that there had been no measurable motion among hot spots during the past 10 m.y. Molnar and Atwater (1973) considered plate reconstructions between 21 and 38 m.y.b.p. and concluded that the principal hot spots in the Atlantic and Indian oceans had moved relative to the Hawaiian hot spot at 8-20 mm/yr. Molnar and Francheteau (1975) found that the principal hot spots in the Atlantic and Indian oceans moved relative to one another at 10-20 mm/yr during the Cenozoic (<70 m.y.b.p.). Burke et al. (1973) considered the Azores and Colorado seamounts in the North Atlantic, and Tristan da Cunha-Gough, Discovery seamount, and Bouvet island in the South Atlantic. They concluded that during the past 125 m.y. there had been little relative motion within each group, but that the two groups had moved relative to each other at an average rate of 18 mm/yr. This rate varies from 50 mm/yr (100 to 80 m.y.b.p.) to 5 mm/yr (25 to 0 m.y.b.p.). Some of these reconstructions may have assumed an incorrect direction of motion for Iceland (Morgan, personal communication), which may account for the high rates of relative motion of hot spots.

In terms of the present analysis, the greatest uncertainty would occur if a hot spot were moving rapidly at right angles to the Hawaiian ridge. If the relative motion between hot spots is 50 mm/yr and the plate is moving at 75 mm/yr relative to the Hawaiian hot spot, the discrepancy between the volcanic chain and small circles about the Hawaiian poles could be as large as 34°. This is the worst possible case and obviously requires a unique set of circumstances. In general, the relative motion between hot spots will be much less than 50 mm/yr and the hot spots
will not be moving at right angles to the Hawaiian ridge. In any case, the possibility that coeval volcanic chains may deviate from small circles will be considered in the following analysis.

2.9. Age date on volcanoes on the Pacific plate

At the time of the compilation of Jarrard and Clague (1977), reliable dates had been obtained from only 44 volcanoes on the Pacific plate. Of these, 19 are in the Hawaiian-Emperor chain, 6 in the Marquesas, 5 in the Austral-Cook chain, 4 in the Gulf of Alaska, and 2 each in the Samoan, Line, Musicians, Society, and Pitcairn-Gambier chains. In addition, Jarrard and Clague list 9 dates as "probably reliable," 5 as "single age-reliability unconfirmed," and 30 as "minimum age." Since this summary, dates have been obtained from six additional volcanoes in the Hawaiian-Emperor chain: Midway (Dalrymple et al., 1977), Lanai (Bonhomme et al., 1977), Suiko (Saito and Ozima, 1977), Jingu, Northampton, Laysan (Dalrymple, personal communication with M. Garcia) Ojin, Nintoku, and Suiko (J. Morgan, personal communication). The date for Midway is particularly significant because it is close to that predicted by a linear rate of propagation of volcanism along the Hawaiian ridge and therefore, drastic changes in plate motion, as suggested by Clague and Jarrard (1973) for example, are no longer necessary to explain the age data.

In addition to Suiko, Saito and Ozima (1977) give dates for seven seamounts in the Line islands and a date for Necker ridge (plus dates for two DSDP samples). Ozima et al. (1977) give dates for six volcanoes in and to the west of the Marshall islands. Two of these dates, for Renard and Seiko, may not be reliable. Dymond and Windom (1968) give dates for three volcanoes just south of the Hawaiian ridge. Thus, at present, there are about 60 reliable K-Ar dates on Pacific volcanoes.
3. MELTING ANOMALY UNDER THE HAWAIIAN RIDGE

The existence of the Hawaiian ridge requires that there be a source of magma at some depth under the ridge. Present activity indicates that this source is now located under the island of Hawaii. The exact nature of this magma source is fundamental to resolving the question of the origin of linear volcanic chains. The source of magma will be referred to as a melting anomaly since melting at some depth in the mantle is necessarily a part of all hypotheses on the origin of linear volcanic chains.

This section will discuss the size of the melting anomaly and some of its petrologic aspects.

Hawaiian volcanoes are composed mostly of tholeiitic basalt. Toward the end of the principal period of volcanism there is a change in composition. Late stage lavas constitute from 0.1 to 3% of the volcano (Macdonald, 1963) and are composed mostly of alkali basalts and related differentiates. These lavas may be interlayered with tholeiitic lavas, or there may be a hiatus between the last tholeiitic eruption and the late stage eruptions (Carmichael et al., 1974). Following a hiatus of 0.2 to 2 m.y. there is a renewal of activity with the eruption of a small volume of highly undersaturated basalts. These "post-erosional" lavas are composed of alkalic olivine basalt, nephelinites, and basanites (Macdonald and Abbott, 1970). Thus the composition of lavas erupted during the last stages of activity show a progression from tholeiitic to alkalic to nephelinitic—from saturated to very undersaturated. This progression is common to most of the Hawaiian islands, and may also occur on the submerged volcanoes along the northwest part of the ridge. This progression is often extrapolated to ocean island volcanism in general, but it may not be a universal progression.
There have been a number of estimates of the size of the melting anomaly beneath the Hawaiian ridge. Morgan (1971, 1972a) suggested that plumes from the core mantle boundary have a diameter of about 150 km. Jackson et al. (1972) connected Hawaiian volcanoes with sigmoidal loci and pointed out that the distance between loci is about 50 km, except in the Midway area. They also pointed out that coeval eruptions along the Hawaiian chain occurred on volcanoes 200-400 km apart; and, therefore, suggested that the melting anomaly was roughly 300 km in diameter. The source region for an individual volcano appears to be smaller. Jackson and Wright (1970) studied the distribution of xenoliths on Oahu and concluded that the source area had a diameter of about 20 km. Koyanagi and Endo (1971) showed that under Kilauea the earthquakes accompanying the rise of magma from depth were confined to a cylinder 25 km in diameter.

The two obvious surface manifestations of the size of the melting anomaly are, as pointed out by Jackson et al. (1972), the cross chain width and the distance between coeval eruptions along the chain. Using the poles of rotation discussed in section 2 the Hawaiian ridge volcanoes can, with a few exceptions, be confined to a one degree or 111 km band (see Figure 2.8). If the post-erosional eruptions and the 3 m.y. date on Niihau are eliminated, then the distance between coeval eruptions is generally less than 100 km (see Figure 2.13). If we include post-erosional eruptions, then the distance between coeval eruptions is at least 300 km—the distance between Kauai and west Maui, and may be as much as 1500 km if the young age for Koko post-erosionals (Moberly and Larson, 1975) is correct.

The fact that the cross chain width is nearly the same as the distance between coeval tholeiitic and alkalic eruptions suggests that the
melting anomaly at the base of the lithosphere is on the order of 100-120 km in diameter, and that the post-erosional nephelinitic eruptions occurred after the volcano was past the melting anomaly.

If, however, the post-erosional eruptions are eliminated in determining the size of the melting anomaly, the question of the relationship of the melting anomaly to the post-erosional lavas must be addressed. The following aspects of the melting anomaly will be considered: fractional crystallization, partial melting, and different sources.

Fractional crystallization - Yoder and Tilley (1962) showed that the thermal divide between tholeiite and alkalic basalt types does not exist at high pressures. Alkalic magmas can be produced by fractional crystallization of an olivine tholeiitic parent at pressures of 10-20 kbars (Ringwood, 1975, p. 138). Alkalic magmas can in turn fractionate to basanitic and nephelinitic magmas at pressures of 20-35 kbars (Ringwood, 1975, p. 140). These pressures correspond to depths of 35-70 km and 70-122 km. Wright and Fiske (1971) and Wright (1973) show that lavas erupted at Kilauea have a history of fractionation and mixing in shallow magma chambers. Fractionation in deeper magma chambers may also occur. Thus it is possible to account for the major element chemistry of Hawaiian lavas by fractionation of a tholeiitic magma which is derived from the melting anomaly. As a volcano passes over the melting anomaly tholeiitic magma is injected into the lithosphere. Some of this magma might not go immediately to the surface but be trapped in chambers in the lower lithosphere where fractional crystallization produces undersaturated magmas. The late stage alkaline lavas might have spent some time in the lower lithosphere at depths of 35-70 km, and might have been pushed up by the pressure from late erupting tholeiitic magmas. At some later time, perhaps as the result of
stresses due to loading by younger volcanoes (Jackson and Wright, 1970, and Moore, 1970), magmas trapped at depths greater than 70 km would come to the surface to produce the post-erosional lavas.

Gast (1968) showed, however, that trace element abundances in tholeiitic and alkalic basalts were not consistent with a fractional crystallization origin. The trace element distribution in Hawaiian nephelinites may be compatible with a derivation by fractional crystallization from an alkalic parent, however.

Partial Melting - Ringwood (1975) points out that the experimental results on magma fractionation are also applicable to formation of basaltic magmas by partial melting. Just as an olivine tholeiitic parent magma can fractionate to produce alkali basalts, basanites and nephelinites within certain pressure ranges, these magmas can be produced by varying degrees of partial melting of hydrous mantle material (pyrolite or garnet peridotite) within the same pressure ranges. The amount of partial melting required is dependent on the water content of the mantle, the depth of melting and the depth at which the liquid separates from the residual crystals. However, the amount of partial melting required decreases with decreasing silica saturation; on the order of 30% for tholeiitic magmas to less than 1% for highly undersaturated magmas such as olivine melilite nephelinites (Gast, 1968; Ringwood, 1975).

Thus the progression of rock types observed on Hawaiian volcanoes could be produced if the degree of melting decreases near the edge of the melting anomaly. The Hawaiian ridge is apparently not chemically zoned across the chain, which suggests that either: (1) the melting anomaly is not symmetric, i.e., partial melting decreases along the chain but not across the chain; or (2) the melting anomaly is symmetric but the
undersaturated magmas are not sufficiently voluminous to reach the surface unless they can follow the conduit system established by earlier tholeiitic eruptions. There is uncertainty as to how much melt is necessary before diapiric rise of magma will occur. Yoder (1976, p. 112) suggests, based on the data of Wright et al. (1968), that under undisturbed conditions approximately 45% melting is required before diapir will form. Ringwood (1975) suggests that, depending on physical conditions, 2 to 30% of a volume must be melted before magma will separate from the source. Obviously, if the source region is disturbed by some regional tectonic compression the degree of melting required will be reduced. It is difficult to account for the hiatus between the late stage and post-erosional eruptions if partial melting alone is the process which forms the Hawaiian lavas. As pointed out above, if the post-erosional magmas come from the same melting anomaly as the rest of the volcano, the melting anomaly must be very large. It does not seem reasonable for the tholeiitic and alkalic producing regions of the melting anomaly to be confined to a diameter of $\sim 100$ km while the region which produces the post-erosional lavas continues outward for another 300 to 1000 km.

Trace element abundances appear to be compatible with a model in which Hawaiian alkali basalt magmas result from a smaller degree of partial melting and tholeiitic basalt magmas from a greater degree of partial melting of the same source rock (Carmichael et al., 1974).

It may be that the trace element abundances are compatible with a mechanism whereby the late stage alkalic lavas are derived from the edge of the melting anomaly and the post-erosional lavas result from fractional crystallization of alkalic magmas in the lower lithosphere. As a volcano leaves the melting anomaly, the degree of melting decreases and alkalic
magma is injected into the lithosphere. Since the degree of melting is small, the volume is small. Some alkalic magma remains in chambers in the lower lithosphere after the volcano has passed over the melting anomaly and here the magmas fractionate to nephelinites and basanites. There are a number of factors which will control the subsequent evolution and eruption of these magmas, and these factors may be responsible for the differences in the length of the hiatus and the duration of post-erosional eruptions on different Hawaiian volcanoes. The volume of alkalic magma, the rate of ascent of the magma, and the rheological properties of the magma are interrelated and will influence the evolution of the magma (Sparkes et al., 1977). Variation of one of these factors, volume for example, may control the duration of the hiatus and the duration of the post-erosional eruptions. In addition, loading of the lithosphere by younger volcanoes will tend to reopen the conduits and force the magma to the surface.

This is similar to a model proposed by Green (1971), in which he suggested that rapid upwelling leads to extensive partial melting and the formation of tholeiitic magmas. During the late stage volcanism the magma source is isolated and begins moving with the lithosphere. Late stage magmas are the result of either a small degree of partial melting or high-pressure crystal fractionation of tholeiitic magma. In his model, the post-erosional volcanism is caused by local transverse tensional faulting (caused by loading) tapping the source region in the lower lithosphere. He suggests that a two-stage melting process might account for the trace element distribution.

Different sources - In recent years isotope geochemists have presented numerous data and arguments for a heterogenous mantle. For example, $^{87}\text{Sr}/^{86}\text{Sr}$ ratios for ocean island basalts are generally higher
and more variable than for mid-ocean ridge basalts, which implies that the mantle is heterogeneous both vertically and horizontally (Hofmann and Hart, 1978). These heterogeneities, at least for lead and strontium, appear to have existed for 1-3 b.y. (Sun and Hanson, 1975). It is hypothesized that the mantle was originally homogeneous and that some thermal event resulted in the production of local regions enriched in Rb/Sr and a large volume of material that is depleted in Rb/Sr (Hedge, 1978). Mid-ocean ridge basalts are presumably derived from the depleted material. Ocean island basalts are derived from the undepleted or the enriched material with perhaps some mixing with depleted material. There is some question about how this material is zoned in the present mantle. Schilling (1973) suggested that in the Atlantic the asthenosphere is depleted and is underlain by an undepleted lower mantle. Hedge (1978) finds a horizontal zonation in the Pacific and suggests that the asthenosphere is undepleted and contains local enriched regions. The lower mantle is depleted and is the source of mid-ocean ridge basalts. Ocean island magmas would come from the asthenosphere, or in some cases, such as Samoa, from the enriched regions. Differences in isotopic abundances are generally interpreted as implying a heterogeneous source. For example, O'Nions et al. (1977) analysed a number of Hawaiian rocks for \( \frac{^{143}Nd}{^{144}Nd} \) and \( \frac{^{87}Sr}{^{86}Sr} \) and concluded that these ratios provide evidence for long-term heterogeneities in Rb/Sr and Sm/Nd in the source region of Hawaiian basalts. Their data show no correlation with rock type. Leeman et al. (in press) studied REE abundances from Mauna Loa and from Kilauea and concluded that different degrees of melting could not account for the differences in REE patterns but that these differences were consistent with origin by partial melting of different mantle source regions.
These authors suggest that the source for Mauna Loa magmas is deeper than the source for Kilauea.

Fundamental to the interpretation of isotope and trace element data is the assumption that during partial melting the melt fraction is in equilibrium with the source rock for the elements in question. If equilibrium obtains, then variabilities in isotopic composition of fresh volcanic rocks are assumed to reflect isotopic heterogeneities of the source, (Hofmann and Hart, 1978). These authors consider the kinetics of elemental diffusion and conclude that local equilibrium prevails in a partially molten mantle and disequilibrium prevails in a totally crystalline mantle. Thus they favor a vertically stratified mantle to explain the observed isotopic variations.

Figure 3.1 (from Hofmann and Hart, 1978) shows $^{87}\text{Sr}/^{86}\text{Sr}$ for mid-ocean ridge basalts and for ocean islands. Figure 3.2 shows the $^{87}\text{Sr}/^{86}\text{Sr}$ data of Hart (1973) and O'Nions et al. (1977) for Hawaiian rocks. These data show that, with the exception of four groups of islands: the Azores, Kerguelen, St. Paul, and Samoa, the range in $^{87}\text{Sr}/^{86}\text{Sr}$ ratios for ocean island basalts is less than for mid-ocean ridge basalts, although the absolute value of $^{87}\text{Sr}/^{86}\text{Sr}$ is generally higher for the islands. This suggests that while there may be large regional heterogeneities, the source region for an individual island, or series of islands in the case of Hawaii, is relatively homogeneous. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios for Hawaiian rocks (Figure 3.2) show no correlation with rock type or with an individual island (since the range on the island of Hawaii is large). The mechanism causing the volcanism on the Azores, Kerguelen, St. Paul and Samoa may be more complex than that causing volcanism on the other islands. The Azores and St. Paul are located on major fracture zones;
Figure 3.1. Comparison of $^{87}\text{Sr}/^{86}\text{Sr}$ for mid-ocean ridge basalts (MORB) and oceanic islands. The MORB data are plotted against the number of samples $n$. The number of samples is indicated by the number in the square; a blank square indicates one sample. From Hofmann and Hart (1978).
Figure 3.2. Strontium isotope data for Hawaiian volcanoes. The first four values are from Hart (1973); the remainder are from O'Nions et al. (1977).
Kerguelen is located on an oceanic plateau which presumably has thick crust; and Samoa is apparently located on the hinge line where the Pacific plate is downbuckled and probably faulted into the Tonga trench (Hawkins and Natland, 1975).

Tatsumoto (1978) gives a comprehensive discussion of lead isotope abundances in oceanic basalts with particular reference to Hawaii. He finds that the Pb isotopic composition of the five volcanoes on the island of Hawaii are distinctly different, and that the Pb isotopic composition is variable for different lava flows on the same volcano. Significantly, he finds that the Pb isotopic compositions of late stage alkaline lavas are within the variation of the Pb isotopic composition of the tholeiitic lavas for each volcano. He says: "This result is consistent with a hypothesis that the later stage alkalic lava is a fractionated product of tholeiitic lava. In the case of Hawaiian eruptions the alkali basalts and tholeiites of each volcano appear to originate from the same source or closely related sources, and they could not have come from different depths in the heterogeneous mantle." Tatsumoto prefers a two-source mixing model, and for Hawaii he suggests that the two sources are the mantle plume and the lithosphere, with different reservoirs containing different proportions of plume and remelted lithospheric material. As the lithosphere moves over the melting anomaly the reservoirs are isolated from the source. Each reservoir then differentiates to produce magmas which become progressively less silica saturated. Based on his analysis of Hawaiian Pb concentrations, Tatsumoto suggests that if lithospheric assimilation is not considered, the scale of regional mantle homogeneity is on the order of 50-100 km.
Thus Tatsumoto's model is consistent with a homogeneous melting anomaly with a diameter of ~100 km located below the lithosphere under Hawaii. It is also consistent with the major element variations observed in Hawaiian volcanoes. It remains to be seen if his model is consistent with other trace element concentrations in Hawaiian lavas.
4. EFFECTS OF PRE-EXISTING STRUCTURAL FEATURES ON VOLCANIC CHAINS

4.1. Effects of pre-existing structure on the Hawaiian ridge

Structures which date from 68-125 m.y.b.p. had a pronounced effect on the Hawaiian ridge. This effect is most noticeable where the extensions of the Wentworth, North Gardner, and Musicians chains intersect the Hawaiian ridge (Figures 2.12 and 6.1). The volume of extruded material at these locations is much larger than elsewhere along the ridge. The volume of extrusion in the Midway area was less than in the Gardner Pinnacles and Hawaii areas and, therefore, the Midway volcanoes did not coalesce into a single edifice. The volcanoes in the intersecting chains are much smaller than those in the Hawaiian ridge, so the increased volume of extruded material cannot be due solely to incorporation of older volcanoes in the Hawaiian ridge. The old dates for Wentworth and Necker (Clague and Dalrymple, 1975), indicate that the Hawaiian ridge does include older volcanoes, however. In section 6 I suggest that the Wentworth, North Gardner, and Musicians chains are the result of ridge jumps. If so, there may be some residual structural or thermal anomaly which caused, or allowed, an increased in the volume of extruded lavas, and perhaps an increase in magma production when the ridge-jump chains passed over the melting anomaly. These increases in the volume of extrusion are more likely related to local structural effects than to some global synchronossness of mantle plume convection as suggested by Vogt (1972).

It appears that the trend of rift zones of isolated Hawaiian volcanoes is controlled by 68-127 m.y. old structure. In their study of the orientation of rift zones of Hawaiian volcanoes, Fiske and Jackson (1972) noted that the average trend of the rift zones of isolated volcanoes deviates by about 40° clockwise from the trend of the Hawaiian ridge.
In the vicinity of the Hawaiian ridge, small circles about the 68-127 m.y. pole deviate from small circles about the 0-23 m.y. pole by 36°, clockwise.

