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THE OCEAN BASINS AND MARGINS

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Spec. Publ. 32, p. 209–266.
Deep Sea Drilling Project,
Office.
Leg 19 (DSDP) results: far
Reports of the Deep Sea
Washington, D.C.: United

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and geologic implications
Geol. Soc. Am. Bull. v. 94,

hysics of the Pacific Ocean
v. 19.
f an asymmetric zonal pa-
its in the Atlantic Ocean:
W. W., and Ryan, W. B.
275–296.
C. G., 1981, The geologic
ific Ocean—a synthesis of
Drilling Project, Thiede, J.,
tates Government Printing

Sea Drilling Project, v. 62,

mpson, S., Sangree, J. B.,
and global changes in sea
Exploration, Payton, C. E.,

c Tectonics Sedimentation
Soc. Am. Mem. 143.
D-I active margin transects
margins, in: *The Deep Sea*
Winterer, E. L., eds., *Soc.*

in: *Initial Reports of the*
eds., v. 18, Washington,

in the early Cretaceous: an
cade of Progress, Douglas
l. Spec. Publ. 32, p. 547–

acific Ocean Basin since 74

J. Phys., v. 41, p. 863–

in the Pacific Ocean: steps
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Chapter 3

PACIFIC PLATE MOTION RECORDED BY LINEAR VOLCANIC CHAINS

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I. INTRODUCTION

Seamounts and islands are quite common features of the deep-ocean basins, particularly the Pacific Basin. A conspicuous but relatively small number of these volcanoes are arranged in long linear chains (Figure 1). The vast majority, however, occur as isolated edifices. Recent work on a small number of these isolated volcanoes shows that many were formed at or very close to mid-ocean spreading axes (Clague and Dalrymple, 1975; Batiza, 1980) but that others are significantly younger than the underlying oceanic crust (G. B. Dalrymple, D. A. Clague, H. G. Greene, unpublished data). These isolated volcanoes require much additional study before their origin is understood. The volcanoes arranged in linear chains have been the focus of a great deal of work, and much has been learned about their origin and evolution. Most of the linear volcanic chains in the Pacific Basin are oriented roughly west-northwesterly and apparently formed sequentially above stationary hot spots during the past 42 m. y. as the Pacific plate rotated clockwise about a pole located near 69°N, 68°W (Clague and Jarrard, 1973a). Another group of linear chains exhibit roughly north-trending orientations and apparently were formed by the same mechanism between at least 80 and 42 m. y. ago as the Pacific plate rotated about a pole of rotation located near 17°N, 107°W (Clague and Jarrard, 1973b). Earlier age data available from linear island and seamount chains were summarized by Jackson (1976), Jarrard and Clague (1977), and McDougall and Duncan (1980); we will briefly review the information presented there and update it with more recent data.

Offshore Acapulco !

We have focused our attention on the age relations along and among the linear island chains that occur in the Pacific Ocean. A detailed summary and bibliography of the geology, petrology, and geophysics of the Hawaiian–Emperor volcanic chain is presented in Jackson *et al.* (1980). No similar summaries or detailed bibliographies exist for the other linear volcanic chains. Detailed information of the geology, petrology, and geophysics of these volcanoes can be found through the references cited in the various articles that report radiometric age data.

Jarrard and Clague (1977) discussed the reliability of the available age data using several specific examples. We emphasize here that nearly all submarine volcanic rocks are altered to some degree, which makes the interpretation of the analytically determined radiometric ages less than straightforward. We do not consider an age to be reliable unless we have obtained several concordant ages, have dated fresh mineral separates, or have obtained $^{40}Ar/^{39}Ar$ incremental heating data showing a well-defined plateau and isochron. Clague *et al.* (1975), Dalrymple and Clague (1976), and Dalrymple, *et al.* (1980) have shown that total-fusion $^{40}Ar/^{39}Ar$ ages of somewhat altered submarine rocks commonly give ages consistent with K-Ar ages on feldspars and with ages based on $^{40}Ar/^{39}Ar$ incremental heating experiments. We urge caution, however, since this is not always the case, particularly for tholeiitic basalt samples.

Another factor that affects the interpretation of available age data is the finite period of time during which volcanoes form. The sequence and duration of volcanic events are relatively well known in the Hawaiian Islands, where the time from the pretholeiitic-stage alkalic lavas (Moore *et al.*, 1982) to the last posterosional eruptions of strongly alkalic lavas can be as long as 4.5 m. y. (Clague *et al.*, 1983). Whereas for Hawaiian volcanoes the tholeiitic shield stage was probably less than 1 m.y. in duration (McDougall, 1964; McDougall and Duncan, 1980), and the formation of the volcano up to and including the postcaldera alkalic stage probably took less than 2 m.y., evidence is mounting that the duration of volcanic activity is considerably longer for some of the volcanoes in the Austral–Cook Islands (Dalrymple