There is a third, intriguing correlation between 68-125 m.y. old structure and the Hawaiian ridge. The changes in trend of the Hawaiian ridge, which occur at 1 and 15 m.y., are located very near the intersections with the Musicians and North Gardner chains. This is probably not a cause and effect relationship, however, since changes in trend occur at the same times in other volcanic chains on the Pacific plate.

There is only one obvious correlation between Hawaiian ridge structure and the 42-68 m.y. old trend. The north-south striking trough between Gardner Pinnacles and St. Rogatien bank is exactly parallel to small circles about the 42-68 m.y. pole. The cause of this trough is unknown. A similar feature exists in the Emperor seamount chain. The southern flank of Nintoku seamount is very straight and steep, and, in this case, is perpendicular to small circles about the 68-125 m.y. pole.

The Mendocino, Murray, and Molokai transform fault traces do not appear to have had an effect on the volume of Hawaiian ridge volcanism. The section of the Hawaiian ridge where the Mendocino intersects has the least amount of extruded material of any section of the ridge. The section of the ridge where the Murray intersects has an average amount of extruded material, and the section where the Molokai intersects has a high volume of extruded material. The lithosphere changes age across a transform fault and, therefore, the rate of thermal contraction will change across a transform fault trace. This differential contraction will tend to maintain the transform; however, by the time the lithosphere is 70-80 m.y. old, the differential contraction will be small. If the lithosphere is thickening with age, the new material must be added to the
bottom. This will tend to heal the transform fault. Thus it seems unlikely that a transform fault trace will have any expression at the bottom of old lithosphere. Consequentially, the transform trace will probably have no effect on a melting anomaly as the lithosphere passes over. Once magma is injected into the lithosphere, however, it may tend to follow old fractures that still exist in the upper part of the lithosphere.

4.2. Effect of fracture zones in controlling the trend of individual and composite volcanoes

In a number of volcanic chains there are short cross trends which appear to have been controlled by fracture zones or transform fault traces. This effect is most apparent in the Musicians seamounts where continuous ridges parallel the Murray fracture zone. In this case, the relationship is complex since the Musicians may be the result of a ridge jump (section 6).

In the Gulf of Alaska there are several cross trends which appear to be related to transform fault traces. For example Bean ridge parallels the Sila fracture zone, and in the Cobb chain there are three east-west trending ridges that appear to lie on an eastward extension of the Sila. The northeast trending Guide ridge, the Parker-Shaw-Gilbert group, and the north-south trending Hook ridge appear to be controlled by fractures which have no obvious relation to plate motions.

Mururoa island in the Pitcairn-Gambier chain, and Marutea island in the Tuamotu chain, form an east-west trend which parallels the Austral fracture zone. In the Society chain, a series of four small volcanoes, including Bora-Bora and Maupiti islands, form a short east-west trend roughly parallel to the Tuamotu fracture zone.
The fact that these short cross trends are parallel to transform fault traces suggests that fracture zones have some local effect on volcanism, even though they do not control the overall trend of the volcanic chain. The fracture zones may be zones of weakness, at least in the crust. When the fracture zone passes over a melting anomaly, some magma may be injected into the fracture zone, and, if the volume of magma is sufficiently large, a volcano or series of volcanoes may be formed along the fracture zone. This process may be analogous to the injection of magma from the summit reservoir into the east rift zone of Kilauea.
5. AGE PREDICTIONS ON VOLCANIC CHAINS

5.1. Chains contemporaneous with the Hawaiian-Emperor chain

Table 5.1 lists the volcanic chains that are contemporaneous with the Hawaiian ridge, 0-42 m.y., and the Emperor seamount chain, 42-68 m.y., and the angle each chain makes with small circles about the appropriate pole. It is noted that there are 13 chains in the 0-42 m.y. age range, and only four in the 42-68 m.y. age range.

Gulf of Alaska - Morgan (1972b) claimed that two minor hot spots in the Gulf of Alaska generated the Explorer-Pratt-Welker seamount chain, and the chain of seamounts from Cobb to Kodiak. The bathymetric chart of Chase et al. (1971) allows a more detailed examination of these seamount chains. Figure 5.1 shows the location of the seamounts in the Gulf of Alaska. Superimposed on this chart is an oblique grid system about the 0-23 m.y. pole at 65°N 40°W. An oblique grid system about the average motion pole (section 7) at 81°N 70°W is also shown. The seamounts fall into three obvious chains. The northern chain extends from Bowie to Kodiak, and is underlain by a broad basement ridge (Silver et al., 1974). This chain follows an oblique line of latitude about 65°N 40°W from Bowie to Pratt and an oblique line of latitude about 81°N 70°W from Pratt to Kodiak (see section 7). R. L. Chase (1977) proposed that this chain was generated by a hot spot that is presently located under the J. Tuzo Wilson knolls (JTW). The second chain extends from Cobb seamount, on the western flank of the Juan de Fuca ridge, to the area around Marchand seamount. This chain changes trend near Miller seamount. South of the Cobb chain a third, shorter chain of seamounts extends from Scott to Parker. This chain has a change in trend similar
Table 5.1. Volcanic chains in the 0-42 m.y. and 42-68 m.y. age ranges

<table>
<thead>
<tr>
<th>Volcanic chain</th>
<th>Angle relative to small circles (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-42 m.y.</td>
<td></td>
</tr>
<tr>
<td>Hawaiian ridge</td>
<td>0</td>
</tr>
<tr>
<td>Kodiak-Bowie</td>
<td>0</td>
</tr>
<tr>
<td>Cobb-Miller</td>
<td>0</td>
</tr>
<tr>
<td>Scott-Parker</td>
<td>0</td>
</tr>
<tr>
<td>Line cross</td>
<td>0</td>
</tr>
<tr>
<td>Austral-Cook</td>
<td>0</td>
</tr>
<tr>
<td>Pitcairn-Gambier</td>
<td>4</td>
</tr>
<tr>
<td>Society</td>
<td>0</td>
</tr>
<tr>
<td>Samoan</td>
<td>0</td>
</tr>
<tr>
<td>Marquesas</td>
<td>25</td>
</tr>
<tr>
<td>Guadalupe</td>
<td>6</td>
</tr>
<tr>
<td>Southern Louisville chain</td>
<td>0</td>
</tr>
<tr>
<td>Southern Moonless Mountains</td>
<td>0</td>
</tr>
</tbody>
</table>

| 42-68 m.y.                         |                                           |
| Emperor                           | 0                                         |
| Tuvalu-Gilbert-Radak              | 7                                         |
| Musicians N-S                     | 0                                         |
| Louisville chain                  | 8                                         |
Figure 5.1. Oblique grid system superimposed on seamounts in the Gulf of Alaska. The grid system on the right is about 65°N 40°W; the grid system on the left is about 81°N 70°W. Oblique latitude and longitude spacing is 1° and 5° respectively.
to that of the Cobb and the Kodiak-Bowie chains. The group of seamounts on the northwest end of the Scott-Parker chain has an overall east-west trend, while within this group, Guide ridge and the Parker-Shaw-Gilbert group have an east-northeast trend. The Sila fracture zone passes just to the south of this group of seamounts. Further to the east in the Scott-Parker chain, Hook ridge has a clear north-south trend which cuts across the Sila fracture zone.

On the basis of the alignment with the oblique grid lines, the predicted age for these chains is in the 0-23 m.y. age range, with the bend corresponding to the 15 m.y. bend in the Hawaiian ridge. This prediction can be compared with the dates in the Kodiak-Bowie chain. Turner et al. (1973, 1974) have dated Hodgkins, Dickins, Giacomini, and Kodiak (Table 5.2), and Herzer (1971) has provided a minimum age for Bowie (see also Jarrard and Clague, 1977). In Figure 5.2 these ages are plotted against the degrees of rotation from JTW. These ages do not fall on a straight line, nor do they correlate well with the 0.86°/m.y. rotation rate obtained from the Hawaiian ridge. Dickins is located slightly north of the main line of seamounts in the chain. If this date is omitted, the dates for Hodgkins, Giacomini, and Kodiak fall on a straight line; however, the rate is less than the rate determined for the Hawaiian ridge.

Assuming that JTW is a hot spot with an age near zero, and using the rate of rotation (0.86°/m.y.) found for the Hawaiian ridge, the ages predicted for Kodiak and Giacomini are somewhat younger than the K-Ar dates, and the ages predicted for Hodgkins and Dickins are older than the K-Ar dates by a factor of two or three (see Table 5.2). However, the change in trend, which occurs in each chain near the same oblique
Figure 5.2. Age versus degrees rotation for the Kodiak-Bowie volcanic chain in the Gulf of Alaska. Ages are from Turner et al. (1973, 1974). The 0.86°/m.y. line is from Hawaiian ridge data.
Table 5.2. Distance and age relationships for Gulf of Alaska seamounts.

<table>
<thead>
<tr>
<th>Volcano</th>
<th>Rotation from JTW (degrees)</th>
<th>Age* (m.y.)</th>
<th>Calculated Age (m.y.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>JTW</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Hodgkins</td>
<td>5.2</td>
<td>2.65</td>
<td>6.3</td>
</tr>
<tr>
<td>Dickins</td>
<td>6.65</td>
<td>3.7</td>
<td>8.1</td>
</tr>
<tr>
<td>Pratt</td>
<td>11.65</td>
<td>-</td>
<td>14.2</td>
</tr>
<tr>
<td>Giacomini</td>
<td>14.3</td>
<td>19.3-20.5</td>
<td>17.44</td>
</tr>
<tr>
<td>Kodiak</td>
<td>16.42</td>
<td>21-29</td>
<td>20.0</td>
</tr>
</tbody>
</table>

*K-Ar ages from Turner et al. (1973, 1974).*
longitude, would have an age of about 14 m.y., consistent with the Hawaiian ridge data (see section 7). Alternately, we can assume that the K-Ar dates for Giacomini and Kodiak are approximately correct and that the hot spot is located on the order of 1.5 km southeast of JTW; just west of the northern tip of Vancouver island. Thus the existing age data agrees in a general way with the predicted ages, however, in detail there are discrepancies. These discrepancies are most probably the result of dating errors - the dates for Hodgkins and Dickins may be minimum ages, since the alternate explanation - a change in the rate of rotation, does not fit with the data from the Hawaiian ridge.

**Line cross trend** - A number of investigators have noted the presence of bathymetric trends which cross the main Line islands trend. In a detailed discussion of the Line islands, Winterer (1976) suggests the presence of a number of en echelon structures parallel to the cross trend in addition to more prominent cross trends at 14-16°N, 9-10°N, and 1°N-1°S. Only the cross trend that intersects the Line islands at about 10°N (Figure 5.3) is bathymetrically prominent. The significance of the less pronounced trends is unknown. Malahoff (1971) found other evidence for the existence of cross trends. He noted a cross trend in the magnetic anomalies between 3 and 4°N, whereas other magnetic anomalies are parallel to the main Line islands trend. In the zone of the cross trend (3-4°N) magnetic anomalies are aligned with both the main and the cross trend.

Natland (1976) reports potassic nephelinites from two seamounts on the cross trend, two seamounts at the intersection of the cross trend and the main trend, and, in addition, from two seamounts in the Wake island area. Potassic nephelinites had apparently not been found previously in
Figure 5.3. Oblique grid system superimposed on the Line-Tuamotu and Line cross chains. Oblique latitude and longitude spacing is $1^\circ$ and $5^\circ$ respectively.
the ocean basins, but are similar to rocks found in the East African rift valleys. On the basis of these rocks he suggests (1) that the Line cross trend extends to Wake, and (2) that the cross trend is the result of an extensional zone that produced little extension. There is little or no bathymetric evidence that the Line cross trend extends to Wake island. If it did, this chain would be more than 4200 km long; longer than the Hawaiian ridge.

Saito and Ozima (1977) report one date (45.3±2.5 m.y. at 10°18'N 168°00'W) that is located on the prominent 10°N cross trend (Figure 5.3). A second date (49.0±9.0 m.y. at 9°15'N 158°20'W) is located on an unnamed seamount east of Carol guyot. The unnamed seamounts and Carol guyot trend parallel to the cross trend, but are located about 200 km north of the prominent cross trend. These two dates suggest that the cross trend is 45-50 m.y. old. This is older than the age predicted from the alignment with oblique grid lines. The prominent 10°N Line cross trend (Figure 5.3) is parallel to small circles about the 0-23 m.y. pole at 65°N 40°W, which suggests a hot spot origin within the past 23 m.y. None of the older poles of rotation will fit this trend. The possibility that this trend was formed by a Class II mechanism 45-59 m.y. ago, and that it cannot be confined to the 0-23 m.y. age group only on the basis of its alignment with small circles about the 0-23 m.y. pole must be considered.

**Austral-Cook chain** - Macdonald seamount is an active volcano at the southeastern end of the Austral chain (Johnson, 1970; Johnson and Malahoff, 1971). The melting anomaly which formed the Austral and Cook volcanic chains is considered to be located under (or near) Macdonald. There is a plausibility of bathymetric data in this area (track lines show up in the contours on the charts of Mammerickx et al., 1975); however,
it appears that this melting anomaly is weak compared to the Hawaiian melting anomaly inasmuch as there are fewer volcanoes and in general less extruded material in the Austral-Cook chain than in the Hawaiian ridge. The closest volcano to Macdonald, Marotiri island, is located over 300 km to the west. Consequentially, the trend of the Austral-Cook chain is not well determined, and there is no way to determine the trend for the past few million years. The trend that is apparent in the bathymetry is not simple. There appears to be a northward offset of the chain at about 146°W, and Rarotonga and Mangaia islands are located south of the chain. The group of volcanoes that includes Marotiri and Rapa islands (located west of Macdonald) and Rarotonga and Mangaia may have been formed at a hot spot slightly offset from Macdonald hot spot.

The oblique grid system about 65°N 40°W fits the Austral chain within a 1° band (Figure 5.4), except that Macdonald and the group of volcanoes that include Marotiri and Rapa islands fall slightly south of this 1° band. This is consistent with the 1 m.y. change in the direction of plate motion suggested in section 7. The 1° band about 65°N 40°W also contains the Cook and Samoan islands. The section of the Austral chain between Rurutu and Maria islands is parallel to small circles about the 15-21 m.y. pole of average motion (section 7). The oblique grid system about 59°N 54°W (23-42 m.y.) contains the Southern Cook islands within a 1° band (as does the 65°N 40°W grid system), and then passes north of Palmerston, Rose, and Manua islands.

Figure 5.5 shows the Austral-Cook ages given by Jarrard and Clague (1977) plotted against degrees of rotation about the poles found for the Hawaiian ridge. In addition to the age discrepancies for Mangaia and Rarotonga, the dates for Rurutu, Aitu, and Aitutake islands are younger
Figure 5.4. The Pitcairn-Gambier, Society, Austral and Samoan chains are fit by an oblique grid system about 65°N 40°W. The Cook chain is fit by a grid system about 59°N 54°W. A grid system about the 15-21 m.y. average motion pole at 81°N 70°W is shown between the Austral and Cook chains.
Figure 5.5. Age versus degrees rotation for the Austral–Cook volcanic chain. Age data summarized by Jarrard and Clague (1977). The 0.86°/m.y. and 0.67°/m.y. lines are from Hawaiian ridge data.
than predicted. Thus there are four reliable dates (for Macdonald, Rapa, Raevavae, and Tubai) that agree with the comparison with the Hawaiian ridge, and two reliable dates (eliminating Mangaia and Rarotonga) which do not agree.

There is a question about where the 42 m.y. bend occurs in the Austral-Cook chain. Using oblique grid systems about 65°N 40°W and 59°N 54°W the angle of rotation from Kilauea to the Hawaiian-Emperor bend is about 32.4°, and the angle of rotation from Macdonald to the Austral-Gilbert-Marshall bend is about 47°. Thus about these poles, the Austral-Cook chain, from Macdonald to the southern extension of the Tuvalu (Ellice) islands, is about 45% longer than the Hawaiian ridge. Morgan (1972b) reported that the Austral-Cook chain was about 10% too long; however, using an oblique grid system about Morgan's (1972b) pole at 67°N 73°W, the angles of rotation are about 34° and about 42°; a 24% discrepancy. There are two possible explanations for this difference in length. (1) The Macdonald hot spot is moving opposite the direction of plate motion at 20 mm/yr (for Morgan's pole) to 40 mm/yr (for the pole found in this investigation) relative to the Hawaiian hot spot. (2) The Tuvalu-Gilbert-Radak (Ellice-Gilbert-Marshall) chain was not formed at the Macdonald hot spot. As discussed above, hot spots might move relative to one another at these rates. However, it seems too coincidental that the Macdonald hot spot would be moving relative to Hawaii at a fast rate in a direction opposite the direction of plate motion. The second explanation seems more likely.

If the Tuvalu-Gilbert-Radak chain is not an extension of the Austral-Cook chain, was the Macdonald hot spot active before 42 m.y.b.p.? The western end of the Austral-Cook chain, predicted by rotations about
the above poles, lies south and slightly east of the Tokelau island chain. This chain trends at an angle of about 16° to the small circles about the 42-68 m.y. pole at 10°N 98°W. If this chain is an extension of the Austral-Cook chain, the hot spot must have migrated normal to the small circles at a rate of about 22 mm/yr during the interval 42-68 m.y.b.p. This may not be the total rate of motion of the hot spot, but is the required component normal to the small circles about 10°N 98°W. Since the true direction of migration is not known, the components relative to the 0-23 or 23-42 m.y. small circles cannot be found. However, if we assume that the direction is normal to the 42-68 m.y. small circles and that 22 mm/yr is the rate of migration, then the rate of migration must have slowed somewhat since 42 m.y.b.p.; otherwise the end of the Austral-Cook chain would be about 170 km too far west to intersect with the Tokelau chain. Thus, allowing for a reasonable rate of migration of the Macdonald hot spot relative to the Hawaiian hot spot, the Tokelau island chain could have been formed at the Macdonald hot spot between 42 and 68 m.y.b.p. It appears that unreasonable rates of migration would be required in order for the Tuvalu-Gilbert-Radak chain to have been formed at the Macdonald hot spot. If, on the other hand, the Macdonald hot spot did not migrate with respect to the Hawaiian hot spot, then the chain of volcanoes generated at the Macdonald hot spot began with the Southern Cook islands.

Pitcairn-Gambier chain - Morgan (1972b) suggested that a hot spot located at 27°N 114°W, near Easter island, formed the Tuamotu and Line island chains. It appears now that this suggestion is in error. First, the bathymetric chart of Mannerickx et al. (1975) does not show a chain of volcanoes between Easter and Pitcairn. Only two small volcanoes,
Henderson and Ducie islands, lie between Easter and Pitcairn. There is, admittedly, a plaucity of data in this area; however, a chain of volcanoes should be more apparent in the existing data. Second, a line from Easter to Pitcairn lies at an angle of about 20° to the small circles about 65°N 40°W. This requires that the Easter island hot spot migrate at least 34 mm/yr relative to the Hawaiian hot spot. Third, the age of Pitcairn is 0.53-0.87 m.y. (Duncan et al., 1974); much too young to have migrated from the East Pacific rise.

The islands of Pitcairn, Temore, Gambier, and Mururoa form a line which is very nearly parallel to the small circles about 65°N 40°W (Figure 5.4). Morane and Fangataufe islands are slightly south of this line. Pitcairn and Gambier have reliable dates of 0.54-0.87 and 5.2-6.8 m.y., respectively (Jarrard and Clague, 1977). There is 5.3° of rotation about 65°N 40°W between these islands (Figure 5.6); and even though the average rate of rotation is somewhat high, these dates are consistent with the rates of rotation determined from the Hawaiian ridge. The date for Murora island (7±1 m.y.; Chevalier, 1973) is about 4 m.y. younger than predicted. This date is from a Hawaiian type andesite obtained in a drill core from near the top of the basaltic formation (Chevalier, 1973). This andesite is probably a late stage lava. It is not known if there was a hiatus between the shield building and late stage eruptions on this volcano.

Thus, the alignment with oblique grid lines and the available age data are consistent with a hot spot origin for the Pitcairn-Gambier chain between 0 and 42 m.y.b.p. The hot spot must be presently located 60-70 km southeast of Pitcairn; not near the East Pacific rise. The Easter island melting anomaly apparently generated a volcanic chain on the Nazca plate,
Figure 5.6. Age versus degrees rotation for the Pitcairn-Gambier volcanic chain. Age data summarized by Jarrard and Clague (1977). The 0.86°/m.y. line is from Hawaiian ridge data.
but not on the Pacific plate. Ducie, Henderson, and Oeno islands were not formed at this hot spot. Marutoa and Maria islands appear to be a part of the Tuamotu chain and not the Pitcairn-Gambier chain. Within the Pitcairn-Gambier chain three volcanoes trend east-northeast from Mururoa island. This trend (and the trend of Marutea island) appears to follow the Austral fracture zone, suggesting control by this fracture zone.

Society chain - According to the compilation of Jarrard and Clague (1977), there are only two reliable dates (for Tahiti and Moorea) in this chain. If these dates are correct, the Society islands cannot be a part of the Pitcairn-Gambier chain, even though a westward extension of the Pitcairn-Gambier trend nearly coincides with the trend of the Society chain (Figure 5.5). Figure 5.7 shows the available age data. The dates for Tahiti and Moorea just fit the rate of rotation, 0.86°/m.y., found for the Hawaiian ridge. This, together with the alignment of the chain with oblique lines of latitude, suggests that the Society chain was formed at a hot spot that is presently located about 90 km east of Tahiti. The Pacific plate has rotated only about 6.5° since the start of the Society chain; therefore, this melting anomaly must have started forming volcanoes less than 8 m.y. ago.

There are a number of volcanoes south of the main Society islands which roughly parallel the main island chain. Some of the smaller volcanoes are obviously located along ship tracks, which suggests a lack of bathymetric data in this area. Manuae and Maspioha islands also constitute a short chain which is parallel to the main island chain. Within the main chain, a series of four small volcanoes, including Bora-Bora and Maupiti islands, form a short east-west trend roughly parallel to the Tuamoto fracture zone. Thus, in addition to some control by a previously
Figure 5.7. Age versus degrees rotation for the Society volcanic chain. Age data summarized by Jarrard and Clague (1977). The 0.86°/m.y. line is from Hawaiian ridge data.
existing fracture zone, the volcanoes in the Society islands suggest a complex origin. Perhaps this group was formed by two or three small melting anomalies, or a single large melting anomaly which established more than one conduit to the surface. Also it should be noted that Glaucester island is located between the Pitcairn-Gambier chain and the Society chain and has the same trend. Glaucester may be an older part of the Pitcairn-Gambier chain, but, on the other hand, if the age data is wrong, the Pitcairn-Gambier chain could extend to the northwest and include the Tahiti-Bora-Bora group; with an offset near the Austral fracture zone (see also Dymond, 1975).

Samoan chain - The Samoan islands lie just north of the Tonga trench; very close to the Pacific plate boundary. The main islands form a chain of volcanoes that is parallel to small circles about 65°N 40°W (Figure 5.4). Manua and Savaii islands have had historic eruptions. Hawkins and Natland (1975) point out that except for Manua, recent eruptions are post-erosional nephelinites and basanites, whereas the volcanoes are composed predominantly of alkalic olivine basalt. The post-erosional lavas were apparently erupted along a single major rift zone extending from Savaii to Tutuila. According to these authors, the Samoan chain appears to be located along the hinge line where the Pacific plate is downbuckeled and probably faulted into the Tonga trench. So the post-erosional eruptions in the Samoan chain could be related to the subduction of the Pacific plate and not necessarily to the activity of the original melting anomaly (section 3). If this is the case, a progression of ages in the post-erosional lavas would not be expected. Unfortunately, there are no age data on the shield building alkalic lavas. To the west of the main island group the topography becomes complex and may reflect interaction with the plate
boundary. Thus the pattern in the present topography might not reflect simple intraplate volcanism. Age data on the alkalic lavas and better definition of the plate boundary in this area are obviously needed to determine the tectonic and age relationships of this volcanic group.

Marquesas chain - The Marquesas islands form a short broad chain that trends north-northeast. There are six reliable dates in this chain (Duncan and McDougall, 1974; Brousse and Bellon, 1974) which fall between 1.3 and 8.7 m.y. and show a fairly consistent progression with the youngest on the southeast end of the chain (see Jarrard and Clague, 1977, Figure 10; and Duncan and McDougall, 1974, Figure 2). Thus there is little doubt that this chain belongs in the 0-23 m.y. age group. However, this age data does not agree with the age that would be predicted on the basis of the alignment with oblique grid lines. The Marquesas chain trends at an angle of 25° to small circles about the 0-23 m.y. pole at 65°N 40°W (Figure 5.8), and is parallel to small circles about the 68-125 m.y. pole at 36°N 76°W. Thus the alignment with oblique grid lines suggest that the Marquesas were formed more than 68 m.y. ago. The reason for this discrepancy is, as yet, unknown.

Duncan and McDougall (1976) suggest that the orientation of the Marquesas chain, together with the orientation of the eastern end of the Hawaiian ridge (sections 2 and 7), indicate a change in the direction of motion of the plate with respect to the mantle during the past 4 m.y. The date of Eiao, the northern most island in the Marquesas chain, is 5.14-8.73 m.y. (Brousse and Bellon, 1974). There is no apparent change in the trend of the Marquesas chain, so presumably the change in direction suggested by Duncan and McDougall (1976) would have occurred prior to this date. The data from the Hawaiian ridge, on the other hand (section 2),
Figure 5.8. Oblique grid system about 65°N 40°W superimposed on the Marquesas Islands. Oblique latitude and longitude spacing is 1° and 5° respectively.
does not support a change in direction at this time, but indicates that if a change did occur, it was in the past 2 m.y. This suggested change in the motion of the Pacific plate is discussed in more detail in section 7.

The possibility that this chain was formed by a Class II mechanism must also be considered. This chain exhibits two characteristics which would be expected of a fracture propagating at an angle to the direction of plate motion: an age progression and a trend at an angle to plate motion. The north-northeast trend of the Marquesas is parallel to small circles about the 68-125 m.y. old pole at 36°N 76°W. Thus the angle of the main trend with respect to the plate versus mantle motion may be controlled by a fracture system that was formed more than 68 m.y. ago. The short cross trends may be an indication that, in addition to the influence of the old fracture system, volcanism has a tendency to propagate opposite the direction of plate motion.

**Guadalupe chain** - The line of volcanoes from Guadalupe island to Fiebergling guyot may have been formed at a hot spot. The trend of the chain falls only 6° from the small circles about 65°N 40°W suggesting an origin between 0 and 23 m.y.b.p. According to Jarrard and Clague (1977) Guadalupe is between 1000 years and 7 m.y. old. Erben guyot, which has a minimum age of 19-22.5 m.y. (Jarrard and Clague, 1977), has been included in the Guadalupe chain by some investigators (e.g., Jarrard and Clague, 1977); however, it falls considerably south of the westward extension of the Guadalupe line and, therefore, seems more likely to be related to the Murray fracture zone.
Southern Moonless Mountains - Just east of the Moonless Mountains (which parallel the Murray fracture zone) there is an indistinct chain of volcanoes that is roughly parallel to the small circles about 65°N 40°W (Figure 5.9). This suggests that these volcanoes were formed at a hot spot between 0 and 23 m.y.b.p. There are no age dates on these volcanoes.

Tuvalu-Gilbert-Radak (TGR) chain - The eastern most volcanoes in the Marshall islands form a chain of volcanoes, called the Radak (also spelled Ratak) chain, that continues southward to the Gilbert and Tuvalu (Ellice) islands. The main trend in the Gilbert islands is parallel to small circles about the 68-125 m.y. pole (Figure 5.10), and the Tuvalu islands have a trend that is nearly (within 11°) parallel to 68-125 m.y. small circles. However, there is some indication in both the Gilbert and Tuvalu islands that the Radak trend continues to the south. Three of the northern islands in the Gilberts (Maiaua, Tarawa, and Abaiang islands) form a chain which appears to be a continuation of the Radak chain. Likewise, several of the western islands in the Tuvalu group follow the 42-68 m.y. trend. The TGR chain appears to end north of the Pacific plate boundary. Funafuti lies on the cross trend east of the main trend. Another cross trend intersects the Radak chain at 9.5°N.

The TGR chain trends at an angle of 10° to small circles about the 42-68 m.y. pole at 10°N 98°W (Figure 5.10). This is consistent with formation at a hot spot between 42 and 68 m.y.b.p. Unfortunately, there are no age data on this chain.

The TGR chain appears to be a continuation of the Louisville chain. However, the oblique grid system about the average motion pole which fits the Emperor, TGR, and Louisville chains (section 7), show that the TGR chain is offset from the Louisville chain by about one degree of latitude.
Figure 5.9. Oblique grid system about 65°N 40°W superimposed on the South Moonless Mountains and Guadalupe chains. Oblique latitude and longitude spacing is 1° and 5° respectively.
Figure 5.10. Oblique grid system about 10°N 98°W and 36°N 76°W superimposed on the Tuvalu-Gilbert-Radak chain. Oblique latitude and longitude spacing is 1° and 5° respectively.
If the TGR chain were a continuation of the Louisville chain, the Pacific plate would have had to rotate about the same pole for over 96 m.y.

The TGR chain is more complex than other chains. It definitely forms a boundary between the Magellan seamounts area to the west and the Mid-Pacific Mountains-Magellan rise area to the east. There is a notable change in sea-floor morphology across this chain. Volcanoes to the west are relatively large and distinct, whereas those to the east are small and do not form distinct chains. There are certain similarities between the TGR chain and the Line islands chain in that both appear to be boundaries between different sea-floor morphologies, and both have crossing trends. The TGR cross trends, however, are much more distinct than the Line cross trends, and appear to be older than the main trend, whereas the Line cross trends appear to be younger than the main trend.

The TGR chain will be discussed further in sections 8 and 9.

Musicians N-S chain - Within the Musicians seamounts there appears to be a north-south trending chain of volcanoes (Figure 6.1). Chopin and Mendelssohn seamounts are the most prominent volcanoes in this chain. The chain may intersect the Hawaiian ridge just west of Nihoa and may continue to the south. An east-west HIG seismic reflection profile shows a seamount north of Nihoa. There is nothing anomalous about the Hawaiian ridge at this intersection; unlike the intersections with the Wentworth, North Gardner, and Musician chains where the Hawaiian ridge has a high volume of extrusion.

The significance of this north-south trend is not clear. It is parallel to small circles about the 42-68 m.y. pole; suggesting a hot spot origin. This possibility is discussed in section 6.
Louisville chain - Based on the evidence that every traverse across the Louisvillle chain showed an elevation, Hayes and Ewing (1971) suggested that this is a continuous ridge rather than a chain of volcanoes. More recent bathymetric data indicate, however, that it is not a continuous ridge. Hayes and Ewing (1971) suggested that the Louisville ridge continues into the Eltanin fracture zone, and they interpreted the ridge and fracture zone as being an old plate boundary and fit this line by a small circle about a pole at $5^\circ N 120^\circ W$. Larson and Chase (1972) supported the Hayes and Ewing interpretation and continued the trend northward about a pole at $10^\circ N 118^\circ W$ to terminate the western edge of the Phoenix magnetic lineations.

Outside of the fact that the Louisville chain is a prominent, rather narrow feature, the outstanding characteristic of the chain is a change in trend at $39.2^\circ S 167.5^\circ W$ (Figure 5.11). This change in trend was also noted by Hayes and Ewing. For the purposes of discussion I will call the section of the chain north of this bend the Northern Louisville chain, and the section south of the bend the Southern Louisville chain.

Based on alignment with small circles, the Northern Louisville chain could fall into either the 42-68 m.y. or the 68-125 m.y. age range. This section of the ridge lies at an angle of 8-9$^\circ$ to small circles about the pole at $10^\circ N 98^\circ W$, and an angle of 1-2$^\circ$ to small circles about the pole at $36^\circ N 76^\circ W$ (Figure 5.11). There is strong evidence, however, that the Northern Louisville chain is 42-68 m.y. old; contemporaneous with the Emperor seamount chain. First, the bend in the Louisville chain can correlate only with the Hawaiian-Emperor bend. None of the other bends in the Hawaiian-Emperor chain are in the same direction. Second, the Southern Louisville chain lies at an angle of less than 2$^\circ$ to small circles
Figure 5.11. Oblique grid system superimposed on the Louisville chain. Oblique latitude and longitude spacing is 1° and 5° respectively.
about the 23-42 m.y. pole at 59°N 54°W; suggesting that the Southern Louisville chain is less than 42 m.y. old. Third, the lithosphere under the Louisville chain may be too young for the ridge to be greater than 68 m.y. old. A linear extrapolation of the Cenozoic magnetic lineations located to the southeast indicates that the lithosphere near the northwestern end of the Louisville chain cannot be much older than 100 m.y. And finally, the southern end of the Louisville chain consists of three volcanoes which are parallel to small circles about the 15-23 m.y. average motion pole (section 7).

The northern end of the Louisville chain is presently being subducted. The southern end of the chain appears to die out at about 18-20 m.y.b.p. It may be, however, that bathymetric data is so sparse in this area that the young end of the chain has gone undetected. The hot spot should be presently located near 53.5°N 144°W. The fact that the Northern Louisville chain lies at an angle to small circles about the 42-68 m.y. pole, and the Southern Louisville chain is nearly parallel to small circles about the 23-42 m.y. pole, suggests that the Louisville hot spot moved southeast parallel to 23-42 m.y. small circles relative to the Hawaiian hot spot. It also appears that the Louisville chain does not continue into the Eltanin fracture zone, since the fracture zone diverges from small circles about 59°N 54°W. Thus I conclude that the Louisville chain is a hot spot trace that was formed in the past 68 m.y.

5.2. Chains formed before 68 m.y.b.p.

Musicians, North Gardner, and Wentworth chains - These chains were used to determine the 68-125 m.y. pole (Table 2.3), and will be discussed in section 6.
**Line islands-Tuamotu chain** — The Line islands is probably the most complex chain of volcanoes on the Pacific plate. It appears to have a complex tectonic history that may be related to both Class I and Class II mechanisms. The Initial Reports for DSDP leg 33 (Schlanger, Jackson et al., 1976) contain extensive discussions on various aspects of the geology and geophysics of the Line islands and the reader is referred to this work for background information.

In terms of the present analysis, the most striking feature about the Line islands is that the entire chain, including most of the Tuamotu volcanoes, falls within a 2° latitude band on an oblique grid system plotted about the 68-125 m.y. pole at 36°N 76°W (Figure 5.3). In the vicinity of the Tuamotu islands, small circles about 36°N 76°W are parallel to small circles about the 42-68 m.y. average motion pole at 15.5°N 105.2°W (section 7). Small circles about 15.5°N 105.2°W are highly curved in this region so that two sets of small circles are parallel only between about 15° and 22°S. The alignment of the Line islands with small circles about 36°N 76°W indicates that this chain was formed at a hot spot before 68 m.y.b.p. The Tuamotus may be younger or older than 68 m.y. If they were formed before 68 m.y.b.p., the 68 m.y. bend must occur at about 15°N. It should be noted that because of the curvature of the oblique lines of latitude, the sense of this bend is opposite of that of the 68 m.y. bend in the Emperor chain.

Although considerable effort has been directed toward obtaining dates along this chain, there are at present only five reliable dates. Only one of these dates is less than 68 m.y. That date was obtained by Saito and Ozima (1977) for three samples of aegirine phonolite which yielded dates between 54 and 56 m.y. Saito and Ozima (1977) obtained
three other dates which range from 71.5 to 127.5 m.y., and Lanphere and Dalrymple (1976) report a date of 91.2 m.y. for the Fanning volcanic edifice. The 127.5 m.y. date is located in the northern end of the Line islands, and must be close to the old age limit for the Line islands since the lithosphere in this area cannot be much older. Thus, with one exception, the available age data are consistent with an origin between 68 and 128 m.y.b.p.

The origin of the Line-Tuamotu chain is uncertain. A number of investigators have argued that because the dates on the Line islands show no progression along the chain, it cannot be a hot spot trace. Other proposed origins include an abandoned ridge crest (Winterer, 1976) and a transform fault (Orwig and Kroenke, submitted). Besides the lack of an age progression, I note the following characteristics. (1) The Line-Tuamotu chain forms one continuous volcanic chain with no offsets as would be expected in a spreading ridge. (2) The large east Pacific transform fault traces cannot be traced into the Line-Tuamotu chain; nor can the Nova-Canton trough. (3) The Line islands chain is a boundary between two different sea floor morphologies. (4) The Necker ridge is perpendicular to the Line islands. (5) Line islands volcanoes are composed dominantly of mid-plate island basalts which are unlike spreading ridge basalts (Jackson et al., 1976). (6) Shallow water carbonate banks which date from 70-80 m.y.b.p. are found along the center section of the Line islands. The petrology and long linear nature of the chain suggest a hot spot origin; however, (2), (3), and (4) are not characteristic of hot spot traces. Thus the Line-Tuamotu chain has characteristics of both Class I and Class II chains, suggesting an origin related to more than one mechanism. This possibility will be discussed further in sections 8 and 9.
Emperor seamount chain north of 50°N - The Emperor chain bends to the west north of 50°N and this short section of the chain is parallel to small circles about the 68-125 m.y. pole (Figure 2.9). As discussed in section 2, the age of this bend, determined by age data along the Emperor chain, was used to determine the young age limit for this pole. The Emperor trough is also parallel to small circles about this pole and appears to intersect the Emperor chain in the area of the bend. This suggests that the pre-68 m.y. history of the Emperor chain may be more complex than the post-68 m.y. history. There is no evidence, however, that the section of the Emperor chain formed before 68 m.y.b.p. was not formed at the Hawaiian hot spot.

Necker ridge - The Necker ridge appears to be a continuous ridge rather than a chain of individual volcanoes. This ridge trends exactly 90° from small circles about the 68-125 m.y. pole, suggesting an origin before 68 m.y.b.p. A single date of 82.4 m.y. (Saito and Ozima, 1977) supports this interpretation. The origin of the Necker ridge is uncertain, but is probably related to the origin of the Line islands.

Mid-Pacific Mountains - This is a rather amorphous group of volcanoes with no distinct chains. There are a number of short, indistinct trends, and I have somewhat tentatively picked out three trends which are more or less parallel to small circles about the 68-125 m.y. pole. I am not convinced that these chains have any significance. Dredged samples from the submerged reefs on these volcanoes indicate that the volcanoes were formed during mid-Cretaceous time (≈100 m.y.b.p.; Hamilton, 1956; Matthews et al., 1974). The amorphous character of these volcanoes suggests a Class II origin; perhaps related to the origin of the Magellan rise.
Magellan-Marshall area - There are several fairly distinct chains in this area (Figure 5.12); however, none of these chains is parallel, or close to parallel, to small circles about any of the pole positions used in this analysis. Ozima et al. (1977) have obtained four reliable dates from volcanoes in this area and all are greater than 68 m.y. The relative large size of the volcanoes in this area and the fact that many of them form linear groups is indicative of a hot spot origin. This is the oldest area of the Pacific plate and there is about 100 m.y. of plate history during which these chains could have been formed. A better knowledge of plate to mantle motion during this time and more age data are needed to sort out the age relationships of these volcanoes.

5.3. Chains of uncertain age

Tuamotu chain - Because the oblique grid lines about the 42-68 m.y. pole and the 68-125 m.y. pole are parallel in the Tuamotu region, it is not possible to decide between these age ranges. Unfortunately, there are no age data on this chain.