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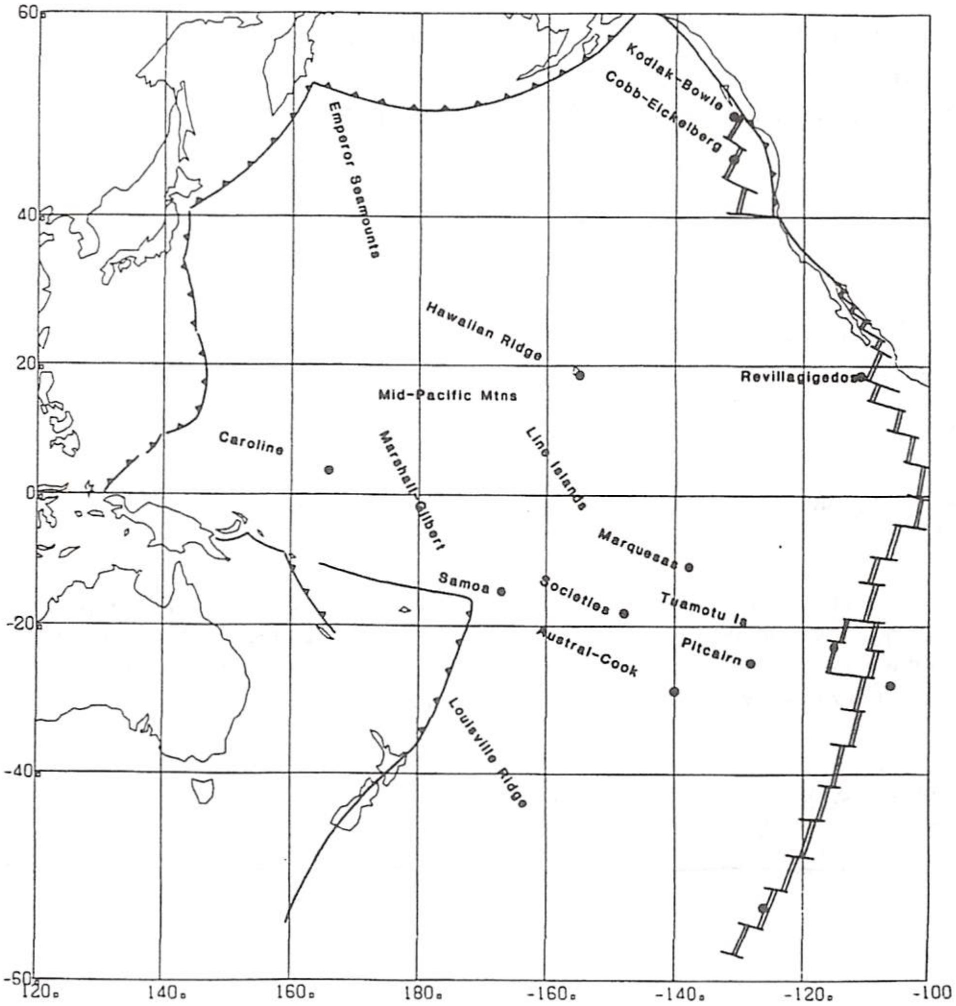

Fig. 1. Location map showing the Pacific Basin and the linear volcanic chains discussed in the text. Dots mark the location of hot spots.

et al., 1975; Duncan and McDougall, 1976) and in the Pratt–Welker Seamount chain in the Gulf of Alaska (Turner *et al.*, 1980).

Plate rotation models of the absolute motion of the Pacific plate relative to the underlying hot spots are based on two types of data: (1) the geometry of the volcanic chains, and (2) the rate of volcanic migration along the chains. Early models used the geometry of the chains to determine the location of the rotation pole and, separately, the rate of volcanic propagation along the chains to determine the rate of rotation about that pole (e.g., Clague and Jarrard, 1973a,b). More recent models (e.g., McDougall and Duncan, 1980;

Turner *et al.*, 1980) have used both the geometry of the various chains and the rate of volcanic propagation along those chains to locate the rotation pole and determine a least-squares-fitted rate of rotation. This evolution of methodology became possible due to the availability of reliable age data from chains other than the Hawaiian volcanic chain. In the following section we will summarize the age data available from the coeval Hawaiian, Austral–Cook, Society, Marquesas, Caroline, Pitcairn–Gambier, Samoan, and Islas Revillagigedos island chains, and from the Pratt–Welker and Cobb–Eickelberg seamount chains (Fig. 1). The next section will review chains that formed prior to the bend between the Hawaiian and Emperor volcanic chains at 42 m.y. Chains included here are the Emperor and Musician seamounts, the Line Islands, and the Louisville Ridge (Fig. 1). A final section will discuss motion of the Pacific plate in the hot spot reference frame.

II. LATE TERTIARY VOLCANIC CHAINS

Most of the better-studied seamount and island chains on the Pacific plate are late Tertiary in age and are oriented west-northwesterly subparallel to the Hawaiian chain. The following sections review the radiometric data available from these volcanic lineaments.

A. Hawaiian Volcanic Chain

The classic example of a linear island chain exhibiting a systematic age progression is the Hawaiian–Emperor chain. The Emperor Seamount portion of this chain formed from about 70 to 42 m.y. ago, as the Pacific plate moved in a northerly direction, and the Hawaiian Ridge formed from 42 to 0 m.y. ago, as the Pacific plate moved in a west-northwesterly direction. The Emperor chain will be discussed in Section III, describing Cretaceous and early Tertiary chains. The Hawaiian chain includes the high volcanic Hawaiian Islands, the low pinnacles and atolls of the Leeward Islands, and numerous seamounts and guyots. Age data are available from 31 volcanoes in the chain. The only major gap in ages is for the far western end of the chain. Work in progress (Duncan and Clague, 1984) on dredged samples from Colahan and Abbott seamounts has determined the age of volcanism in this area to be between 36 and 40 m.y.

Table I lists "best" ages for each edifice. All data have been converted to current decay constants (Steiger and Jager, 1977). Distances have been recalculated from Loihi Seamount instead of from Kilauea because Loihi is the youngest Hawaiian volcano (Moore *et al.*, 1982). For many of the dated volcanoes, particularly those older than Northampton Bank, tholeiitic lavas

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suitable for K-Ar dating have not been recovered. The ages of these volcanoes are based on ages of alkalic lavas. These alkalic lavas were thought to all postdate the shield-building tholeiitic stage. The recent discovery that young Loihi Seamount is erupting both tholeiitic and alkalic lavas (Moore *et al.*, 1982) suggests that at least some of the alkalic lavas dredged along the chain, particularly from small volcanoes, may represent the early rather than the late alkalic eruptive phase.