Tokelau chain - This is a rather indistinct chain located between the TGR chain and the Line islands. It appears to cross the Nova-Canton trough without being offset. Unfortunately, there are no age data on this chain. In section 5.1 I suggested that the Tokelau chain might be an extension of the Austral-Cook chain if the Macdonald hot spot moved relative to the Hawaiian hot spot. There is some question about this interpretation, however, because the Tokelau chain trends at an angle of 17° to small circles about the 42-68 m.y. pole at 10°N 98°W. In section 7 an average plate to mantle pole is determined using the Emperor, TGR, and Louisville chains. The Tokelau chain trends at an angle of only 7° to small circles about
Figure 5.12. Magellan seamount area. The lines delineate the obvious chains of volcanoes.
this pole. This is only one degree more than the deviation of the TGR chain from small circles about this pole. On the other hand, the Tokelau chain trends at an angle of only 8° from small circles about the 68-125 m.y. pole. Thus it is not possible to predict the age of this chain beyond the constraint that it was formed either 42-68 m.y.b.p. or before 68 m.y.b.p.

Caroline islands chains - There are two possible interpretations of the age relationships of the volcanic chains in this area. The first interpretation is shown in Figure 5.13. A relatively distinct chain of volcanoes extends northwest from Kusaie island, through Ponape island, to at least Murilo atoll, and perhaps another 400 km to the northwest. This chain is parallel to small circles about the pole at 59°N 54°W; indicative of a hot spot origin between 23 and 42 m.y.b.p. A second chain passes through Truk island and trends at an angle of less than 2° to small circles about the 68-125 m.y. pole.

In the second interpretation (Figure 5.14), a single chain extends from Kusaie to Truk. This chain is nearly parallel to small circles about the 0-23 m.y. pole at 65°N 40°W. Unfortunately, in this area, small circles about this pole are parallel to small circles about the 15-21 m.y. average motion pole (section 7); so, on the basis of this alignment, the age of this chain is between 1 and 21 m.y. There is only one date in this area; Truk has a minimum age of 9-23 m.y. (Jarrard and Clague, 1977).

The islands of Kusaie, Ponape, and Truk are high basaltic islands, whereas other islands in the Carolines are coral atolls. Along the Hawaiian ridge the last subaerial basalt occurs at Gardner Pinnacles; older islands to the west are atolls. Thus, along the Hawaiian ridge, the basaltic edifice has subsided below sea level by the time the volcano is
Figure 5.13. Oblique grid system about 59°N 54°W superimposed on the Kusaie-Ponape chain, and a grid system about 36°N 76°W superimposed on the Truk chain. Oblique latitude and longitude spacing is 1° and 5° respectively.
Figure 5.14. Oblique grid system about 65°N 40°W superimposed on the Caroline islands. A slightly better fit to this chain is obtained (dotted line) if Kusaie is fit by the 0-1 m.y. average motion pole (section 7) at 36°N 76°W.
15-20 m.y. old. Assuming a similar mechanism for the subsidence of the Hawaiian ridge and the Caroline chain, Kusaie, Ponape, and Truk should have subsided below sea level if they are older than about 20 m.y. The fact that these are basaltic islands supports the younger age interpretation.
6. CRETACEOUS TECTONICS BETWEEN THE MENDOCINO AND MURRAY FRACTURE ZONES

The Mendocino fracture zone extends through the Mesozoic magnetic lineations south of the Hawaiian ridge and offsets these lineations by about 370 km. It offsets the Cenozoic lineations to the east by about 1200 km. This is the only fracture zone in the Pacific that offsets both the Cenozoic and Mesozoic anomalies. Larson and Chase (1972) attributed the increase in offset to faster spreading on the Pacific-Farallon ridge between the Mendocino and Murray fracture zones between 110 and 85 m.y.b.p. Hilde et al. (1976) suggested, on the other hand, that the increased offset was due to jumps of the spreading ridge.

The Musicians (Figure 6.1) are a complex group of seamounts and east-west trending ridges (see Chase et al., 1971; Naugler, 1968; Rea, 1969). The Musicians chain appears to continue through the Murray fracture zone without being offset. In addition, there is a second, north-south trending chain of seamounts (Musicians N-S chain) which also appears to pass through the Murray, and may continue south through the Hawaiian ridge.

The general morphology of the Musicians changes across the Murray. South of the Murray the topography is dominated by long east-west trending ridges which parallel the Murray. To the north there is only one, much broader, east-west trending ridge. A close inspection of the bathymetric charts of Naugler (1968) and Rea (1969) shows that the seamounts in the Musicians chain south of the Murray tend to have an east-west trend. In addition, Chopin and Mendelssohn seamounts, which are a part of the Musicians N-S chain south of the Murray, are located west of the Musicians chain, whereas there are no seamounts west of the Musicians chain north of the Murray.
There are two dates on the Musicians chain. Khachaturian is located on the Murray and has a date of 65.2 m.y. Rachmaninoff, to the north, is dated at 84.2-88 m.y. (Clague and Dalrymple, 1975). In addition, Wentworth has a minimum age of 71 m.y. (Clague and Dalrymple, 1975; Jarrard and Clague, 1977). This suggests that Wentworth is part of the northwest trending chain and not a part of the Hawaiian ridge.

Naugler and Erickson (1968) report that the Murray changes west of the Musicians. It loses about half of its vertical relief, changes trend toward the south, and acquires a strong negative magnetic lineation along its southern margin. It retains its topographic expression to about 165°W, about 200 km west of the Musicians, and these authors claim it continues westward and crosses the Hawaiian ridge just north of Laysan island. Forman (1978) finds two bathymetric trends south of the Hawaiian ridge which may be continuations of the Murray. The Hawaiian magnetic lineations have not been traced far enough south to detect the Murray, however.

Two possible explanations for the origin of the Wentworth, North Gardner, and Musicians chains are: (1) they are remnants left from ridge crest jumps, or (2) they were formed by short lived hot spots. Neither explanation is completely satisfactory.

These three volcanic chains were first assumed to be hot spot traces and were used to find the 68-125 m.y. pole located at 36°N 76°W. Figure 6.2 shows an oblique grid system about this pole superimposed on the region shown in Figure 6.1. Mesozoic and Cenozoic magnetic lineations are also shown. South of the Mendocino, the Mesozoic anomalies older that M10 are parallel to small circles about 36°N 76°W. Just before M10 time (~124 m.y.b.p.) the ridge crest abruptly changes strike by about 15° clockwise. The Mendocino shows a more gradual change in trend. Thus the
Figure 6.2. Bathymetry and magnetics in the Mendocino-Murray region with an oblique grid system about 36°N 76°W superimposed. Oblique latitude and longitude spacing is 1° and 5° respectively.
Wentworth, North Gardner, and Musicians chains are not quite perpendicular to the Mendocino nor is the Musicians chain perpendicular to the Murray.

As discussed above, the Emperor chain north of 50°N is parallel to small circles about 36°N 76°W. The Emperor chain was almost certainly formed at a hot spot, so even though the section of the chain parallel to these small circles is short, this pole is approximately representative of plate to mantle motion for some period before 68 m.y.b.p. Thus, in the region between the Mendocino and Murray fracture zones, the Pacific-Farallon ridge would have been very nearly parallel to plate to mantle motion. This might have resulted in some complex interactions between plate to mantle and plate to plate motion. The plate to mantle motion may have forced the Pacific-Farallon out of an orthogonal pattern with respect to fracture zones, and the ridge may have jumped trying to regain this energy conservative configuration. The first jump would have been from the Wentworth chain and would have occurred shortly after MO time. There is no way of knowing how far the ridge jumped, but it probably did not jump as far as the North Gardner chain. The second jump would have occurred when the ridge reached the North Gardner chain, and the third when the ridge reached the Musicians chain. There is a significant change in the character of the sea floor north of the Mendocino, and there is no way to tell if there were ridge jumps north of the Mendocino. If there were, they must have been smaller than those between the Mendocino and Murray because of the increase in lineation offset across the Mendocino. Extrapolation of the ages for the Mesozoic lineations gives an age of about 107 m.y. for the Wentworth jump; considerable older than the 71 m.y. date for Wentworth. Jarrard and Clague (1977) classify this as a minimum age however. The 84-88 m.y. age for Rachmaninoff may be the
correct age for the Musicians jump. Khachaturian (65.2 m.y.) is considerably too young, but since it is located on the Murray it may have been affected by the ridge south of the Murray. At about 68 m.y.b.p. there was a change in the direction of plate to mantle motion which would have changed the effect of plate to mantle motion of the Pacific-Farallon ridge.

Fast spreading between the Mendocino and Murray fracture zones is an alternative to ridge jumps to explain the change in offset across the Mendocino. Prior to MO time, the spreading rate on the Pacific-Farallon ridge was on the order of 24 mm/yr. During the late Cenozoic in the eastern Pacific the rate was around 33 mm/yr. If the spreading rate north of the Mendocino remained at 24 mm/yr during the Cretaceous, then to produce the increased offset, the rate south of the Mendocino would have had to be about 42 mm/yr. At about 70 m.y.b.p. the rate must have dropped to about 33 mm/yr.

Ridge jumps seem like the more likely alternative. However, this interpretation fails to explain (1) the apparent continuation of the Musicians chain through the Murray, although the change in character of the Murray east of the Musicians suggests that the offset along the Murray may have been small before the Musicians jump; (2) the origin of the Musicians N-S chain; and (3) the origin of the east-west ridges in the Musicians. Ridge jumps have been suggested for the origin of the Mathematician and Clipperton seamount chains in the eastern Pacific (Sclater et al., 1971). These authors showed that this origin is consistent with the heat flow and bathymetric data. In studying the complex plate reorientations in the east Pacific, Menard (1978) attributed the Mathematicians seamounts topography to rotation and jumping of spreading
ridges. He attributed the east-west Clipperton ridges to transform faults that leaked during the reorientation.

The second explanation for the origin of the Wentworth, North Gardner and Musicians chains is that they are traces of short-lived hot spots. As pointed out above, these chains are parallel to the very northern end of the Emperor seamount chain; and the Musicians N-S chain is parallel to small circles about the pole of rotation found for the southern part of the Emperor chain (sections 2 and 5). In the Musicians the hot spot trace would follow the NW-SE Musicians chain to the Murray and then the Musicians N-S chain (Figure 6.3). The age of Khachaturian (65.2 m.y.) is close to the 68 m.y. age suggested for the Emperor bend, and the age progression from Rachmaninoff to Khachaturian is in the correct direction. The North Gardner chain may also have a bend.
Figure 6.3. Wentworth, North Gardner, and Musicians chains showing possible hot spot traces.
7. AVERAGE MOTION OF THE PACIFIC PLATE RELATIVE TO THE MANTLE

The poles of rotation found in section 2 represent the motion of the Pacific plate relative to the Hawaiian hot spot. Those poles were used to predict the ages of other volcanic chains on the Pacific plate. Chains which fall in the same age range can be used to determine poles which represent the average motion of the Pacific plate relative to the underlying mantle. These average motion poles were determined in the same way as those in section 2 (see Figures 2.6 and 2.7), except in this case the pole was determined by the oblique grid system which best fit all (or most) of the chains in an age range. Table 7.1 lists the data relevant to the poles in each age range, and the pole positions are plotted in Figure 7.1. Figures 7.2, 7.3, and 7.4 show how oblique lines of latitude about these poles superimposed on the Hawaiian, Austral-Cook and Louisville chains.

0 to 1 m.y. - The possibility that the motion of the Pacific plate relative to the mantle changed in the past few million years was discussed in section 2. The evidence for this change that is observed in volcanic chains is (1) the trend of the Marquesas (section 5.1), (2) the location of Kilauea and the southern part of the island of Hawaii south of the trend of the rest of the chain (section 2), and (3) the location of Macdonald seamount south of the trend of the Austral chain (section 5.1; see also Duncan and McDougall, 1976).

The age of this change is not well determined, but on the basis of the alignment of the Hawaiian ridge with oblique grid lines, it must have occurred close to 1 m.y. ago. The propagation of volcanism along the Hawaiian ridge shows a change that occurred between 0.5 and 2.0 m.y.b.p.
Table 7.1. Poles of average motion of the Pacific plate relative to the mantle.

<table>
<thead>
<tr>
<th>Age Range (m.y.)</th>
<th>Pole</th>
<th>Rate of Rotation (°/m.y.)</th>
<th>Age Data</th>
<th>Chains Fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-1</td>
<td>36°N</td>
<td>76°W</td>
<td>0.84</td>
<td>Marquesas, Hawaiian ridge</td>
</tr>
<tr>
<td>1-15</td>
<td>65°N</td>
<td>40°W</td>
<td>0.86</td>
<td>Hawaiian ridge, Gulf of Alaska, Austral, Society</td>
</tr>
<tr>
<td>15-21</td>
<td>81°N</td>
<td>70°W</td>
<td>0.6 ?</td>
<td>Hawaiian ridge, Gulf of Alaska, Austral-Cook, Louisville</td>
</tr>
<tr>
<td>21-23</td>
<td>36°N</td>
<td>76°W</td>
<td>?</td>
<td>Hawaiian ridge, Austral-Cook, Louisville</td>
</tr>
<tr>
<td>23-42</td>
<td>59°N</td>
<td>54°W</td>
<td>0.5 ?</td>
<td>Hawaiian ridge, Cook, Kusaie-Ponape, Louisville</td>
</tr>
<tr>
<td>42-68</td>
<td>15.5°N</td>
<td>105.2°W</td>
<td>0.78</td>
<td>Emperors, Emperor, Louisville, Ellice-Gilbert-Marshall</td>
</tr>
<tr>
<td>68-?</td>
<td>36°N</td>
<td>76°W</td>
<td>?</td>
<td>--</td>
</tr>
</tbody>
</table>

Poles of average motion of the Pacific plate relative to the mantle.
Figure 7.1. Pole positions for the average motion of the Pacific plate relative to the mantle.
Figure 7.2. Hawaiian ridge fit by small circles about average motion poles.
Figure 7.3. Louisville chain fit by small circles about average motion poles.
Figure 7.4. Austral-Cook chain fit by small circles about average motion poles.
(section 2.7). There are six reliable dates in the Marquesas (Duncan and McDougall, 1976; Brousse and Bellan, 1974) which show a fairly consistent progression with the youngest on the southeast end of the chain. The northernmost island, Eiao, is between 5.14 and 8.72 m.y. old; which indicates that this trend started at least 5 m.y. ago. So there is disagreement between the Hawaiian age data and the Marquesas age data.

The volcanic chains generated in this age range are too short to accurately determine a pole position. Perhaps coincidentally (and perhaps not), the Marquesas are almost exactly parallel to small circles about the pole at 36°N 76°W (Figure 7.5) which was determined for the Wentworth, North Gardner, and Musician chains (section 2). This pole also fits the Hawaiian ridge (Figure 7.1) and Austral chain (Figure 7.2) as well as can be determined. Consequentially, this pole was chosen as the best estimate for a 0-1 m.y. average motion pole. Because of the shortness of the chains, confidence limits cannot be determined for this pole. In the Gulf of Alaska, small circles about this pole trend just a few degrees west of north and consequentially do not provide a good fit to the northern two chains in this area. This may be an indication that the young end of these chains is poorly determined, or that the pole position for this age range should be shifted somewhat.

1-15 m.y. - The pole at 65°N 40°W (the 0-23 m.y. pole in sections 2 and 5) gives a good fit to nearly all of the chains in this age range (Table 5.1). Only the Pitcairn-Gambier and the Guadalupe chains deviate from small circles about this pole; and these by only 4° and 6° respectively.

The 15 m.y. age for the start of rotation about this pole is consistent with the age data from the Hawaiian ridge and the Kodiak-Bowie chain.
Figure 7.5. Oblique grid system about 36°N 76°W superimposed on the Marquesas islands. Oblique latitude and longitude spacing is 1° and 5° respectively.
The rate of rotation (0.86°/m.y.) was determined from Hawaiian ridge age data, and is the same as determined for the 0-23 m.y. pole in section 2.

15-21 m.y. - The change in direction of motion which occurred ~15 m.y. ago is most pronounced in the Gulf of Alaska chains (Figure 5.1) because these chains are closest to the poles of rotation. A change in trend is also apparent in the Hawaiian ridge, the Austral chain, and the Louisville chain. Morgan (personal communication) suggested that these changes might have resulted from a change in the pole of rotation and he suggested a pole at 80°N 110°W. This pole is located at one end of the confidence limits (Figure 7.1) established for the pole position for this age range. The average pole position is 81°N 70°W.

There are no age data in this section of the Hawaiian ridge, so the rate of rotation was determined from the ages of Giacomini (19.3 - 20.5 m.y.) and Kodiak (21-27 m.y.), which are separated by about 3° of rotation. Thus the rate of rotation (0.7°/m.y.) for this age range is not well determined. The decrease in rate of rotation at 15 m.y. (Table 7.1) may be due to an error in the 15-21 m.y. rate.

21-23 m.y. - In order to fit the Hawaiian ridge, a small amount of northward motion is required between Lisianski island and Pearl and Hermes reef. The Austral-Cook and Louisville chains do not help to constrain this motion because there are few volcanoes in these chains. Small circles about 36°N 76°W fit all chains sufficiently well, so this pole was chosen to represent motion between 21 and 23 m.y. Obviously this pole position is not well constrained.

23-42 m.y. - There are only three volcanic chains in this age range, so the confidence in this pole position is somewhat less than for the other
poles (except the 0-1 and 21-23 m.y. poles). The pole at 59°N 54°W, which was determined to best fit this section of the Hawaiian ridge (section 2), also fits the Cook and Kusaie-Ponape chains, and is, therefore, the best estimate for the average motion pole for this age range.

The rate of rotation (0.5°/m.y.) about this pole was determined from Hawaiian ridge age data; however, there are only three dates in this section of the ridge and consequently the rate is not well determined.

42-68 m.y. - There are three prominent chains in this age range: the Emperor, Louisville, and Tuvalu-Gilbert-Radak. There is some question about the origin of the Tuvalu-Gilbert-Radak chain (section 5) so less importance was given to this chain in determining this pole. The oblique lines of latitude about the best fit pole (15.5°N 105.2°W) are parallel to the Emperor and Louisville chains and form an angle of only 3.5° with the Tuvalu-Gilbert-Radak chain. Because of the length of these chains and the distance between the Emperor and Louisville chains, the confidence limits on this pole (Figure 7.1) are small. The rate of rotation about this pole was determined from age data along the Emperor chain, but here again only three dates were used, so the rate is not well determined.

68-? m.y. - The Emperor chain north of 50°N is parallel to small circles about 36°N 76°W (section 5.2). Since this section of the Emperor chain is short, the pole is not well constrained, nor is it yet possible to determine the old age limit on this phase of motion.

Discussion - One of the significant implications of this investigation is that there has been very little relative motion among Pacific hot spots. In the 1-15 m.y. age group, only the Pitcairn-Gambier and the Guadalupe chains are not parallel to small circles about the pole which was
determined to best fit the Hawaiian ridge; and the angles between these chains and the small circles are small (Table 5.1). Thus, during this age range, the Pitcairn-Gambier and the Gaudalupe hot spots were moving slowly relative to the other hot spots, and there was no relative motion among the other hot spots. The Scott-Parker chain in the Gulf of Alaska (Figure 5.1) lies at a small angle to small circles about the 15-21 m.y. average motion pole, implying some motion of this hot spot. The Kodiak-Bowie, Cobb-Miller, and Hawaiian ridge are essentially parallel to small circles about this pole, implying no relative motion of these hot spots. The 15-21 m.y. sections of the Austral-Cook and Louisville chains are relatively indistinct. In the 23-42 m.y. age range, the Cook and the Kusaie-Ponape chains are parallel to small circles about the best fit Hawaiian ridge pole; implying no relative motion of these hot spots. The Tuvalu-Gilbert-Radak chain deviates by only $3.5^\circ$ from the small circle which are parallel to the Emperor and Louisville chains. Thus, even though some hot spots die out and new hot spots are formed, once formed, the hot spots move very little relative to one another.
8. INTER-RELATIONSHIPS AMONG LINEAR FEATURES ON THE PACIFIC PLATE

In section 2 I obtained poles of rotation which are representative of the motion of the Pacific plate relative to the Hawaiian hot spot; and in addition, a pole which appears to be related to both plate to mantle and plate to plate motion between 68 and 125 m.y.b.p. In section 5 I used oblique grid systems about these poles to constrain the ages of volcanic chains on the Pacific plate, and in section 7 to obtain poles of average plate to mantle motion. These same oblique grid systems reveal relationships between plate to mantle motion, as expressed by volcanic chains, and other linear features on the Pacific plate.

Perhaps most significant are the relationships between plate to mantle and plate to plate motion. The pole at 10°N 98°W was determined from the Emperor seamount chain and represents motion of the Pacific plate over the Hawaiian hot spot between 42 and 68 m.y.b.p. The pole at 15.5°N 105.2°W was determined from the Emperor, Tuvalu-Gilbert-Radak (TGR), and Louisville chains (section 7), and represents the average motion of the Pacific plate relative to the underlying mantle. Small circles about both of these poles are approximately parallel to transform faults in the Phoenix magnetic lineations, with the 10°N 98°W small circles giving a somewhat better fit. The TGR chain deviates by only about 3.5° from small circles about 15.5°N 105.2°W. Thus this volcanic chain is nearly parallel to the adjacent transform faults. The magnetic lineations are offset slightly across the chain. If the TGR chain was formed at a hot spot between 42 and 68 m.y.b.p., as its orientation with respect to the Emperor chain suggests (section 5), it would be much younger than the transform faults in the Phoenix lineations. This implies that in this region of the Pacific, the TGR hot spot followed (or approximately followed) the trend
of previously existing transform faults. The interaction between the hot
spot and a transform fault may account for some of the complexity of the
TGR chain.

A similar relationship holds in the northwestern Pacific. South of
the Aleutian trench, transform faults delineated by the Cenozoic magnetic
lineations trend north-south. The western most transform fault is paral­
lel to a small circle about 15.5°N 105.2°W. The Emperor chain is also
parallel to a small circle about this pole. Transform faults in the Japa­
nese lineations are not parallel to small circles about 15.5°N 105.2°W;
however, these transform faults are not orthogonal to the lineations.
The angle between the lineations and the transforms is about the same as
the angle between the transforms and the small circles. The lithosphere
east of the northern Emperor chain (and Emperor trough) is about 70 m.y.
old (anomaly 32), and to the west about 108 m.y. (anomaly M0). Thus there
is 40 m.y. difference in lithospheric age across the Emperor chain. This
is greater than the age difference across the Mendocino fracture zone
(about 30 m.y.). This evidence suggests that the Emperor chain is paral­
lel to (or follows) an older, very large transform fault. Two other re­
lationships should be noted. First, both the Mesozoic and Cenozoic anom­
lies young to the north, while the Emperor chain increases in age to the
north. Second, north of 50°N the Emperor chain bends to the west, the
Emperor trough appears to intersect the chain at this bend, and the Emper­
or trough and Emperor chain north of 50°N follow the same trend. At this
bend the Emperor chain is about 68 m.y. old; nearly the same age as the
lithosphere to the east. Presumably, at some point now subducted, the
chain would have been the same age as the lithosphere west of the chain.
The relationship between magnetic lineations and the Wentworth, North Gardner, and Musicians chains was discussed in section 6. Small circles about the pole (36°N 76°W) determined from these chains is parallel to the Emperor chain north of 50°N. Thus small circles about 36°N 76°W are parallel to plate to mantle motion, and nearly perpendicular to Pacific-Farallon plate to plate motion between the Mendocino and Murray fracture zones.

Thus between 42 and 68 m.y.b.p. plate to mantle motion was parallel to the direction of spreading (parallel to the transform faults) on the older Pacific-Phoenix and Pacific-Kula spreading ridges, and prior to 68 m.y.b.p., plate to mantle motion was parallel to at least one section of the Pacific-Farallon ridge. The 68-125 m.y. pole may also represent 0-1 m.y. plate to mantle motion (section 7); so plate to mantle motion may once again parallel the trend of an older ridge crest.

The Emperor trough, the Nova-Canton trough, the Necker ridge, and the north-south ridge between the Magellan rise and Gilbert and Radak chains are linear features of undetermined origin. The Emperor trough is parallel to small circles about the 68-125 m.y. pole at 36°N 76°W, and appears to intersect with the Emperor seamount chain near the 68 m.y. bend. The Necker ridge is perpendicular to small circles about this pole. The Nova-Canton trough is parallel to small circles about the 42-68 m.y. pole at 10°N 98°W. The ridge west of the Magellan rise is perpendicular to small circles about this pole, and also perpendicular to the Phoenix lineations.

The Pacific plate boundary in the Fiji-Solomon islands area is irregular, however, the general trend of this boundary follows a small circle
about 65°N 40°W, which represents the average motion of the Pacific plate relative to the mantle between about 1 and 15 m.y.b.p.

Fracture zones, e.g., the Blanco fracture zone, in the Juan de Fuca area are roughly parallel to small circles about 65°N 40°W. Thus these fracture zones are approximately parallel to plate to mantle motion, and to the southeastern end of the Gulf of Alaska volcanic chains. The pole at 81°N 70°W represents the average plate to mantle motion between 15 and 21 m.y. The Sila fracture zone, which follows the western end of the Scott-Parker volcanic chain, trends at an angle of 7° to small circles about this pole.

Thus, in the Pacific there are some very complex geometric relationships between plate boundaries and hot spot traces. These relationships may account for some of the complexities observed in volcanic chains, e.g., the Line islands and TGR chains. The significance of these relationships with respect to the evolution of the Pacific plate is, as yet, unknown.
9. SUMMARY AND DISCUSSION

The Hawaiian ridge is the longest volcanic chain on the Pacific plate and it provides, therefore, a good indication of plate to mantle motion for the past 68 m.y. It is significant that most of the volcanic chains formed in the past 68 m.y. are closely parallel to small circles about plate to mantle poles of rotation, and are, therefore, most probably formed at a hot spot. Only the Marquesas and Line cross chains are of doubtful origin because they parallel small circles about a plate to mantle pole that is of a different age than the K-Ar dates for the islands. Prior to 68 m.y.b.p. plate to mantle motion is less certain, and consequently the origin and age relations of volcanic chains older than 68 m.y. are uncertain. Most of these chains are located in the older western Pacific between the Japanese, Hawaiian, and Phoenix magnetic lineations. This part of the Pacific plate is generally older than 160 m.y., so there is a 100 m.y. interval during which these volcanic chains were formed. Once the plate to mantle motion is determined for the pre-68 m.y. history of the plate, many of these older volcanic chains will undoubtedly be related to a hot spot origin.

Volcanic chains are of different lengths, indicating that the life of melting anomalies varies. Also there is a notable variation in the number of melting anomalies that are active in any given time span. For example, between 0 and 23 m.y.b.p., 12 volcanic chains were formed, between 23 and 42 m.y.b.p. 3 or 4 were formed, and between 42 and 68 m.y.b.p. 3 were formed. The number formed in each 20 m.y. interval from 160 to 68 m.y., is probably also less than ten. In addition, some melting anomalies, e.g., Hawaii, produce relatively large volumes of extrusive material resulting in large, well defined volcanic chains, whereas other
melting anomalies produce much less extrusive material. This suggests that there are variations in the volume, depth, degree of melting, and amount of heat supplied to hot spot melting anomalies.

Only four chains appear to have had a Class II origin (including the Mathematicians chain which was not included in this investigation but was studied by Sclater et al., 1971). This raises some question as to the viability of Class II mechanisms. These four chains are rather small, however, and the possibility that they resulted from ridge jumps seems reasonable.

Class and age relationships are summarized in Table 9.1.

Volcanic chains formed before 42 m.y.b.p. are geometrically related to older plate boundaries. It seems unlikely that these plate boundaries controlled Pacific plate to mantle motion; however, these relationships complicate the structure of pre-42 m.y. volcanic chains. The Emperor, Louisville and Tuvalu-Gilbert-Radak chains were formed between 42 and 68 m.y.b.p. and follow, or nearly follow, the trend of older transform faults. The Emperor chain is related to a transform between the Mesozoic and Cenozoic magnetic lineations in the northwest Pacific, the Tuvalu-Gilbert-Radak chain is related to a transform in the Phoenix lineations, and the Louisville chain follows nearly the same trend as the Eltanin fracture zone. The structure of the Emperor and Louisville chains is relatively uncomplicated, suggesting that either these hot spots followed very closely the old transform trace, or the hot spots were far enough away from the transform trace so that the transform trace had no effect on the volcanic chains. Pre-existing lithospheric structure under the Tuvalu-Gilbert-Radak chain appears to have been more complicated, and the Tuvalu-Gilbert-Radak hot spot apparently deviated slightly from the
Table 9.1. Class and age range of volcanic chains of the Pacific plate

<table>
<thead>
<tr>
<th>Volcanic chain</th>
<th>Class</th>
<th>Age</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hawaiian ridge</td>
<td>I</td>
<td>&lt; 68 m.y.</td>
</tr>
<tr>
<td>Kodiak-Bowie</td>
<td>I</td>
<td>&lt; 68 m.y.</td>
</tr>
<tr>
<td>Cobb-Miller</td>
<td>I</td>
<td>&lt; 68 m.y.</td>
</tr>
<tr>
<td>Scott-Parker</td>
<td>I</td>
<td>&lt; 68 m.y.</td>
</tr>
<tr>
<td>Austral-Cook</td>
<td>I</td>
<td>&lt; 68 m.y.</td>
</tr>
<tr>
<td>Pitcairn-Gambier</td>
<td>I</td>
<td>&lt; 68 m.y.</td>
</tr>
<tr>
<td>Society</td>
<td>I</td>
<td>&lt; 68 m.y.</td>
</tr>
<tr>
<td>Guadalupe</td>
<td>I</td>
<td>&lt; 68 m.y.</td>
</tr>
<tr>
<td>Louisville</td>
<td>I</td>
<td>&lt; 68 m.y.</td>
</tr>
<tr>
<td>Emperor</td>
<td>I</td>
<td>&lt; 68 m.y.</td>
</tr>
<tr>
<td>Tuvalu-Gilbert-Radak</td>
<td>I</td>
<td>&lt; 68 m.y.</td>
</tr>
<tr>
<td>Line islands</td>
<td>I</td>
<td>&gt; 68 m.y.</td>
</tr>
<tr>
<td>Tuamotu</td>
<td>I</td>
<td>?</td>
</tr>
<tr>
<td>Truk</td>
<td>I ?</td>
<td>?</td>
</tr>
<tr>
<td>Tokelau</td>
<td>I ?</td>
<td>?</td>
</tr>
<tr>
<td>Line cross</td>
<td>?</td>
<td>&lt; 68 m.y.</td>
</tr>
<tr>
<td>Marquesas</td>
<td>?</td>
<td>&lt; 68 m.y.</td>
</tr>
<tr>
<td>South Moonless Mountains</td>
<td>I</td>
<td>&lt; 68 m.y.</td>
</tr>
<tr>
<td>Samoan</td>
<td>I</td>
<td>&lt; 68 m.y.</td>
</tr>
<tr>
<td>Kusaie-Ponape</td>
<td>I</td>
<td>?</td>
</tr>
<tr>
<td>Musician N-S</td>
<td>I ?</td>
<td>?</td>
</tr>
<tr>
<td>Mid-Pacific Mountains</td>
<td>II ?</td>
<td>&gt; 68 m.y.</td>
</tr>
<tr>
<td>Magellan chains</td>
<td>?</td>
<td>&gt; 68 m.y.</td>
</tr>
<tr>
<td>Musicians</td>
<td>II</td>
<td>&gt; 68 m.y.</td>
</tr>
<tr>
<td>North Gardner</td>
<td>II</td>
<td>&gt; 68 m.y.</td>
</tr>
<tr>
<td>Wentworth</td>
<td>II</td>
<td>&gt; 68 m.y.</td>
</tr>
<tr>
<td>Mathematicians</td>
<td>II</td>
<td>&lt; 68 m.y.</td>
</tr>
</tbody>
</table>
transform trace. Thus the structure of the Tuvalu-Gilbert-Radak chain is complex.

Pre-68 m.y. chains are geometrically related to older spreading ridges. The Emperor chain north of 50°N and the Line-Tuamotu chain are parallel to some segments of the Pacific-Farallon ridge. The complicated structure of the Line-Tuamotu chain may be related to the interaction of a hot spot with an older structural weakness generated at a ridge crest, or to the interaction of plate to plate and plate to mantle motion.

If a hot spot trace intersects an older transform trace at an acute angle, as in the case of the Hawaiian hot spot and the Mendocino, Murray, and Molokai fracture zones, the transform seems to have no effect on the hot spot trace. If, on the other hand, on the other arm, the hot spot trace is nearly parallel to the older transform, magma from the melting anomaly may be channeled along this old zone of weakness. In this case, the hot spot trace might deviate somewhat from plate to mantle motion.

The Tuvalu-Gilbert-Radak, Line islands, Marquesas, Gilbert, and Tuvalu chains may be examples where magma from a melting anomaly followed a pre-existing structural weakness instead of forming new conduits to the surface. It is more difficult to understand how lithosphere generated at a normal spreading ridge would have a zone of weakness paralleling the ridge. However, there may be some residual structure parallel to the ridge, especially if there have been changes in spreading rate or ridge jumps.

In addition to all the volcanoes which form linear chains, there are a great number of volcanoes which do not appear to be related to any linear structure. These volcanoes may have been formed at a ridge crest at the time the lithosphere was generated. If these volcanoes have any lineation, these lineations should be related to plate to plate motion. Individual
volcanoes which have a lineation parallel to plate to mantle motion, e.g., Gloucester, probably have an origin related to plate to mantle motion.

During this investigation, a number of questions have arisen. Some of these are listed below.

1. What are the directions and durations of plate to mantle motion before 68 m.y.b.p.?

2. What is the age and origin of the Magellan seamounts?

3. How do hot spot traces relate to the reconstruction of the Pacific?

4. What is the origin of the 70-100 m.y. old event that affected the region from the Line islands to the Marshall islands?

5. What is the origin of the Emperor and Nova-Canton troughs, and the Necker and Phoenix ridges?

6. What is the relationship of volcano spacing to the melting anomaly, lithospheric thickness, crustal structure, and lithospheric age?

7. What is the relationship of the ridge-jump volcanic chains to an abandoned magma chamber?

8. Why is there an increased volume of extrusion on the Hawaiian ridge at the intersection of the ridge-jump chains?

9. How does crustal structure affect local trends in volcanic chains?

10. What is the mechanical and thermal structure of transform fault traces? What is the effect of differential thermal contraction? To what depth is a transform trace a zone of weakness? Why does the topography of transform traces remain distinct while surrounding topography is smoothed by sedimentation? What is the effect of lithospheric thickening?
11. What is the origin and significance of the Line cross trends?

12. Where is the Pacific plate boundary north of the Fiji plateau and what is the effect of this boundary on the Samoan islands area?

13. What is the origin of Marquesas islands and why is there a conflict between the ages of the Marquesas and Hawaiian ridge with respect to plate motion?

14. Can the proposed 1 m.y. change in plate to mantle motion be verified by other data?

15. Can the complexity of the Tuvalu-Gilbert-Radak and Line islands chains be explained by an interaction of a hot spot and an old plate boundary?

16. Why do hot spot melting anomalies die out and start?

17. Do different melting anomalies originate at different depths in the mantle as suggested by Morgan? Is there a relation between depth of the melting anomaly, the amount of radioactive elements in a melting anomaly, the volume of the melting anomaly, the type of rocks erupted, the volume of extrusion and the duration of the melting anomaly?

18. What is the relation of volcanoes to oceanic plateaus?

19. What is the origin of the east-west ridges in the Musicians? Can they be explained by ridge jumps combined with a reorientation of the spreading ridge, or are they better explained by a melting anomaly next to a ridge generating a chain of volcanoes?

20. Is there really a change in the rate of rotation of the Pacific plate relative to the mantle at 15 m.y. (see Table 7.1), or is this apparent change due to a lack of data?

21. What is the relationship between the Necker ridge and the Line island?
22. Is hydrothermal circulation in the oceanic crust characteristic of hot spots?

23. Why are there so few volcanoes in the northwestern Pacific around the Shatsky rise?
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APPENDIX A. HYPOTHESES ON THE ORIGIN OF LINEAR VOLCANIC CHAINS
Hypotheses on the origin of linear volcanic chains fall into five major categories: (1) regional fracture system, (2) hot spot and/or mantle plume, (3) propagating fracture, (4) thermal feedback, and (5) plate boundary. The primary observations that must be explained are the large volume of volcanic material extruded onto the ocean floor and the linearity of the volcanic chains. This requires at least partial melting at some depth, and a renewable source of material.

Regional Fracture System

The hypothesis that lines of volcanoes result from fractures dates back to the early nineteenth century. During the cruise of the H.M.S. Beagle from 1831 to 1836, Darwin (1897) recognized that the volcanoes in the Galapagos islands lie on two sets of nearly parallel lines, "so that the principal craters appear to lie on the points where two sets of fissures intersect each other". He also pointed out that the Canary and Cape Verde groups show similar intersecting trends.

Dana (1849) goes to considerable extent describing the linear arrangement of volcanoes in the Pacific. "The epithet scattered, as applied to the islands of the ocean, conveys a very incorrect idea of their positions. There is a system in their arrangement, as regular as in the mountain heights of a continent; and ranges of elevations are indicated, as grand and extensive as any continent presents. Even a cursory glance at a map is sufficient to discover a general linear course in the groups, (as was long since remarked by Malte Brun and other geographers), and a parallelism even between these in distant parts of the ocean . . .

"This arrangement, in lines, has often been correctly attributed to the opening of fissures, . . . ."
"A frequent effect of change of level in the earth's surface, is a breaking of the crust by the action of forces within. The linear arrangement of the volcanic islands of the Pacific is thus explained; . . .

"This fact . . . is recognized by von Buch in his work on the Canary Islands; and the general principle has long been admitted in the science of Geology.

". . . fissures formed by subterranean forces are not long uninter rupted vents, but a series of linear ruptures, approximately regular, separated by longer or shorter intervals, sometimes two or more being in parallel series, or one starting to the right or left at the point where another ceases; also . . . that transverse fissures at right angles with the main line are a natural result of the same causes; also, the common fact, that fissures, after the first ejection, often remain open for a while, wherever widest or deepest, and continue the ejections. These principles fully explain the double line of islands, which we have denominated the Loa and Kea ranges."

Green (1887) noted the regular spacing of Hawaii volcanoes:

". . . this group of volcanic islands is not only situated on parallel sets of fissures having the main volcanic vents at the intersection of two of those fissures about twenty miles apart, but that the groups of such regularly placed volcanoes tend to appear at regular distances apart along the grand volcanic line."

In his paper on lineations in the Hawaiian Islands Powers (1917) states that:

"The most satisfactory theory yet advanced for the alignment of the vents appears to be that based on a major fracture system in the
earth's crust, the principal volcanoes arising at about equal distances of 25 miles . . . .

"The superficial fracture system has its major trend following the direction of the island chain on which are superimposed the secondary, divergent fractures arranged en echelon. That there are some deeper-seated lines of weakness on which the above system is superimposed appears probable . . . ."

When bathymetric data became available, hypotheses for the cause of the linear groupings were suggested.

Chubb (1934) says: "Most of the islands in this zone show a linear grouping, and rise from submerged ridges that have the dominant WNW-ESE trend. It seems likely that these ridges are anticlines produced by lateral pressure along a NNE-SSW direction, for gravity observations in the Hawaiian Islands show large positive anomalies, suggesting that stresses have raised this group too high for isostatic equilibrium. Fissures of the nature of strike-faults, and having the same trend as the anticlines, have opened up, and through them lavas have been extruded and volcanoes erected. In places other fissures, of the nature of dip-faults, and trending NNE have been produced."

Williams (1933) thought that volcanoes were formed "by the outpouring of lava from crescentic fissures determined by the outcrop of thrust planes with the curved surface of the globe".