New age data include a near-zero age for Loihi Seamount, based on palagonite thicknesses (Moore *et al.*, 1982). New radiocarbon ages on charcoal beneath surficial flows on Hualalai volcano on Hawaii are all less than 12,000 years old (R.B. Moore, personal communication, 1983), and tholeiitic lavas dredged from the northwest rift of Hualalai still have fresh glassy rinds indicating a probable age of less than 100,000 years (Clague, 1982). New age data from Haleakala, Kahoolawe, West Maui, Lanai, and East and West Molokai (Naughton *et al.*, 1980; Bonhommet *et al.*, 1977) confirm the age relations for these volcanoes published by McDougall (1964). McDougall (1979) has added new data for Kauai, while Dalrymple (cited in Dalrymple *et al.*, 1980a) and Grooms (1980) have added new data for Niihau Island and Kaula Island, respectively. Grooms (1980) has also added limited data for an unnamed seamount between Nihoa and Necker islands, for Brooks Bank, and for Gardner Pinnacles. Only the data for Gardner Pinnacles are based on K-Ar ages of more than one sample; the others must be considered less reliable. New data provide a reliable age of 19.9 ± 0.3 m.y. for Laysan Island, and a less reliable age on one sample of 26.6 ± 2.7 m.y. for Northampton Bank (Dalrymple *et al.*, 1981). Dalrymple *et al.* (1977) redetermined the age of Midway Atoll using less altered alkalic cobbles from the Midway drill core. The new age of 27.7 ± 0.6 m.y. demonstrates that the previously reported age of 17.9 ± 0.6 m.y. (Dalrymple *et al.*, 1974) represents a minimum age due to the highly altered condition of the tholeiitic flows. This example serves to illustrate the difficulties inherent in dating altered submarine volcanic rocks.

Estimates of the rate of volcanic migration along the Hawaiian chain vary considerably. McDougall and Duncan (1980) used a linear regression of all the data available at that time and calculated a rate of 9.66 cm/yr ± 0.27 cm/yr. Using the more complete data set presented in Table I, we have recalculated the best-fit volcanic migration rate as 9.03 ± 0.4 cm/yr for all dated volcanoes older than Mauna Kea. We excluded the youngest volcanoes from the calculations because they are still active, and extrapolation based on Loihi Seamount indicates they will continue to be active for up to another 0.9 m.y. If these volcanoes were sampled several million years from now, it would be these still-to-be erupted lavas that would be sampled and

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TABLE I
Summary of Age Data from the Hawaiian–Emperor Volcanic Chain

Name	Number[a]	Distance from Loihi along Hawaiian–Emperor Trend (km)	Best K-Ar age (× 10^6 yrs)	Source[c]	Remarks
Hawaiian Ridge					
Loihi Seamount	0	0	Active	1	Age estimated from palagonite
Kilauea	1	32	Active	1	Historic tholeiitic eruptions
Mauna Loa	2	56	Active	1	Historic tholeiitic eruptions
Mauna Kea	4	66	0.375 ± 0.05	2	Samples from tholeiitic shield
Hualalai	3	103	0.01	3	^{14}C ages on oldest alkalic flows
Kohala[b]	5	107	0.40 ± 0.02	4	Samples from tholeiitic shield
Haleakala[b]	6	184	0.75 ± 0.04	5, 8	Samples from tholeiitic shield
Kahoolawe	7	213	1.03 ± 0.18	5	Alkalic samples from upper member
W. Maui[b]	8	230	1.63 ± 0.03	5, 8	Samples from tholeiitic shield
Lanai[b]	9	258	1.28 ± 0.04	6	Samples from tholeiitic shield
E. Molokai[b]	10	272	1.48 ± 0.07	5, 8	Samples from tholeiitic shield
W. Molokai[b]	11	302	1.84 ± 0.07	5, 8	Samples from tholeiitic shield
Koolau[b]	12	369	2.3 ± 0.1	7, 8	Samples from tholeiitic shield
Waianae[b]	13	404	2.9 ± 0.1	7	Samples from tholeiitic shield
Kauai[b]	14	549	5.1 ± 0.2	9	Samples from tholeiitic shield
Niihau[b]	15	595	5.5 ± 0.2	10	Samples from tholeiitic shield
Kaula	15	615	4.1 ± 0.1	11	Phonolite blocks in tuff
Nihoa	17	810	7.2 ± 0.3	12	Samples from tholeiitic shield
(unnamed)	21	950	10.1 ± 0.6	11	Dredged hawaiite
Necker[b]	23	1099	10.3 ± 0.4	12	Samples from tholeiitic shield
LaPerouse Pinnacle[b]	26	1239	12.0 ± 0.4	12	Samples from tholeiitic shield
Brooks Bank	28	1330	17.6 ± 0.5	11	Dredged hawaiite

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Brooks Bank	28	1330	17.6 ± 0.5	11	Dredged hawaiite
Gardner Pinnacle[b]	30	1420	16.0 ± 1.2	11	Dredged tholeiite and alkalic basalt
Laysan Island[b]	36	1848	19.9 ± 0.3	13	Dredged hawaiite and mugearite
Northampton Bank	37	1871	26.6 ± 2.7	13	Dredged tholeiitic basalt
Pearl and Hermes Reef	50	2311	20.6 ± 0.5	14	Dredged phonolite, hawaiite and alkalic basalt
Midway Islands[b]	52	2462	27.7 ± 0.6	15	Drilled cobbles of hawaiite and mugearite
(unnamed)	57	2630	28.0 ± 0.4	14	Dredged alkalic basalt
(unnamed)	56, 58	2702	28–31	16	Fossils, turbidites, DSDP 311
(unnamed)	63	2855	27.4 ± 0.5	14	Dredged alkalic basalt
Emperor Seamounts					
Kammu	65	3440	41 ± 3	17	Large foraminifera
Daikakuji	67	3523	42.4 ± 2.3	18	Dredged alkalic basalt
Yuryaku	69	3550	43.4 ± 1.6	14	Dredged alkalic basalt
Kimmei	72	3698	39.9 ± 1.2	18	Dredged alkalic basalt
Koko	74	3788	48.1 ± 0.8	19	Dredged alkalic basalt, trachyte
Ojin	81	4132	55.2 ± 0.7	20	Hawaiite and tholeiite, DSDP 430
Jingu	83	4205	55.4 ± 0.9	21	Dredged hawaiite and mugearite
Nintoku	86	4482	56.2 ± 0.6	20	Alkalic basalt, DSDP 432
Suiko	90	4824	59.6 ± 0.6	22	Single dredged mugearite
Suiko	91	4890	64.7 ± 1.1	20	Alkalic basalt and tholeiite DSDP site 433
Meiji	108	5860	74 ± 3 (61.9 ± 5.0)	23, 24	Nanoplankton, (minimum age on altered tholeiite) DSDP 192

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[a] Volcano number from Bargar and Jackson (1974).

[b] Age data used to calculate "best" volcanic migration rate (see text).

[c] *Sources:* 1. Moore *et al.* (1982); 2. Porter *et al.* (1977); 3. R. Moore (unpublished ^{14}C date); 4. McDougall and Swanson (1972); 5. Naughton *et al.* (1980); 6. Bonhommet *et al.* (1977); 7. Doell and Dalrymple (1973); 8. McDougall (1964); 9. McDougall (1979); 10. G. B. Dalrymple (unpub. data); 11. Grooms (1980); 12. Dalrymple *et al.* (1974); 13. Dalrymple *et al.* (1981); 14. Clague *et al.* (1975); 15. Dalrymple *et al.* (1977); 16. Larson, *et al.* (1975); 17. Sachs, quoted in Clague and Jarrard (1973); 18. Dalrymple and Clague (1976); 19. Clague and Dalrymple (1973); 20. Dalrymple *et al.* (1980a); 21. Dalrymple and Garcia (1980); 22. Saito and Ozima (1975, 1977); 23. Dalrymple *et al.* (1980b); 24. Worsley (1973); 25. McDougall and Aziz-ur-Rahman (1972).

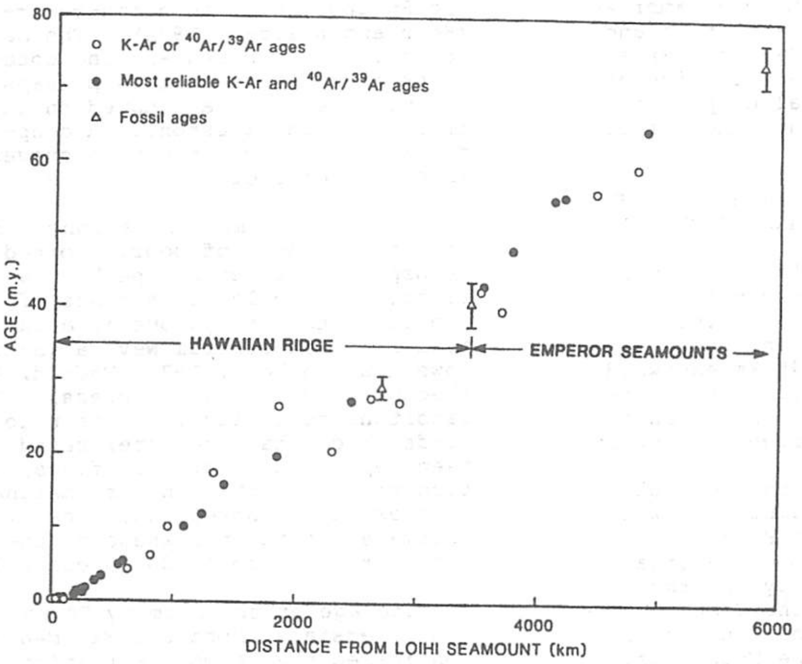

Fig. 2. Age–distance plot of volcanoes in the Hawaiian–Emperor chain. Age data and distance are from Table I.

dated. The best-fit line has a correlation coefficient of 0.979 and a *y* intercept of 0.93 m.y. This correlation line predicts an age of 37.2 m.y. for the Hawaiian–Emperor bend, somewhat younger than the K-Ar and fossil age determinations for volcanoes in the southernmost Emperor Seamounts.

If we recalculate the volcanic migration rate, using only the most reliable age data along the entire Hawaiian chain, we obtain a rate of 8.6 ± 0.2 cm/yr, a correlation coefficient of 0.998, a *y* intercept of −1.44 m.y., and a predicted age for the Hawaiian–Emperor bend of 38.6 m.y. (Fig. 2)

8.6 cm/y

This supposes that the volcanic migration rate has been constant since the change in Pacific plate motion at the Hawaiian–Emperor bend. It is possible that Pacific plate velocity was slower during the early stages of the Hawaiian Ridge, and a faster rate might be more appropriate for the younger part of the ridge. The best-fit volcanic migration rate for dated volcanoes from LaPerouse Pinnacles to Kohala volcano on Hawaii is 9.49 ± 0.40 cm/yr. This portion of the Hawaiian Ridge spans the last 12 m.y. of hot spot activity. Hence, this rate, rather than that determined for the entire Hawaiian chain, is appropriate for comparison with other Pacific volcanic lineaments that are much less extensive or whose pre-Miocene seamounts have not been as well documented.

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B. Gulf of Alaska Volcanic Chains

Two major linear chains of seamounts and guyots occur in the Gulf of Alaska: The Pratt–Welker (Turner *et al.*, 1973, 1980) or Kodiak–Bowie (Silver *et al.*, 1974) chain to the north, and the Cobb–Eickelberg chain to the south (Figure 1). The Pratt–Welker chain extends at least 1000 km across the Gulf of Alaska from Kodiak Seamount in the northwest to Bowie Seamount in the southeast. It is possible that the chain extends an additional 600 km to the southeast and that the present-day hot spot is located at or near Dellwood Knolls (Silver *et al.*, 1974). Dredged lavas include transitional and alkalic basalt and trachyte (Turner *et al.*, 1980).