Betz and Hess (1942), however, found no evidence of normal faulting as suggested by Chubb, or of a crescentic pattern as suggested by Williams. They suggested that the Hawaiian swell resulted from lava ejected onto the sea floor and say: "Any fault to be considered in the formation of the Hawaiian swell was probably of such a nature that great
vertical displacements did not occur generally along its course. This suggests to us the possibility that the swell may lie in a zone of transcurrent, or strike-slip, faults, such as the San Andreas fault, with its dominant movement horizontal". They point out that if the transform fault is irregular, movement of the fault line will cause compression along some parts of the fault and tension along other parts; those parts under tension will be favorable loci for volcanism.

Dietz and Menard (1953) analysed some of the first echo-sounder recordings and showed that the Hawaiian ridge is superimposed on the Hawaiian swell and surrounded by the Hawaiian deep and arch. They discussed three possible explanations for this structure: (1) that it is related to strike-slip faulting; (2) that it is related to a crustal buckle or tectogene and that the effusives have risen to the surface along thrust planes; and (3) that it is related to vertical forces which bowed up the surface and that the lava rose along fissures or normal faults. They favored the third explanation and suggested that the upward force might be supplied by the upward limb of a subcrustal convection cell.

Hot Spot and/or Mantle Plume

The hot spot hypothesis originated in a proposal by Wilson (1963a, b, c) that linear island chains and aseismic ridges were formed as the ocean crust moved over relatively stationary magma sources. The volcanic chains which extend to active mid-ocean ridges were easily explained in terms of a convection system rising under the mid-ocean ridges and providing a nearly continuous source of heat and magma. Bends in the mid-ocean ridge are associated with deflections in the convection system and thus more lava is extruded at these locations than
elsewhere along the ridge. Thus a volcano is formed at the crest of the ridge, and as the ocean floor moves away from the ridge, the volcano is cut off from its magma source and another volcano forms. The source of heat and magma for volcanic chains not associated with spreading ridges is less obvious. Wilson proposed a source within the relatively stagnant center of a convection cell; thus as the upper limb of the cell transports the crust over the source a chain of volcanoes forms.

Morgan (1971, 1972a, b) presented additional evidence to support the hypothesis that rigid lithospheric plates move over hot spots that are relatively fixed with respect to the mantle. He originally defined 20 hot spots. In the Pacific five hot spots generated chains of volcanoes: Hawaii hot spot generated the Hawaiian Ridge and Emperor Seamount chain; Macdonald hot spot generated the Austral, Gilbert, and Marshall volcanic chains; Easter Island hot spot generated the Tuamotu and Line chains, as well as the Salz-y-Gomez and Nazca Ridges; and two hot spots in the Juan de Fuca area generated seamount chains in the Gulf of Alaska. Morgan showed that if these volcanic chains define the motion of the Pacific plate over the hot spots, this motion is consistent with that for a rigid plate, and also with plate motion as determined by paleomagnetics and as deduced from transform fault trends and spreading rates on the mid-ocean rises. Morgan postulated that the source of heat and magma for hot spots is provided by convection plumes which ascend from the core-mantle boundary. He estimated that 20 plumes, each of which is 150 km in diameter with an upward velocity of 2 m/yr, would provide sufficient force to be the driving mechanism for plate tectonics. He argued that the lead isotope data of Oversby and Gast (1970) could be interpreted to require a complete recycling
of the mantle in 1.8 b.y.; consistent with a plume origin at the core-mantle boundary.

From theoretical studies on plume-type convection, Parmentier et al. (1975) find that in order to produce a plume, the layer in which the plume occurs must be heated from below. Internal heating does not produce plume-like flow. In addition, viscosity must be pressure and temperature dependent. These authors suggest that because the plume must be driven by base heating, the upper mantle is the most likely place for plumes to occur. McKenzie and Weiss (1975) argue that the apparent inability of a sinking slab to penetrate the 650-700 km boundary suggests that a rising plume might not be able to do so, and therefore if plumes exist they would not originate below 700 km.

Anderson (1975) assumes a heterogeneous formation of the earth, which implies that the original mantle was chemically heterogeneous. This primitive mantle would be enriched in CaO, Al₂O₃, TiO₂, and the refractory elements (including uranium and thorium), and depleted in MgO, FeO, SiO₂ and the volatile elements, relative to the present mantle. Concentrations of uranium and thorium in the lower mantle would provide the heat necessary to start plume formation. Ringwood (1975), however, favors a homogeneous formation for the earth, which would obviate Anderson's cause and effect relationships.

Ringwood (1975) objects to a lower mantle origin for plumes. He finds it hard to explain how a plume with an extreme ratio of length to cross-sectional area might develop and remain stable for long periods of time. In addition, he points out that the rise of a plume requires a superadiabatic temperature gradient in the deep mantle. Unless this superadiabatic gradient is quite small, lavas reaching the surface would
be greatly superheated, or the lavas would have ultramafic compositions because the superheat would lead to a greatly increased degree of partial melting of the mantle. He thinks the similarity in composition of lavas along the mid-ocean ridges and in the Hawaiian chain suggests a similarity of petrogenetic processes and source regions, and that, therefore, hot spot volcanism originates in the low velocity zone.

Shaw and Jackson (1973) point out that density currents, of either positive or negative sign, tend to be divergent at their leading ends. This divergence would cause a rising plume to lose its coherence as a focusing mechanism.

It has been proposed by Richter (1973), Richter and Parsons (1975), and McKenzie and Weiss (1975) that sublithospheric convection may produce hot spots. In order to account for the equality of oceanic and continental heat flow, these authors feel that some form of Rayleigh-Benard convection must occur beneath the lithosphere. Laboratory experiments by Richter and Parsons show that under a slowly moving lithosphere the convection cells would be small with more or less regular spacing. As the velocity of the lithosphere increases, the cells would become long longitudinal rolls aligned parallel to the motion of the overlying lithosphere. Upwelling nodes in the small scale convection may produce hot spots and magma for volcanism. The long longitudinal cells might produce lines of weakness in the lithosphere that control the formation of linear volcanic chains. Because the shape and size of the sublithospheric convection cells is controlled by the movement of the overlying lithosphere, it would appear that this hypothesis cannot explain the presence of hot spots at spreading ridges or movement of a spreading ridge over a hot spot. Recent plate
reconstructions by Morgan (personal communication) indicate that spreading ridges do indeed move over hot spots.

Deffeyes (1972) suggests that because most of the plumes are associated with spreading ridges, there must be some causal connection keeping the plume centered under the locus of divergence of adjacent plates.

One important test of the plume hypothesis is to determine if hot spots remain fixed with respect to each other. Morgan (1972a) suggested that hot spots might migrate at about 5 mm/yr. If the hot spots are fixed or migrate slowly, they should provide a coordinate system to which plate motions can be referred. Minster et al. (1974) concluded from systematic inversion of all available relative motion and azimuths of hot spot traces that Morgan's hot spots had remained fixed with respect to each other for the last 10 m.y. Molnar and Atwater (1973) considered plate reconstructions between 21 and 38 m.y.b.p. and conclude that hot spots move relative to each other at rates of 8-20 mm/yr. Molnar and Franchateau (1975) find relative motion of hot spots of 10-20 mm/yr among the principal hot spots in the Atlantic and Indian Oceans during the Cenozoic. Burke et al. (1973) considered the Azores and Colorado Seamount in the North Atlantic, and Tristan da Cunha-Gough, Discovery Seamount, and Bouvet Island in the South Atlantic. They conclude that these two groups of hot spots have moved relative to each other at an average rate of 18 mm/yr during the past 120 m.y., and within each group the relative motion has been much less.

Solomon et al. (1977) have determined absolute plate motions for 55 m.y.b.p. and show that "The predicted motions do not agree with the hypothesis of fixed hot spots and the observed trends of seamount chains
and aseismic ridges, the poorest agreement being in the Pacific." They conclude "... that either substantial relative motion among the asthenospheric roots of hot spots is required or an origin unrelated to hot spots for at least some of the seamount chains and aseismic ridges must be postulated." They suggest that the Hawaiian-Emperor bend was caused by a redirection of internal stress in the Pacific plate caused primarily by the subduction of the Kula plate. One of these authors (Jurdy, 1977; also W. J. Morgan, personal communication, 1977), however, has shown that if the Antarctic continent is allowed to split, the fit of hot spot traces in the Pacific is considerably improved.

Reconstructions of the Atlantic and Indian Oceans by Morgan (personal communication) require little relative motion of hot spots. Such reconstructions leave little doubt that hot spots are fixed relative to each other. A plume origin for hot spots is much less certain, however.

Wilson (1973) and co-workers have greatly expanded the original list of hot spots. They now identify over 150 hot spots. It does not seem reasonable to expect that all of these hot spots have the same characteristics as the original 20 hot spots. Wilson (1973) lists the following diagnostic characteristics of hot spots. (1) Each is an uplift, marked by elevated basement rocks on land and shoal water at sea. (2) The uplifts are capped by active volcanoes. (3) Gravity highs accompany at least some of them. (4) In the oceans, and sometimes on continents, one or sometimes two aseismic ridges stretch away from them. (5) They are areas of high heat flow.

In a study of the Hawaiian and all other WNW trending Pacific chains, Jarrard and Clague (1977) found that rates of volcanic
propagation for these chains offer strong support for the hypothesis that they were formed by hot spots which do not move with respect to each other.

Dziewonski et al. (1977) found a negative correlation between long wavelength gravity anomalies and seismic velocity anomalies at depth in the mantle. Possible explanations include a chemical plume of light high velocity material and other indications of mantle wide convection or a static chemical heterogeneity.

Watts (1976) studied the relation between gravity and residual bathymetry and concentrated on the gravity high associated with the Hawaiian swell. The increase in gravity above the swell is not as great as would be expected by the increase in elevation. Watts interpreted this as either a static low density zone at about 140 km depth or an upward moving limb of a convection cell.

A review of hot-spot hypotheses has recently been presented by Holden and Vogt (1977).

Propagating Fracture

Characteristic of propagating fracture hypotheses is a magma source in the upper asthenosphere. Thus a mechanism is needed to fracture at least the base of the lithosphere. A number of authors (Daly, 1933; Bowen, 1928; Yoder, 1952, 1976) have suggested that relief of tensional stress could cause melting in the upper mantle. Yoder's model required a 5-kbar stress release, which is roughly an order of magnitude greater than what is thought to be the tensile strength of the upper mantle (Roberts, 1970). Green (1971) has considered more recent experimental work and suggests that the fracture of the lithosphere produces very rapid upwelling from the low velocity zone.
There have been several suggestions for the fracture mechanism. Jackson and Wright (1970) thought that the extension of the Hawaiian ridge might be due to a slowly propagating fracture that repeatedly tapped fresh mantle.

Green (1971) suggested that fracture could occur in a plate moving over an imperfect sphere. He proposed that intermittent failure of the lithosphere leads to rapid upwelling from the low velocity zone, resulting in a high degree of partial melting (~ 30%) at 40-60 km depth and a very rapid extrusion of magma in the initial phase of volcano formation.

McDougall (1971) proposed that the Hawaiian Islands are the result of a propagating tensional fracture that is the result of a greater than normal concentration of heat-producing elements beneath the lithosphere. He also pointed out that the age data from the Hawaiian chain provide strong evidence for the migration at a uniform rate of the focus of volcanism, which in turn implies that the factors controlling the formation of the island chain have remained unchanged over the last 16 m.y.

The asthenospheric bumps proposed by Menard (1973) might also produce membrane stresses sufficient to fracture the lithosphere. He showed that present volcanic activity in the Hawaiian Islands and other island chains was on the updrift side of an asthenospheric bump, and argued that asthenospheric bumps are as fixed as hot spots and persist as long as hot spots. Asthenospheric bumps might cause turbulence in the lee of the bump which would lead to volcanism, or the bumps might cause fracturing.

Turcotte and Oxburgh (1973) point out that an elastic plate which cools nonuniformly will be subjected to thermal stresses. The decrease in elevation of the ocean floor can be explained by thermal
contraction of the lithosphere as it cools (Sclater et al., 1971).

Horizontal tension must also occur due to this contraction. According to Turcotte and Oxburgh this tension is parallel to the spreading ridge where the lithosphere is formed, and is sufficient to fracture the lithosphere, and, thus, could be responsible for the formation of at least some linear volcanic chains.

Turcotte and Oxburgh (1973) and Oxburgh and Turcotte (1974) also show that the lithosphere is subjected to tensional stress due to movement of the lithosphere over the nonspherical earth. An elastic lithosphere is assumed to take on the curvature of the earth at the point where it was created. As the lithosphere moves to different latitudes, it will deform due to the change in the earth's curvature. Using membrane theory, they calculated the magnitude of the resulting stress and conclude that it is sufficient to cause fracture.

Turcotte and Oxburgh (1976) "suggest that the Hawaiian-Emperor chain is the result of a propagating fracture caused by the cooling and thickening of the plate with time." A paper in preparation by these authors will provide further details.

Walcott (1976) considers the load of the island chain to be sufficient to cause fracture at the base of the lithosphere. For an elastic plate 60 km thick that is displaced a maximum of 1 km under a load, the tensile stress at the bottom of the plate is about $2 \times 10^9$ dyne/cm$^2$, near the estimated strength of rock. The linearity of the chain in the direction of plate motion can be explained by the guidance of a regional or plate-wide stress. Walcott (1976) states the loading hypothesis as: "... the larger seamounts will produce stresses during their growth large enough to cause a disruption of the plate." However, calculations
by Suyenaga (1977) indicate that, at depths where magma originates, stress is relaxed by creep so that stress doesn't build up to the levels envisioned by Walcott. Walcott does not rule out the presence of a hot spot or similar feature below the lithosphere since fracture by loading has difficulty explaining the progression of volcanism in one direction and the apparent equivalence of the rate of propagation of the chain and the plate velocity.

Menard (1964) pointed out the importance of bending, but attributed the formation of the Hawaiian chain primarily to development of new volcanoes at points where the load-produced arch intersects a major fault.

Jackson et al. (1972) suggest that Hawaiian volcanoes were formed as the Pacific plate moved over a melting spot which has a diameter of about 300 km and is due to either excess heat or pressure release. They further suggest that Hawaiian volcanoes fall on en echelon sigmoidal loci which they thought were caused by extensional strain. Jackson and Shaw (1975) extend this idea to other lines of volcanoes in the Pacific and hypothesized that the sigmoidal loci mapped changes in the stress field in the Pacific plate with time.

A new hypothesis in the propagating fracture category has recently been published by Marsh and Marsh (1976). Essentially the same data and related conclusions have been published by Wagner et al. (1977). Starting with the PGS-110 gravity model (degree and order 30), Marsh and Marsh (1976), truncate the complete PGS-110 solution at degree and order 22 and then subtract the degree and order 12 field models, resulting in a free air gravity map of degree and order 13-22. They point out the striking long regular linear pattern of anomalies traversing the
mid-Pacific area and propose that these anomalies are an expression of the sublithospheric convection rolls postulated by Richter (1973), Richter and Parsons (1975), and McKenzie and Weiss (1975). They note that the island of Hawaii lies at the leading edge of a gravity high which extends WNW along the Hawaiian seamounts and a large negative anomaly lies ESE of the island of Hawaii. "This curious relationship between the position of Hawaii and the gravity anomalies suggests a rather simple explanation for the cause of Hawaiian volcanism. As the lithosphere moves WNW and approaches the leading edge of the roll beneath the Hawaiian seamounts, it is deflected upward by probably more than a kilometer. This great change in the local plate radius of curvature can easily produce enough tensional stress to fracture the lithosphere."

Several points should be noted however. (1) Their anomalies cross plate boundaries. (Their Figure 5 is reproduced here as Figure A.1, with lines drawn through the gravity highs and lows.) While sublithospheric convection rolls might possibly pass under a spreading ridge, it is very unlikely that these rolls will pass through the underthrusting lithosphere at converging plate boundaries. (2) The wavelength of anomalies is very nearly the same everywhere on the earth. This wavelength is \( \sqrt{18^0} \), which is close to the \( 16^0 \) (360\(^0\)/22) resonance induced by the filter. (3) The variance (see their Figure 1) for the PGS-110 field model decreases up to about degree 12 and remains nearly constant for degrees higher than 12. This implies that the fit to the data is not improved by including degrees greater than 12. These points suggest that their anomaly pattern may be controlled by the mathematics and not sublithospheric convection. It may be that the Hawaiian ridge produces the dominant gravity anomaly in the central Pacific and therefore controls the trend of their anomaly pattern.
Figure A.1. PGS-110 free air gravity map relative to the twelfth-degree field and to the twenty-second degree and order. The contour interval is 4 mGal. From Marsh and Marsh (1976).
Liu et al. (1976) used a satellite gravity field to calculate membrane stresses in the lithosphere. A gravity high around Hawaii leads to tensional stresses there, especially in the vicinity of the main islands. According to the authors, this result supports any of the propagating fracture mechanisms.

Seeger (1976) suggests that divergence of plate boundaries causes tension within the plate. In the case of the Pacific plate, he notes that its boundaries in the northeast (in the vicinity of Vancouver Island) and southwest (Samoa) diverge from the direction of plate motion. This causes tensional stress within the plate that is perpendicular to the trend of the Hawaiian Islands.

Thermal Feedback

Shaw (1973) and Shaw and Jackson (1977) propose a complicated "thermal feedback" model for the origin of linear volcanic chains. They suggest that the return flow from subduction zones to spreading ridges occurs in the asthenosphere (defined as the zone of decoupling between the lithosphere and the underlying mantle), and that the velocity of this return flow varies with the degree of partial melting in the asthenosphere. The magma originates in the upper asthenosphere and forms in response to shear melting. The principal feedback loop is the relationship between shear stresses, shear ratios, and viscosity; all of which are a function of the percentage of melting in the asthenosphere. The initiation of this feedback system requires some disturbance of the preexisting return flow. They suggest that a thermosiphon may provide the initiating mechanism for melting anomalies which occur at ridge crusts. However, the thermosiphon itself requires an initiating mechanism, in addition to rather specific boundary conditions. They
offer two explanations for the existence of melting anomalies of the Hawaiian type in the central ocean basins: (1) a melting anomaly formed at a ridge may subsequently migrate; (2) heterogeneity of composition, melting temperature, or stresses in the mantle may initiate a melting anomaly in the interior of a plate. Shaw and Jackson (1973) introduce the concept of a "gravitational anchor" to explain why hot spots appear to be fixed with respect to the lower mantle. This anchor is formed by the sinking of the high density residue that remains after basaltic magmas are removed from melted mantle material. Jackson and Wright (1970) point out that the transfer to the surface of the enormous volumes of tholeiitic basalt that make up the Hawaiian Islands must have greatly changed the composition of the mantle beneath the islands. Thus the Hawaiian chain must be underlain by a root of residual material, which, they suggest, extends to depths of about 100 km. Shaw and Jackson postulate that the residue sinks all the way to the core-mantle boundary, and thus effectively pins the melting anomaly to the lower mantle. The sinking of the residue is also part of the feedback system because asthenospheric material must flow into the volume left by the sinking mass. This increases the shear strain heating.

In an analysis of position and age of Pacific islands, Jackson (1976) concluded that the melting anomaly under Hawaii and other Pacific chains may deviate from fixed positions. The thermal feedback hypothesis is compatible with this conclusion.

Mercier and Carter (1975) calculate shear heating at the base of the lithosphere and conclude that it is negligible at viscosities as high as $10^{22}$ poise and at all reasonable strain rates. Based on this they find it unlikely that shear heating causes a steepening in
previously determined pyroxene geotherms.

Plate Boundary

The idea that linear volcanic chains might be the locus of old plate boundaries has not been extensively explored. Wilson (1965) included the Emperor Seamounts, the Line Island ridge, and the Tuamotu, Society, and Austral Islands as part of his ICSU line, which he thought represented the western boundary of the East Pacific Ridge. Using paleomagnetic results from seamounts near Japan, Franchateau et al. (1970) suggest that the south Pacific and the northwestern Pacific may have experienced some differential movement between the Cretaceous and the present, with the Tuamotu ridge being the boundary along which movement occurred. Handschumacher (1973) suggested that the Emperor chain formed along the boundary between an old stable portion of ocean crust and an active spreading ridge migrating parallel to the boundary.

The correlation of Mesozoic magnetic anomalies across the western end of the Hawaiian ridge (Hilde et al., 1976) precludes an old plate boundary origin for the Hawaiian ridge. In addition, the suggestion (I have been unable to find a published reference) that the ocean floor is deeper northwest of the Hawaiian ridge than to the southwest is incorrect. Figure A.2 shows plots of depth versus distance for crossings of the ridge shown in Figure A.3. There appears to be no significant variation in depth. The mean depths at about 190 grid points (located to avoid seamounts, etc.) on each side of the ridge are within 10 m.
Figure A.2. Plots of water depth versus distance (bottom scale) for crossings of the Hawaiian ridge shown in Figure A.3. The solid line is a depth versus age (top scale) plot from Trehu (1975).
Figure A.3. Crossings of the Hawaiian ridge along which depth profiles were plotted in Figure A.2.
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APPENDIX B. NEOGENE RELATIVE MOTION BETWEEN THE PACIFIC PLATE, THE MANTLE, AND THE EARTH'S SPIN AXIS
NEOGENE RELATIVE MOTION BETWEEN THE PACIFIC PLATE,
THE MANTLE, AND THE EARTH'S SPIN AXIS

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Abstract

A comparison between Neogene (0 to -24 Myr) studies of the motion of the Pacific plate over the Hawaiian hot spot, migration of Pacific equatorial sedimentary facies, and paleomagnetism of pelagic sediments from the Central Pacific basin, reveals a difference amounting to a factor of two to three between independently derived rates of plate motion. Northward rates of motion for the central equatorial Pacific vary between about 20-30 mm/yr based on the migration of sedimentary facies, about 30 mm/yr based on the age progression along the Hawaiian ridge, and about 50-60 mm/yr based on paleomagnetically determined sediment and basalt paleolatitudes. In order to resolve these differences it may be necessary to invoke a long-term drift in the orientation of the geomagnetic field, or a northerly component of motion of the Hawaiian hot spot relative to the earth's spin axis.
Introduction

Numerous tectonic reconstructions have been proposed to account for the evolution of the Pacific plate. In principle, all such studies should be mutually consistent; in actuality, however, this is not always the case. There are three principal frames of references which are used to describe relative plate motions: plate versus plate, plate versus spin axis, and plate versus hot spot or mantle. There is a significant discrepancy between the rates of Neogene motion of the Pacific based on migration of equatorial sediment facies, on Pacific plate motion versus the Hawaiian hot spot, and on paleomagnetically determined motion of the plate relative to the earth's spin axis. These disagreements do not appear to be simply the consequence of a lack of data, but rather may be the consequence of the non-validity of one or more of the particular assumptions which underlie each method.

Plate Versus Spin Axis

Migration of Pacific equatorial sedimentary facies. The present-day distribution of relatively thick equatorial sedimentary facies, which were originally deposited in equatorial regions of upwelling and high biological productivity, has been used by several investigators to reconstruct the Cenozoic motion of the Pacific plate. Isopachs delining progressively older sediments are observed to be systematically offset to the north about a series of rotational poles located at mid to high latitudes in the northern hemisphere. The locations and associated rates of rotation of such poles are determined by backtracking the locus of maximum sediment thickness for each discrete time interval to its original equatorial deposition site.
Paleomagnetism of Pacific deep-sea sediments and volcanic rocks. Recent studies have shown that the Pacific plate moved progressively northward throughout the late Mesozoic and the Cenozoic. This persistent northward motion appears to be responsible for the discrepancies, which have been found for older sediments and volcanic rocks, between measured paleomagnetic inclinations and those that are characteristic of the present latitude of the sampling site. Latitudinal migration of the Pacific plate has been inferred from results of paleomagnetic surveys of Pacific seamounts, paleolatitudes from drilled basalts, and paleolatitudes from both drilled and cored sediments. Paleomagnetic inclinations determined from relatively old samples from southern hemisphere sites on the Pacific plate are higher than inclinations characteristic of the sample site, whereas inclinations from old samples from northern hemisphere sites are lower. Inclinations from northern hemisphere sites can be higher as well, however, if, at the time the sediment or rock acquired its magnetic remanence, the site was located at a higher latitude in the southern hemisphere than its present latitude in the northern hemisphere.

The usual assumption underlying the paleomagnetic method is that the earth's magnetic field, when averaged over several thousand years, approximates that of a stationary geocentric axial dipole. This assumption is supported by paleomagnetic results, such as those of Opdyke and Henry, which are based on a world-wide distribution of sediment cores. More recently there have been studies which have concluded that the time-averaged geomagnetic field is better represented by a dipole field that is slightly (about 300 km) displaced into the northern hemisphere or by a pair of unequal axial dipoles. If the geomagnetic field is, in fact, asymmetric with respect to the center of the earth, then paleolatitudes
determined assuming geocentricity will be systematically in error. At relatively low latitudes, however, there is virtually no difference between these models in terms of the rate at which field inclination varies with latitude. Consequently, at low latitudes, the choice of models does not significantly influence the paleomagnetic determination of plate motion.

Whether or not the poles of the geomagnetic field have remained coincident with the geographic poles over long periods of time is not known. At present, however, there is no evidence to suggest that there has been long-term movement of the north geomagnetic pole toward the Pacific, the direction of movement which would be required to reconcile our paleomagnetic results with those derived by other methods.

Other factors which might systematically alter the paleomagnetic remanence of a succession of rock or sediment strata, and thereby produce a spurious rate of paleolatitude change, are magnetic overprinting caused by progressive chemical alteration or, specifically in the case of non-indurated sediments, the acquisition of inclination error resulting from compaction with increasing depth of burial. Chemical alteration is usually recognizable in sediment cores by systematic differences between the direction or magnitude of normal and reversed intervals within a magnetostratigraphic section, or by magnetic instability during alternating-field demagnetization analysis. Neither is observed in the present paleomagnetic data and Hammond et al. 8 have shown that there is no discernible compaction-related rotation of the paleomagnetic vector in Pacific pelagic radiolarian-rich clays ranging in age from 0 to -30 Myr. Their results showed that consistent inclination trends occurred within individual cores recovered north and south of the equator; that is, in
response to northward motion of the Pacific plate, inclination values increased with age in southern hemisphere cores and decreased in northern hemisphere cores.

In the present study twenty-seven chronologically overlapping piston cores, which collectively span the past 25 Myr, have been used to determine the northward motion of the central equatorial Pacific. The cores were recovered from the Central Pacific Basin (averaged depth 5.0-5.5 km), throughout which there are extensive erosional surfaces that made it possible to recover relatively old sediments by piston coring. All of the cores contain homogeneous brown, radiolarian-rich clays (Table 1). The average core length is about 13 m and the average sediment accumulation rate is about 3 mm/10^3 yr. This relatively low sediment accumulation rate means that each sample from the cores contains, on the average, a depositional record spanning about 6000 yr. Magnetic secular variation is therefore largely averaged out within single samples. The cores were dated by correlating their radiolarian- and magnetostratigraphy to the time scale of Theyer and Hammond. The K76 core series (Table 1; Figure 1) is fully oriented, which allows an unambiguous determination of both polarity and the hemisphere in which the cores were deposited.

The stability of depositional magnetic remanence was established by standard alternating-field partial demagnetization analysis of at least six samples from each core. After the stable remanence was resolved (with a cryogenic magnetometer), individual inclination values in each core were converted to paleolatitudes by use of the geocentric dipole formula. A mean paleolatitude was calculated for each core by first determining the mean paleolatitude for each polarity interval, and then
### Table 1

<table>
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<tr>
<th>Core No.</th>
<th>Coring Site</th>
<th>Water Depth (m)</th>
<th>Recovery (m)</th>
<th>Age Span of Core (my)²</th>
<th>Latitude (degrees)</th>
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<td>16.4-17.5</td>
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<tr>
<td>M70-14</td>
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<td>5505</td>
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<tr>
<td>M70-17</td>
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<td>4730</td>
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<td>3.7-12.4</td>
<td>3.6</td>
</tr>
<tr>
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<td>5360</td>
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<td>16.4-21</td>
<td>12.4</td>
</tr>
<tr>
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<td>21.8</td>
<td>2.3-4.8</td>
<td>2.7</td>
</tr>
<tr>
<td>M70-76</td>
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<td>12.5-16.4</td>
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<td>16-19</td>
<td>8.9</td>
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</table>

*Ages greater than 5 Myr are based on correlations of each core's radiolarian- and magnetostratigraphy to the Neogene sediment-based reversal time scale of Theyer and Hammond.17,18 For this interval, a conservative estimate of the accuracy of a given age is about ± 0.5 Myr.*
dividing the sum of the absolute values of the polarity interval means by the total number of polarity intervals.

The mean paleolatitude for each core was normalized for its core site latitude\(^8\) and then plotted versus the mean age of the core (Figure 1). Each core was sampled at 10-cm intervals so that the average northward rate indicated in Figure 1 is based on nearly 3500 discrete paleolatitude determinations. A linear regression of the difference between mean paleolatitude and coring site latitude (\(\Delta\) latitude) versus mean age, assuming mean core age to be the independent variable, indicates an average rate of paleolatitude change for the central Pacific of about 64 mm/yr throughout the Neogene. This rate agrees with that determined in a similar manner by Hammond et al.\(^8\) (using seven cores) for the interval 0 to -13 Myr, but is considerably slower than their previously determined rate of about 110 mm/yr for -13 to -21 Myr. The distribution and resolution of the present data preclude a reliable determination of variations in the rate of northward motion during the Neogene, although such variations may have occurred as a result of reorganization of plate boundaries and change in the rate and/or direction of sea floor spreading. At present there are insufficient paleomagnetic data to reliably estimate an average northward rate of plate motion during the Paleogene, but the Neogene rate shown in Figure 1 is compatible with approximately 30° northward displacement of the Pacific plate since the Cretaceous.\(^2,6\)

There are relatively few other Neogene paleomagnetic results from the Pacific plate which can be compared with the foregoing results. Gromme and Vine\(^19\) determined an average paleolatitude from samples of 13 basalt flows recovered in deep drill core from Midway Island. Their results show that the paleolatitude for Midway is not significantly
Figure 1. Progressive increase, with increasing age, between the observed mean paleolatitude and the coring site latitude (Δ latitude) for chronologically overlapping cores from the Central Pacific Basin. The vertical bars represent the standard error for the mean paleolatitude of each core. The age span and Δ latitude value for the cores are given in Table 1.
different from that of the present location of the Hawaiian hot spot (19°N). Their conclusion supports a hot spot origin for the Hawaiian ridge and their result, together with the revised age of Midway, -27 Myr, is consistent with the central Pacific sediment paleomagnetic results. Using the average rate of northward displacement of Midway during the past 27 Myr (52 mm/yr) to constrain the Hawaiian ridge model of Epp, an average northward velocity in the central Pacific basin of 55 mm/yr is obtained.

In a study of mid-Cretaceous to mid-Miocene basalts recovered at several north Pacific DSDP sites, Marshall concluded that the basalt paleolatitudes were consistent with the tectonic models of Clague and Jarrard and Morgan. The northward rate of plate motion implicit in Clague and Jarrard's model has been subsequentially decreased in accordance with Dalrymple et al's revised age for Midway. Marshall's paleolatitude trend, however, is consistent with the Midway and the Central Pacific basin paleomagnetic results inasmuch as all indicate higher rates of northward motion than do hot spot and sediment facies studies.

Plate Versus Mantle

According to the hot spot hypothesis of Wilson and Morgan, linear volcanic chains are formed as the lithosphere moves over a hot spot or magma source that is relatively fixed with respect to the mantle. Morgan originally defined 20 hot spots and postulated that they were surface manifestations of convection plumes originating in the lower mantle. He argued that the lead isotope data of Oversby and Gast could be interpreted to require a complete recycling of the mantle in 1.8 Byr, consistent with a plume origin at the core-mantle boundary. He estimated that 20 plumes, each 150 km in diameter with an upward velocity
of 2 m/yr, would provide sufficient force to be the driving mechanism for plate tectonics.

One important test of this hypothesis is to determine whether hot spots remain fixed with respect to each other. Morgan\textsuperscript{27} suggested that hot spots might migrate at about 5 mm/yr. If the hot spots are fixed or migrate slowly they could provide a convenient coordinate system to which plate motions can be referred. Minster et al.\textsuperscript{29} concluded that Morgan's hot spots had remained fixed with respect to each other for the past 10 Myr. Molnar and Atwater\textsuperscript{30} considered plate reconstructions between -21 and -38 Myr and concluded that hot spots move relative to each other at rates of 8-20 mm/yr. Molnar and Franchateau\textsuperscript{31} found relative motion of 10-20 mm/yr among the principal hot spots in the Atlantic and Indian Oceans during the Cenozoic. Burke et al.\textsuperscript{32} considered the Azores and Colorado Seamount in the North Atlantic, and Tristan da Cunha-Gough, Discovery Seamount, and Bouvet Island in the South Atlantic. They concluded that these two groups of hot spots have moved relative to each other at an average rate of 18 mm/yr during the past 120 Myr, but that within each group the relative motion has been much less. Reconstructions of the Atlantic and Indian Oceans by Morgan (personal communication) require little relative motion of hot spots.

Since the Hawaiian ridge-Emperor seamount chain is the most prominent and best studied hot spot trace on the Pacific plate, it provides the best estimate of the motion of the Pacific plate with respect to a hot spot coordinate system. Epp\textsuperscript{21} used only this hot spot trace to determine poles of rotation of the Pacific plate relative to the mantle. This analysis made no a priori assumptions about the relative age of other volcanic chains on the Pacific plate. The poles he found, however, do
appear to be representative of other hot spot traces on the Pacific plate, suggesting that there has been little relative motion among Pacific hot spots for at least the past 23 Myr.

**Comparison of Results**

Since northward rates of motion for different locations on a plate vary with distance and azimuth to the pole of rotation, DSDP Site 166 (3.76°N, 175.08°W), located in the Central Pacific Basin (and central to the location of the paleomagnetically studied sediment cores), was chosen as a convenient location where paleomagnetically-derived northward rates of plate motion could be directly compared with the northward rates of motion determined by migration of sediment facies and hot spots.

At Site 166, Winterer's sediment facies model yields a northward plate velocity of about 43 mm/yr between -24 and 0 Myr. Based on a similar, but more comprehensive study by van Andel, the northward rate is 33 mm/yr. The more recent equatorial facies analysis of Lancelot and Larson indicates a considerably slower northward rate of about 22 mm/yr for the same time interval and location. These last two rates are shown in Figure 2.

Using the pole positions and rates of rotation determined by the investigators listed in Table 2, Site 166 has been rotated from its present location to its position at -24 Myr. Figure 2 also shows the change in latitude versus age for these rotations. It should be noted that these lines are not straight but show a slight increase in the northward rate of motion with age. This results from the change in position of DSDP Site 166 relative to the poles of rotation. The analysis of Clague and Jarrard has been amended by the work of Dalrymple et al. to consider the new age for Midway. The rate of rotation obtained by Dalrymple...
Northward Motion of DSDP Site 166

A. Paleomagnetics
B. Minster et al.
C. Epp
D. Clague and Co-workers
E. van Andel
F. Lancelot and Larson

Figure 2. Change in latitude versus age for DSDP Site 166 from:
A-sediment paleomagnetics, B-Minster et al.,\textsuperscript{33} C-Epp,\textsuperscript{24} D-Clague and Jarrard\textsuperscript{8} with a rate of rotation determined by Dalrymple et al.,\textsuperscript{9} E-van Andel,\textsuperscript{3} and F-Lancelot and Larson.\textsuperscript{5}
<table>
<thead>
<tr>
<th>Author</th>
<th>Pole</th>
<th>Age range (Myr)</th>
<th>Rate of Rotation (°/Myr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epp</td>
<td>65°N 40°W</td>
<td>0-23</td>
<td>0.86</td>
</tr>
<tr>
<td></td>
<td>59°N 54°W</td>
<td>23-42</td>
<td>0.67</td>
</tr>
<tr>
<td>Minster et al.</td>
<td>67.3°N 59.4°W</td>
<td>0-10</td>
<td>0.83</td>
</tr>
<tr>
<td>Clague and Jarrard and Dalrymple et al.</td>
<td>69°N 68°W</td>
<td>0-42</td>
<td>0.83</td>
</tr>
<tr>
<td>van Andel</td>
<td>67°N 59°W</td>
<td>0-25</td>
<td>0.83</td>
</tr>
<tr>
<td></td>
<td>67°N 59°W</td>
<td>25-50</td>
<td>0.25</td>
</tr>
<tr>
<td>Lancelot and Larson</td>
<td>67°N 45°W</td>
<td>0-40</td>
<td>0.5</td>
</tr>
</tbody>
</table>
et al.\textsuperscript{20} is very close to that obtained by Epp\textsuperscript{21} and Minster et al.\textsuperscript{29} (Table 2). Clague and Jarrard\textsuperscript{4} used the Hawaiian, Cook-Austral and Guadalupe chains to determine their pole position, while Epp\textsuperscript{21} used only the Hawaiian ridge. Minster et al.\textsuperscript{29} determined their pole position and rate of rotation from a systematic inversion of all available relative motion data and azimuths of hot spot traces. The consistency of the analyses of Epp,\textsuperscript{21} Minster et al.\textsuperscript{29} and Clague and Jarrard\textsuperscript{4} together with Dalrymple et al.\textsuperscript{20} lends some confidence to the result. The average rate of northward motion required by these analyses is about 30 mm/yr.

The location of Midway Island (28.2\textdegree N, 177.6\textdegree W) is another reference point where reconstructions of the Neogene northward motion of the Pacific plate can be compared (Figure 3). The various northward velocities at this location are not much different from the Site 166 results, and the discrepancies between the various reconstructions are just as pronounced. The paleomagnetic data represented by point A in Figure 3 indicate that Midway Island has been displaced northward by approximately 13\textdegree during the past 27 Myr. If averaged over the past 27 Myr, the rate of displacement is consistent with the Central Pacific Basin paleomagnetic results in that it is significantly more rapid than the other rates shown in Figure 3.

Discussion

The obvious general conclusion to be drawn from the results shown in Figures 2 and 3 is that there are significant discrepancies between independently derived Neogene rates of northward motion of the Pacific plate. Specifically, paleomagnetically derived rates are roughly twice as rapid as those determined by rotating the Pacific plate over the
Northward Motion of Midway

A. Midway
B. Minster et al.
C. Epp
D. Clague and Co-workers
E. van Andel
F. Lancelot and Larson

Figure 3. Change in latitude versus age for Midway. Midway data from Gromme and Vine\textsuperscript{23} and Dalrymple et al.\textsuperscript{9} Other lines from the same sources as in Figure 2.
Hawaiian hot spot and differ by a factor of two or three from the rate determined by backtracking equatorial sedimentary facies to their original deposition sites.

The sediment facies analyses of van Andel\(^3\) and Lancelot and Larson\(^5\) describe the motion of the plate relative to the spin axis, and therefore would be expected to be consistent with the paleomagnetic analyses. As shown in Figures 2 and 3, however, the predicted rates of northward motion based on sediment migration are considerably slower than those based on paleomagnetism of both sediments and basalt. It is difficult to quantitatively assess the reliability of reconstructions based on the migration of equatorial sedimentary facies, other than by their consistency with other independently derived results. The accumulation of sediment on a moving plate is, to a large extent, governed by the interaction of a number of dynamic factors including upwelling-induced surface productivity, the width of the area of upwelling, erosion, and CaCO\(_3\) solution. Relatively brief hiatuses within a sedimentary section, due to nondeposition, dissolution, or erosion, for example, may be cumulatively significant as well as difficult to detect. Van Andel and Whaley\(^33\) point out that maxima and minima in rates of sedimentation can vary in response to factors unrelated to the latitude of the deposition site. There can be little doubt that the distribution of equatorial sedimentary facies is strongly influenced by the motion of the Pacific plate; however, it is possible that such factors may be responsible for the differences between the Van Andel,\(^3\) Winterer\(^2\) and Lancelot and Larson\(^5\) results as well as the difference between the sediment facies results and the paleomagnetic results.
The paleomagnetically-derived rate of about 64 mm/yr appears to be reliable from the standpoint of the consistency and the large amount of data from which it was determined. If paleomagnetically determined rates do provide an accurate indication of plate motion relative to the spin axis, then the apparent agreement between facies results and those based on hot spots may be fortuitous.