Turner *et al.* (1980) presented new K-Ar age determinations for four seamounts in the chain and reviewed earlier data from Kodiak and Giacomini seamounts (Turner *et al.*, 1973). Table II lists their data and one additional $^{40}Ar/^{39}Ar$ incremental heating age determination for Welker Seamount (Dalrymple, written communication, 1982). Turner *et al.* (1980) proposed that the data for the chain can best be explained if Denson, Davidson, and Hodgkins seamounts, which are composed of transitional basalt, formed at a spreading axis, while Kodiak, Giacomini, Dickens, and Bowie seamounts represent a hot spot trace. Hodgkins Seamount apparently had a phase of renewed volcanism as it passed over the hot spot as well. This complex interpretation is further complicated by the new 14.9 ± 0.3 m.y. age determination for Welker Seamount, in as much as the model presented by Turner *et al.* (1980) predicts an age of only 10.1 m.y. for this edifice. The calculated volcanic propagation rate for the 600 km length of chain between Kodiak and Welker seamounts is 6.7 cm/yr, which would place the present-day hot spot about 1000 km southeast of Welker Seamount and close to Dellwood Knolls rather than near Bowie Seamount. If this model is correct, Dickens, Hodgkins, and Bowie seamounts have experienced rejuvenated volcanism within the past 4 m.y. If the hot spot is located at Dellwood Knolls, the average rate of volcanic migration for the entire chain is 6.1 cm/yr.

The Cobb–Eickelberg volcanic chain extends from an axial seamount on the Juan de Fuca Ridge (Delaney *et al.*, 1981), through Cobb, Eickelberg, and perhaps Horton seamounts (Turner *et al.*, 1980). The only age data are from Cobb, Horton, Miller, and Murray seamounts (Table II). No simple age relations are evident along the chain except to say that Cobb Seamount to the southeast is much younger than the other seamounts. Calculated volcanic migration rates range from around 5 to 6.4 cm/yr, depending on whether the age of Horton, Miller, or Murray seamount is used. This chain, like the Pratt–Welker chain, appears to have a complex history that will only be resolved with additional sampling and $^{40}Ar/^{39}Ar$ age dating.

TABLE II
Radiometric Ages from Pacific Island and Seamount Chains

Island or seamount	Position		Age range[a]	Source
	Latitude (°N)	Longitude (°W)		
Pratt–Welker				
Bowie	53.3	135.6	0.075–<0.7	Herzer (1971)
Hodgkins	53.5	136.0	2.5–14.4	Turner *et al.* (1980)
Davidson	53.7	136.5	>17.4	Turner *et al.* (1980)
Dickens	54.6	136.9	3.8–4.1	Turner *et al.* (1980)
Denson	54.0	137.4	16.8–19.7	Turner *et al.* (1980)
Welker	55.2	140.3	14.9[b]	Dalrymple, personal communication (1982)
Giacomini	56.5	146.6	20.6–21.4	Turner *et al.* (1973)
Kodiak	56.9	149.2	23.4–24.8	Turner *et al.* (1973)
Cobb–Eickelberg				
Cobb	46.8	130.8	1.6	Dymond *et al.* (1968)
Horton	50.3	142.6	19.4–23.2	Turner *et al.* (1980)
Miller	53.5	144.3	25.2	Dalrymple, personal communication (1982)
Murray	53.9	148.5	25.7	Dalrymple, personal communication (1982)
Islas Revillagigedos				
San Benedicto	19.3	110.8	0.0	Bryan (1966)
Socorro	18.7	111.0	0.0–0.3	Dymond, personal communication (1983)
Clarion	18.3	114.7	1.1–2.4	Dymond, personal communication (1983)
Marquesas Islands				
Fatu Hiva	−10.5	138.6	1.3–1.4	Duncan and McDougall (1974)
Tahuata	−10.0	139.1	1.8–2.1	Duncan and McDougall (1974)
Hiva Oa	−9.8	139.0	1.6–2.5	Duncan and McDougall (1974)
Ua Huka	−8.9	139.5	2.7–2.8	Duncan and McDougall (1974)
Nuku Hiva	−8.9	140.1	3.0–4.3	Duncan and McDougall (1974)
Eiao	−8.0	140.7	5.2–8.8	Brousse and Bellon (1974)
			5.0	McDougall and Duncan (1980)

[illegible]	[illegible]	[illegible]	[illegible]	Dymond, personal communication (1983)
Clarion	18.3	114.7	1.1–2.4	Dymond, personal communication (1983)
Marquesas Islands				
Fatu Hiva	−10.5	138.6	1.3–1.4	Duncan and McDougall (1974)
Tahuata	−10.0	139.1	1.8–2.1	Duncan and McDougall (1974)
Hiva Oa	−9.8	139.0	1.6–2.5	Duncan and McDougall (1974)
Ua Huka	−8.9	139.5	2.7–2.8	Duncan and McDougall (1974)
Nuku Hiva	−8.9	140.1	3.0–4.3	Duncan and McDougall (1974)
Eiao	−8.0	140.7	5.2–8.8	Brousse and Bellon (1974)
			5.0	McDougall and Duncan (1980)
Pitcairn–Gambier Islands				
Pitcairn	−24.1	130.1	0.5–0.9	Duncan *et al.* (1974)
Gambier	−23.2	135.0	5.2–7.2	Brousse *et al.* (1972)
Mururoa	−22.0	139.0	8.0	Chevallier (1973)
Society Islands				
Mehetia	−17.9	148.3	0.0	Talandier and Kuster (1976)
Tahiti–iti	−17.8	149.2	0.4–0.5	Duncan and McDougall (1976)
Tahiti	−17.6	149.5	0.5–1.2	Duncan and McDougall (1976)
Moorea	−17.5	149.8	1.5–1.7	Duncan and McDougall (1976)
Huahine	−16.7	151.0	2.0–2.6	Duncan and McDougall (1976)
Raiatea	−16.8	151.5	2.4–2.6	Duncan and McDougall (1976)
Tahaa	−16.6	151.5	2.6–3.2	Duncan and McDougall (1976)
Bora Bora	−16.5	151.8	3.1–3.4	Duncan and McDougall (1976)
Maupiti	−16.4	152.2	4.0–4.5	Duncan and McDougall (1976)
Austral–Cook Islands				
Macdonald	−29.0	140.2	0.0	B. Keating, personal communication, 1983; Johnson and Malahoff (1971)
Marotiri	−27.6	143.8	3.5–4.0	B. Keating, personal comm. 1983
Rapa	−27.0	144.3	5.9–5.2	Krummenacher and Noetzlin (1966)
Raivavae	−23.9	147.7	5.6–7.6	Duncan and McDougall (1976)
Tubuai	−23.3	149.5	8.5–10.6	Duncan and McDougall (1976)
Rurutu	−22.4	151.3	0.6–12.3	Dalrymple *et al.* (1975); Duncan and McDougall (1976); Turner and Jarrard (1982)

(*continued*)

TABLE II. (*continued*)

Rimatara	−22.8	152.7	(4.8–28.6)	Turner and Jarrard (1982)
Mangaia	−21.9	157.9	13.7–19.6	Dalrymple *et al.* (1975); Turner and Jarrard (1982)
Mauke	−20.1	157.5	4.8–6.1	Turner and Jarrard (1982)
Mitiaro	−19.8	157.8	(12.3)	Turner and Jarrard (1982)
Atiu	−20.0	158.2	7.4–10.3	Turner and Jarrard (1982)
Rarotonga	−21.2	159.8	1.1–2.3	Dalrymple *et al.* (1975); Turner and Jarrard (1982)
Caroline Islands				
Kusaie	5.4	162.9	1.2–2.6	Keating *et al.* (1984)
Ponape	6.9	158.3	3.0–8.6	Keating *et al.* (1984)
Truk	7.3	151.8	4.8–13.9	Keating *et al.* (1984)
New Hebrides–Samoa Lineament				
Taviuni	−12.3	174.6	5.4	Duncan (1985)
Lalla Rookh	−13.0	175.6	10.0	Duncan (1985)
Combe	−12.7	177.6	13.5	Duncan (1985)
Line Islands				
LI-143	19.5	169.0	88.1^b	Schlanger, *et al.* (1984)
LI-142	18.0	169.1	93.4^b	Schlanger, *et al.* (1984)
			128^b	Saito and Ozima (1977)
LI-63	16.5	168.2	86.0^b	Schlanger, *et al.* (1984)
LI-61	15.0	167.5	82^b	Schlanger, *et al.* (1984)
LI-137	14.5	169.0	56^b	Saito and Ozima (1977)
LI-59	12.5	167.0	85.0^b	Schlanger, *et al.* (1984)
LI-133	12.0	165.8	83^b	Saito and Ozima (1977)
LI-134	10.3	168.0	48^b	Saito and Ozima (1977)
LI-128	9.2	160.7	78.7^b	Schlanger, *et al.* (1984)
LI-130	8.3	164.3	72^b	Saito and Ozima (1977)
LI-33	8.2	161.9	39.3^b	Schlanger, *et al.* (1984)
LI-123	5.8	160.7	76.4^b	Schlanger, *et al.* (1984)
LI-119	2.7	165.0	68^b	Saito and Ozima (1977)
LI-PC6	2.5	158.5	69.8^b	Schlanger, *et al.* (1984)
LI-41	[illegible]	[illegible]	[illegible]	Schlanger, *et al.* (1984)

Line Islands			88.1[b]	Schlanger, *et al.* (1984)
LI-143	19.5	169.0	93.4[b]	Schlanger, *et al.* (1984)
LI-142	18.0	169.1	128[b]	Saito and Ozima (1977)
			86.0[b]	Schlanger, *et al.* (1984)
LI-63	16.5	168.2	82[b]	Schlanger, *et al.* (1984)
LI-61	15.0	167.5	56[b]	Saito and Ozima (1977)
LI-137	14.5	169.0	85.0[b]	Schlanger, *et al.* (1984)
LI-59	12.5	167.0	83[b]	Saito and Ozima (1977)
LI-133	12.0	165.8		
LI-134	10.3	168.0	48[b]	Saito and Ozima (1977)
LI-128	9.2	160.7	78.7[b]	Schlanger, *et al.* (1984)
LI-130	8.3	164.3	72[b]	Saito and Ozima (1977)
LI-33	8.2	161.9	39.3[b]	Schlanger, *et al.* (1984)
LI-123	5.8	160.7	76.4[b]	Schlanger, *et al.* (1984)
LI-119	2.7	165.0	68[b]	Saito and Ozima (1977)
LI-PC6	2.5	158.5	69.8[b]	Schlanger, *et al.* (1984)
LI-41	2.1	157.3	35.5[b]	Schlanger, *et al.* (1984)
LI-43	−0.7	155.3	59.0[b]	Schlanger, *et al.* (1984)
LI-44	−7.6	151.5	71.9[b]	Schlanger, *et al.* (1984)
LI-45	−9.1	150.7	70.5[b]	Schlanger, *et al.* (1984)
LI-52	−15.0	149.0	44.6[b]	Schlanger, *et al.* (1984)
Louisville Ridge				
LV-VM36-02	−40.8	165.3	45.5[b]	Duncan (unpublished)
LV-VM36-04	−38.3	167.7	44.6[b]	Duncan (unpublished)
LV-VM36-05	−33.9	171.2	53.3[b]	Duncan (unpublished)
Osborn	−26.0	175.0	(30–36)	Ozima *et al.* (1970)
Musician Seamounts				
Khatchaturian	27.1	162.2	66.9 ± 2.6	Clague and Dalrymple (1975)
Rachmaninoff	28.6	163.5	88.8 ± 5.2	Clague and Dalrymple (1975)
(unnamed)	33.5	166.5	95.6 ± 1.9[b]	M. Pringle, personal communication (1983)

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[a] Ages recalculated where necessary using the following decay and abundance constants: $\lambda\epsilon = 0.581 \times 10^{-10}\ \text{yr}^{-1}$; $\lambda\beta = 4.962 \times 10^{-10}\ \text{yr}^{-1}$; $^{40}\text{K/K} = 1.167 \times 10^{-4}$ mol/mol.

[b] $^{40}\text{Ar}/^{39}\text{Ar}$ total-fusion or incremental-heating age. Ages in parentheses are reported as minimum ages.