Likewise the agreement between the results of Epp, Minster et al., and the combined work of Clague and Jarrard and Dalrymple et al. strongly indicates that 30 mm/yr is a reliable rate for the northward motion of the Pacific plate relative to the hot spot coordinate system. If the earth's magnetic field is fixed with respect to the spin axis and the paleomagnetic results indicate the true velocity of the Pacific plate with respect to the spin axis, then, in order to resolve the difference between the paleomagnetic and hot spot rates, the Hawaiian hot spot must have moved northward relative to the spin axis at an average rate of about 30 mm/yr. The implications of this motion for the motion of mantle with respect to the spin axis depends on the origin of hot spots. If hot spots are fixed with respect to the asthenosphere, then any hot spot versus spin axis motion requires only that the asthenosphere move relative to the spin axis. If, on the other hand, hot spots are the surface manifestation of plumes that ascend from the core-mantle boundary then the entire mantle must be moving relative to the spin axis. Since the total vector of motion of the mantle is unknown, the absolute mantle velocity cannot be determined; however, if this motion is the result of some mantle-wide convection system, then we should detect southerly motion at some other location. Burke et al. found that hot spots in the North Atlantic have moved northward relative to the spin axis, and hot
spots in the South Atlantic have moved southward. In order to conserve matter, the mantle under Asia must be moving southward relative to the spin axis; however, the southward motion of South Atlantic hot spots suggests a more complicated convection pattern. An intermediate possibility is that different plumes come from different depths in the mantle. This could conceivably allow a complex mantle convection system while retaining the fixed nature of hot spots.

An alternative explanation for the differences between plate motion rates, especially in view of the close agreement between Van Andel's results and those of Epp, Minster et al., and the combined results of Clague and Jarrard and Dalrymple et al., is to suggest that the paleomagnetic results are systematically biased with increasing age. As explained previously, Hammond et al. were able to show that the paleomagnetic data derived from Central Pacific deep-sea sediments appear to be unaffected by any compaction-related inclination error. A second possibility, that of tectonic tilting of the Central Pacific Basin, also cannot have influenced the observed rate of paleolatitude change because, as shown in Table 1, cores of varying age were recovered at scattered locations throughout the basin. A third alternative explanation for the relatively rapid paleomagnetic rates of northward plate motion is that the north geomagnetic pole was moving toward the Pacific at a rate of approximately 30 mm/yr during the Neogene. Andrews' analysis of polar wander during the Mesozoic and Cenozoic indicates that the field was moving relative to the Pacific plate during the Neogene, but the apparent motion was in essentially the opposite direction needed to reconcile the paleomagnetic, sedimentary facies, and hot spot results. If her conclu-
sion is correct, the paleomagnetic rates, relative to a fixed Hawaiian
hot spot, are even more rapid than indicated in Figures 2 and 3.

At the present time the differences in Pacific plate motion deter-
mined by migration of sediment facies, hot spots, and paleomagnetic are
unresolved.
Acknowledgements

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APPENDIX C. THERMAL CONTRACTION AND ALTERATION OF THE OCEANIC CRUST
THERMAL CONTRACTION AND ALTERATION OF THE OCEANIC CRUST

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and
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ABSTRACT

We propose that thermal stresses generated by the cooling of the lithosphere fracture the upper part of the lithosphere and that the depth of fracturing increases with the age of the lithosphere. Penetration of sea water into this fracture system alters the ocean crust; the amount of alteration increases with age and decreases with depth.
INTRODUCTION

Clague and Straley (1977) and Lewis and Snydsman (1977) have revived the hypothesis, suggested by Hess (1962) and later by Moores and Jackson (1974), that the oceanic Moho is a hydration boundary between partially serpentinized and unserpentinized ultramafic rocks. Clague and Straley (1977) place the Moho within the tectonized harzburgite layer found in most ophiolites. Their model accounts for the seismic anisotropy observed in the upper mantle and, in addition, explains the increase in thickness of layer 3 with age and the difference in thickness between some ophiolites and seismic crustal sections. They point out that their model requires that water must be available at depths of about 7 km within the oceanic crust. This is somewhat greater than the depth proposed for hydrothermal circulation at active ridge crests (Lister, 1977).

We suggest that thermal contraction of the oceanic lithosphere is responsible for fracturing the upper part of the lithosphere near ridge crests, and that this contraction continues throughout the cooling history of the lithosphere and tends to maintain and deepen the permeability of the upper lithosphere. Hydrothermal circulation begins at spreading ridge crests and this circulation, or at least deep penetration of water, continues until the lithosphere is 80-100 m.y. old. This provides a mechanism for a continual progressive alteration of the oceanic crust, and an increase in the depth of alteration with age.
THERMAL CONTRACTION AND STRESSES

The increase in water depth with increasing age of the lithosphere is caused by thermal contraction of the lithosphere as it cools (Sclater and others, 1971). This cooling must result in horizontal, as well as vertical, contraction. In fitting theoretical models of the contracting lithosphere to observed bathymetry, Davis and Lister (1974) use a coefficient of thermal expansion of $4.0 \times 10^{-5} \degree C^{-1}$; Trehu (1975) uses $3.6 \times 10^{-5} \degree C^{-1}$. Since these models are concerned only with the vertical contraction, $4.0 \times 10^{-5} \degree C^{-1}$ approximates the linear coefficient of thermal expansion of the lithosphere. The cubical coefficient would be about three times as large (Skinner, 1966). Horizontal contraction of the lithosphere generates stress. Thermal stresses normal to the ridge crest will be small because the ridge is a zone of weakness and because stresses will be relieved by the motion of the lithosphere. Contraction of the lithosphere will be confined in the direction parallel to the ridge crest, thus, as proposed by Turcotte (1974), the dominant thermal stresses will be aligned parallel to the ridge. These stresses will cause fracturing normal to the ridge. The upper part of the crust, which cools from $\sim 1200^\circ C$ to $\sim 0^\circ C$, will contract by nearly 5%. With increasing depth in the lithosphere the change in temperature will be less and the amount of contraction will be less.

Turcotte (1974) postulated that tensional thermal stress will cause fracture when it exceeds the hydrostatic pressure. This thermal stress, however, accumulates slowly enough so that it is dissipated by steady state creep in all but the uppermost portion of the lithosphere (Turcotte, 1974). The ratio of temperature to melting temperature ($T/T_m$) is the controlling factor in determining the thickness of the...
portion of the lithosphere that behaves elastically over long time periods (Murrell, 1976). If $T/T_m$ is less than about 0.3-0.5, steady state creep is suppressed, allowing stress to accumulate. From estimates of the oceanic geotherm and the dry solidus, Murrell (1976) found an elastic thickness of 24 km. Thicknesses on the order of 10 to 30 km are derived from the study of loads on the earth by means of a model of an elastic layer overlying a weak fluid (Walcott, 1970; Hanks, 1971; Watts and Cochran, 1974). Thus stress due to thermal contraction accumulates only at depths above 20 to 30 km. The temperature at these depths is 300-500°C; Turcotte (1974) sets the limit at 300°C.

The rate of cooling of the lithosphere is greatest near the ridge crests, with cooling being nearly completed by the time the lithosphere is 100 m.y. old. Thus, thermal stresses will accumulate rapidly near the ridge crest, and it is in this area where the primary thermal fracturing occurs. The thermal elastic thickness will be relatively thin near the ridge crest and fracturing will be shallow. However, as the lithosphere cools, the thickness of the lithosphere that reacts elastically to thermal stresses will increase, and the depth of thermal fracturing will increase. After the period of primary thermal fracturing, thermal stresses will act to maintain and deepen this fracture system for as long as the lithosphere is cooling.

HYDROTHERMAL CIRCULATION AND ALTERATION OF THE OCEANIC CRUST

Theoretical models of the cooling lithosphere explain the decrease in heat flow with increasing age (see, for example, Langseth and others, 1966; Sclater and Francheteau, 1970; Bottinga and Allegre, 1973; Parker and Oldenburg, 1973); however the heat flow observed near the
crests of spreading ridges is lower than predicted. From analysis of
continental geothermal systems, Elder (1965) suggested that there might
be hydrothermal circulation of sea water through the crust at the crest
of spreading ridges. The existence of this circulation has been
supported by recent work (e.g., Anderson and others, 1977; Crane and
Circulation of sea water through the upper lithosphere will remove heat
from the lithosphere provided that the system is open and there is
exchange with the deep ocean water. Thus there are two processes which
remove heat from the lithosphere: conduction, which is the observed
heat flow; and hydrothermal circulation of sea water, which is not
observed.

Anderson and others (1977) and Langseth and others (1977) show,
from an analysis of heat flow data, that hydrothermal circulation
affects the observed heat flow from the ridge crest out to a transition
zone, after which the observed heat flow agrees with the theoretical
models. Thus in crust older than the transition zone, there is no
hydrothermal exchange with the deep ocean water. There have been two
suggestions (see Anderson and others, 1977, p. 3404) to explain why
hydrothermal exchange with the deep ocean water stops at the transition
zone: (1) sediments eventually become thick enough to form an imperme-
able layer above a permeable ocean crust, and (2) hydrothermal precipi-
tation within the crust seals pores and stops the convection. In (1)
circulation may continue beneath the impermeable sediment layer beyond
the transition zone.

Analyses of dredge and Deep Sea Drilling Project samples have shown
that the amount of alteration of the top of layer 2 increases with the
age of the ocean floor (Christensen and Salisbury, 1972, 1973; Hart, 1970, 1973; Salisbury and Christensen, 1973). Salisbury and Christensen (1973) show that the density of DSDP layer 2 basalts decreases out to an age of at least 100 m.y., which suggests that alteration continues well past the heat flow transition zones. We see no reason for this alteration to stop at the bottom of layer 2, and suggest that layer 3 is also progressively altered.

It is difficult to estimate the depth of penetration of the hydrothermal circulation. The permeability of the fractured lithosphere will provide an important constraint. Williams and others (1974) find that for the Galapagos spreading center the horizontal wavelength of convective flow is about 6 km. Bodvarsson and Lowell (1972) suggest that water circulates through relatively widely spaced fractures, and they assume the vertical extent of the circulation is twice the distance between fractures. If this is the case for the Galapagos spreading center, hydrothermal circulation would reach to about 12 km. Williams and others (1974) suggest, however, that their heat flow observations indicate a finer scale of permeability than that proposed by Bodvarsson and Lowell (1972). This would increase the aspect ratio of the circulation cell and decrease the depth of circulation. Lister (1977) suggests that the aspect ratio may be similar to that found in laboratory experiments with uniform permeability. This would limit the circulation to less than 4 km. If the depth of the circulation is controlled by the depth of the 500°C isotherm, the depth of circulation would be about 3 km at the ridge crest (see Forsyth, 1977, Figure 2) and would increase with age.

The analogy between ophiolites and oceanic crust is useful as long
as we recognize that inasmuch as obduction is not a common plate
tectonic process, ophiolites probably do not represent normal oceanic
crust, and that some ophiolites may have been formed in an environment
other than a mid-ocean ridge (Miyashiro, 1975; Sinton, personal communi-
cation). Clague and Straley (1977) point out the importance of the
timing of the alteration present in ophiolites, i.e., whether it was
prior to, during, or subsequent to emplacement. Oxygen isotope data
may help to resolve this question, but since we cannot be certain that
the ophiolite sequence is normal crust we cannot be certain of a
correlation between the amount of alteration in ophiolites and in the
oceanic crust. At present the most reliable estimates probably come
from comparison of laboratory velocity data with seismic crustal
sections. Hess (1962) used this method and, assuming an average velocity
of 6.7 km/sec, estimated that layer 3 was 70% serpentine. Christensen
(1966, 1972) measured compressionaly and shear velocities in partially
serpentinized peridotites and showed that both velocities decrease as
the percent serpentine increases. This is the only systematic study of
the effects of alteration on velocity of which we are aware and,
therefore, the remaining discussion will deal with serpentinization of
layer 3, while recognizing that hydration of layer 2 will also occur.

Table 1 gives the amount of serpentine in layers 3A and 3B
determined from Christensen's velocity versus percent serpentine data.
If serpentinization is an isochemical process, with the exception of the
addition of water, there will be an increase in volume. Serpentiniza-
tion can occur with no increase in volume if MgO and SiO₂ are removed
(Turner and Verhoogen, 1960; Hostetler and others, 1966; Engin and
Hirst, 1970; Page, 1976). Hostetler and others (1966) show that,
Table 1

Velocities and Percent Serpentine in Layer 3

<table>
<thead>
<tr>
<th>Layer</th>
<th>( V_p )</th>
<th>% Serpentine</th>
</tr>
</thead>
<tbody>
<tr>
<td>3A</td>
<td>6.5-6.8</td>
<td>45-36</td>
</tr>
<tr>
<td>3B</td>
<td>7.0-7.7</td>
<td>30-8</td>
</tr>
</tbody>
</table>
depending on the ratio of pyroxene to olivine, complete serpentinization increases the volume by 35-40%. This is volume expansion; the linear expansion coefficient would be about one-third as large, ~12% for 100% serpentine. By filling the fractures and stopping the circulation of water, serpentinization of layer 3 could be a self-limiting process. The minimum dimension of the fractures will be controlled by the amount of contraction, and circulation will stop when the expansion equals this dimension. In the deep ocean basins the temperature at the top of layer 3 is on the order of 120°C, which allows a thermal contraction of ~4.3%. Thus, unless MgO and SiO_2 are removed, 36% is the maximum amount of serpentine that can be accommodated in layer 3. This is close to the amount of serpentine required by the velocity data for layer 3A (Table 1).

DISCUSSION

The Mohorovicic discontinuity is traditionally defined as a discontinuity in seismic velocity. There is no a priori reason why this discontinuity should also be a petrologic boundary. The thickness of the petrologic layers is probably controlled by the processes generating new lithosphere at ridge crests, and may vary from place to place along the ridge. Seismic crustal sections, on the other hand, are controlled by the original petrology and any subsequent alteration, which will tend to make the petrologic layers seismically obscure. Thus, there need not be a unique one-to-one correlation between petrologic sections and seismic section.

Clague and Straley's (1977) model explains the thickening of layer 3 with age. Seismic refraction data should be treated with caution
because many of the published models may not be sufficiently accurate
to ascertain an increase in layer 3 thickness with age (Hussong, per-
sonal communication). There have been, however, a number of papers
reporting this observation (LePichon, 1969; Goslin and others, 1972;
Woollard, 1975; Christensen and Salisbury, 1975; Lewis and Snydsman,
1977). Trehu and others (1976) suggest that the crust does not thicken
after the first 30 m.y. Since most of the cooling, and consequent
fracturing, occurs when the lithosphere is young, most of the crustal
thickening will occur early. Thickening will proceed slowly after
30 m.y. (cf. Goslin and others, 1972, Figure 5) and this thickening may
be lost in the scatter in the present seismic data. In addition to an
increase in crustal thickness with age, Woollard (1975, Figure 36)
observed an increase in heat flow at an age of ~80 m.y. which correlates
with a relative minimum in crustal thickness. This is exactly the cor-
relation we would expect since high heat flow implies that the 500°C
isotherm is closer to the surface and consequentially thermal fracturing
would not penetrate as deeply. The thermal fracturing and alteration
proposed is an irreversible, or at best slowly reversible process, which
requires that these anomalies are fixed with respect to the lithosphere,
i.e., the heat flow anomaly was generated at the ridge crest and both
anomalies migrated away from the ridge with the lithosphere. It should
be noted that fracturing by other mechanisms, loading for example, may
result in localized thickening of the crust.

As seismic refraction techniques have become more sophisticated,
the observed velocity discontinuity across the Moho has decreased and
the number of observed crustal layers has increased. The interpretation
of seismic refraction data is largely dependent on the assumed model.
Layered models as well as models in which the layers are replaced by velocity gradients (Kennett and Orcutt, 1976) can be made to fit the observed data. The velocity gradient models are consistent with the fracturing and alteration processes suggested above. These processes would result in the amount of serpentine in layer 3 decreasing with depth in some regular fashion. Velocity would increase with depth and the Moho would be a gradational boundary. The fracturing might extend below the Moho, but the alteration would stop at or near the Moho.

Reflections from the Moho have been observed, however (see for example, Hussong and others, 1976); and these observations require a velocity discontinuity, or at least a relatively steep velocity gradient at the Moho.

If layer 3 is serpentinized peridotite and the amount of serpentine decreases with depth, Poisson's ratio would decrease with depth. A number of authors (e.g. Christensen, 1974) have objected to a serpentinized layer 3 because the few seismic experiments that have measured both compressional and shear velocities indicate that Poisson's ratio is lower than that expected for serpentinized peridotite. If we assume that the compressional and shear velocities in layer 3 are 7.5 and 4.3 km/sec respectively, and that we know each velocity to ±3%, then the maximum range of Poisson's ratio we might expect is 0.21-0.29. It is curious, therefore, that there is little scatter in the reported values. Christensen's (1966, 1972) velocity versus percent serpentine data can be used to calculate Poisson's ratio versus percent serpentine in peridotite. The difference in Poisson's ratio between zero and 45% serpentine is only 0.03. We obviously need more data on Poisson's ratio in layer 3 before we can use seismic data to constrain the hypothesis.
that layer 3 is serpentinized peridotite.

As mentioned above, it has been suggested that hydrothermal precipitation might close the fracture system and prevent circulation in crust older than the heat flow transition zone. If thermal contraction can accommodate most of the volume increase due to serpentinization required by the seismic velocities in layer 3, then the fracture system may remain open, at least to deep penetration of water, for the 80-100 m.y. the lithosphere is cooling. Whether there is return flow of water to the surface depends on the amount of water going down and the amount used in the alteration reactions. It may be that in crust older than the heat flow transition zones, water penetrates to the base of the crust but does not return to the surface. There will be two other minor effects on heat flow. First, hydration reactions are exothermic. Second, the alteration process will remove uranium from sea water and deposit it in the crust. This concentration has been observed in sediments (Fisher and Bostrom, 1969; Bender and others, 1971; Bostrom and Fisher, 1971; Rydell and Bonatti, 1973; Rydell and others, 1974) and in basalts (Aumento, 1971; MacDougall, 1977), and similar concentration probably occurs with layer 3 alteration. Potassium is apparently also concentrated in basalts by weathering (Hart, 1973; MacDougall, 1977). The effects of alteration on the concentration of thorium in the crust is less well known. The data of Bender and others (1971) indicate that thorium is not enriched by the hydrothermal circulation at ridge crests. Both the hydration reactions and the increased uranium concentrations will contribute heat to the observed heat flow.
CONCLUSION

There is substantial evidence that (1) the lithosphere cools as it moves away from ridge crests, and (2) there is hydrothermal circulation of sea water through the ocean crust near active spreading ridges. On the basis of this knowledge we suggest two hypotheses. (1) Thermal stresses generated by the cooling of the lithosphere fracture the upper part of the lithosphere and the depth of fracturing increases with the age of the lithosphere. (2) Water penetrates this fracture system and causes alteration of the ocean crust. These processes result in a continual progressive alteration of the ocean crust and an increase in the depth of alteration with age.

If there is deep penetration of water into the ocean crust, then it is reasonable to expect that the crust is partially altered. The seismic characteristics of the crust will then be controlled by the composition of the crust and the amount and depth of alteration. It is obvious that we need more data on the effects of alteration on the physical properties of crustal rocks, the effects of thermal stresses on the lithosphere, and additional determinations of Poisson's ratio in the oceanic crust and upper mantle.

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