C. Caroline Islands

The Caroline Island chain consists of the volcanic islands of Truk, Ponape, and Kusaie, as well as additional coral atolls and seamounts. The volcanic islands have recently been studied by Mattey (1981, 1982) who distinguished a mildly alkaline Main Lava series, a Transitional Lava series, and a Nephelinite series of post erosional lavas. The sequence of eruptions is similar to that observed in Hawaii with the exception that the shield-building lavas are mildly alkalic rather than tholeiitic basalt, and the post-erosional lavas postdate the shield-building phase by as much as 5 m.y.

The available age data indicate that the Caroline Islands decrease in age to the east with the subaerial shield-building lavas of Truk being 13.9–9.9 m.y., those from Ponape 5.2 m.y., and those of Kusaie ~1–3 m.y. (Keating *et al.*, 1984). The rate of volcanic migration then is 12.1 ± 3.9 cm/yr. Keating *et al.* (1981) cited evidence that the hot spot that formed the chain is located at 4.8°N, 154.7°E, and is still seismically (and presumably volcanically) active. Mattey (1981, 1982) argued that the Caroline hot spot is declining in activity because Truk, Ponape, and Kusaie have progressively smaller volumes, and the shield-building lavas become progressively more alkaline (i.e., generated by smaller degrees of partial melting).

D. Islas Revillagigedos

This small island group is located near the intersection of the Clarion Fracture Zone with the East Pacific Rise, just south of the Baja California Peninsula (Fig. 1). San Benedicto, Roca Partida, and Socorro islands form a cluster at the northern end of the Mathematician Seamounts, a north-trending lineament thought to be an abandoned spreading axis left as spreading moved to the East Pacific Rise between 11 and 3.5 m.y. (Klitgord and Mammerickx, 1982). Clarion Island lies 400 km to the west. Lavas within this group belong to the alkali olivine basalt association (Bryan, 1966, 1967) and culminate in eruptions of soda-rich rhyolite on Socorro Island, and trachyte on Clarion Island. Active Barcena Volcano on San Benedicto Island is a palagonitic ash cone with a central dome of trachyte.

Historic eruptions have occurred at Socorro and San Benedicto islands. No evidence exists for recent volcanism on Clarion Island (Bryan, 1967). Potassium–argon age determinations (Dymond, unpublished data) show that the shield-building alkali basalts at Socorro Island are 0.18–0.30 m.y. old, whereas trachytic rocks are essentially age zero. At Clarion Island the oldest exposed rocks are 2.35–1.43 m.y. old, and later differentiated lavas are as young as 1.05 m.y. old. Volcanism apparently was initiated earlier in the west, at Clarion, and has shifted eastward to Socorro and San Benedicto.

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We hesitate to assign a volcano migration rate to this trend on the basis of only two dated volcanoes. Note, however, that the calculated rate of 16.0 cm/yr is much faster than any other Pacific island chain. The position of Clarion Island may be controlled by the Clarion Fracture Zone, since the island is south of a line subparallel with the Hawaiian Ridge, which passes through Socorro or San Benedicto.

E. Island Chains of French Polynesia

After the Hawaiian Ridge, the best-documented age-progressive subparallel volcanic lineaments on the Pacific plate lie in French Polynesia. These include the Marquesas Islands (Duncan and McDougall, 1974), the Society Islands (Duncan and McDougall, 1976, Dymond, 1975), the Pitcairn–Gambier islands (Brousse *et al.*, 1972; Duncan *et al.*, 1974), and the Austral–Cook islands (Dalrymple *et al.*, 1975; Duncan and McDougall, 1976; Turner and Jarrard, 1982; B. Keating, personal communication, 1983). The Tuamotu Islands are coral atolls but undoubtedly have volcanic pedestals. Subaerial lavas comprise alkali olivine basalts, ankaramites, basanites, and their differentiates. Tholeiitic compositions have been reported from the Marquesas only.

Studies of radiometric ages of these island chains have been reported elsewhere. We summarize these data, with recalculated new decay and abundance constants in Table II, and with calculated volcano migration rates in Table III. Historic eruptions have occurred at Mehetia (southeast end of the Society Islands), and volcanism is active at two seamounts near Mehetia (Talandier and Kuster, 1976) and at Macdonald Seamount at the southeast end of the Austral–Cook lineament. The Marquesas Islands and the Society Islands exhibit monotonically decreasing volcano ages towards the southeast, with volcanic migration rates of 10.4 ± 1.8 and 10.9 ± 1.0 cm/yr, respectively (McDougall and Duncan, 1980). A less well-defined but similar age progression exists in the Pitcairn–Gambier islands chain (Duncan *et al.*, 1974).

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Volcano ages in the Austral–Cook island chain do not provide such a simple pattern (Dalrymple *et al.*, 1975; Duncan and McDougall, 1976; Turner and Jarrard, 1982; B. Keating, personal communication, 1983). In addition to the presently active Macdonald Seamount, Pleistocene volcanism has occurred at three sites along this lineament: Aitutaki, Rarotonga, and Rurutu. At Aitutaki and Rurutu these young rocks were erupted onto older edifices (Duncan and McDougall, 1976; Turner and Jarrard, 1982). Age determinations from seven volcanoes (Mangaia, Rurutu, Tubuai, Raivavae, Rapa, Marotiri, and Macdonald) do yield an age progression of 10.7 ± 1.6 cm/yr (Duncan and McDougall, 1976), which is in good agreement with other

TABLE III
Rates of Migration of Volcanism for Pacific Island and Seamount Chains

Lineament	Age range	Extent of dated volcanism (km)	Rate ± 1σ (cm/yr)
Phase I			
Pratt–Welker	0–24.8	600	6.7 ± 2.0
Cobb–Eickelberg	0–25.7	1540	5.7 ± 2.0
Hawaiian Ridge	0.–28	2855	9.5 ± 0.4 (8.6 ± 0.2)[a]
Islas Revillagigedos	0.–2.4	400	16.0
Marquesas	1.3–5.0	360	10.4 ± 1.8
Pitcairn–Gambier	0.5–8.1	1100	12.7 ± 5.5
Society	0.–4.5	500	10.9 ± 1.0
Austral–Cook	0.–19.6	2000	10.7 ± 1.6
Caroline	1–13.9	1280	12.1 ± 3.9
New Hebrides-Samoa	0.–27.7	1600	7.2 ± 2.3
Phase II			
Emperor Seamounts	42–64.7	1450	6.3 ± 0.4
Musicians	67–95	830	(3.0)
Line Islands	44–93	4500	8.5 ± 1.3

[a] Rate for entire Hawaiian chain. First figure gives rate for last 12 m.y. of activity.

rates from French Polynesia. Remaining ages in this lineament could be reconciled with the hot spot model by postulating hot spots at Rurutu and Rarotonga, in addition to the Macdonald Seamount activity (Turner and Jarrard, 1982). The alignment of these three possible hot spots together with Samoa, Pitcairn, and proposed hot spots on the Nazca plate to the east (Easter, Sala y Gomez, San Felix), led Turner and Jarrard (1982) to favor a model of "hot line" volcanism (Bonatti and Harrison, 1976) for the islands and seamounts in this long swath. According to this hypothesis, eruptions may occur sporadically along volcanic lineaments in response to either plate boundary stress or longitudinal convective rolls in the mantle (Richter, 1973).

F. New Hebrides–Samoa Lineament

The Samoa Islands have posed a problem for the hot spot model. Pleistocene to Holocene volcanic activity has occurred at both ends of this lineament, which is subparallel to other Pacific island chains that exhibit well-defined age progressions. Natland (1980) proposed that Pleistocene to Holocene undersaturated posterosional lavas overlie alkali basalt shield-building lavas that geomorphologically seem to get younger to the east. This shield-building phase could be related to hot spot activity (now at the eastern end of the Samoa Islands), and the later undersaturated lavas in the west

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could be a rejuvenated volcanic episode triggered by subduction tectonics near the Tonga Trench. Such a model is easily tested with radiometric ages from these volcanoes, which will be available soon (I. McDougall, personal communication).

Support for a hot spot origin, however, comes from age determinations on rocks dredged from seamounts to the west of the Samoa Islands. The New Hebrides–Samoa Lineament (Hawkins, 1976) is a volcanic swath of seamounts, ridges, and islands that stretches westward from the Samoa Islands to just east of Vanuatu. This volcanic province lies within a region of considerable tectonic complexity, at the northern margin of the Fiji Plateau and the Lau Basin, slightly north of the current transform boundary between the Pacific and Australia–India plates. Some features of this volcanic lineament, then, may be related to plate margin tectonics, either transform-faulting or failed subduction (Halunen, 1979). But radiometric ages (^{40}Ar/^{39}Ar) from Taviuni Bank (4.2 ± 0.3 m.y.), Lalla Rookh Bank (9.8 ± 0.3 m.y.), and Combe Bank (14.1 ± 1.1 m.y.) fit well with age-progressive volcanism from zero age in eastern Samoa (Duncan, 1985). The calculated volcano migration rate is 7.7 ± 2.5 cm/yr. Younger volcanoes such as Wallis Island (0.82 ± 0.03 m.y.) and Rotuma Island may be associated with development of the Lau Basin and Fiji Plateau.

III. LATE CRETACEOUS TO EARLY TERTIARY VOLCANIC CHAINS

The older volcanic chains on the Pacific plate are not well documented. Volcanic portions of these lineaments are entirely below sea level, so that samples can be collected only by dredging and drilling operations. Hence the stratigraphic relationship of multiple samples from the same volcano are not often known. In addition all samples have experienced some degree of alteration by seawater. It is not surprising then that only a few late Cretaceous and early Tertiary volcanic chains include enough well-dated seamounts to warrant disucssion. Those that have provided useful information are the Emperor Seamounts, the Line Islands, the Musician Seamounts, and the Louisville Ridge. These lineaments are oriented north-northwest, subparallel to the Emperor Seamounts.

A. Emperor Seamount Chain

The Emperor Seamounts are the older, northward continuation of the Hawaiian Ridge. Age data are now available for 11 volcanoes in the chain including fossil age determinations for Meiji and Kammu Seamounts. Early radiometric studies of the Emperor Seamount chain were based on dredged lavas from the southern end of the chain (Clague and Dalrymple, 1973; Clague *et al.*, 1975; and Dalrymple and Clague, 1976) and from Suiko Seamount (Ozima *et al.*, 1970; Saito and Ozima, 1975, 1977). More recent work is based on drilled samples from DSDP Leg 55 (Dalrymple *et al.*, 1980a) and a few dredged samples from Jingu Seamount (Dalrymple and Garcia, 1980). The data are summarized in Table I. The new data confirm that the Emperor Seamounts increase in age to the north, as predicted by the hot spot model. The only age that is inconsistent with this trend is the 39.9 ± 1.2 m.y. age of altered alkali basalt from Kimmei Seamount (Dalrymple and Clague, 1976). Even this age is only 4 m.y. younger than predicted by a linear age-progression model. The age for the southern portion of Suiko Seamount presented by Saito and Ozima (1975, 1977) is based on a single sample of mugearite selected from among numerous ice-rafted erratics. In addition, Dalrymple *et al.* (1980a) demonstrate that Saito and Ozima (1975, 1977) handled their $^{40}Ar/^{39}Ar$ data in a way that mathematically forced the age-spectrum age to agree with the isochron age. For these reasons, we have not used this age in calculating a rate of volcanic migration along the chain. A best-fit line through the remaining data yields an average rate of volcanic migration of about 6.4 cm/yr and predicts an age of 42 m.y. for the Hawaiian–Emperor bend and an age of 80 m.y. for Meiji Seamount. The lack of radiometric age data for seamounts north of Suiko Seamount will probably not be rectified without additional drilling, inasmuch as these volcanoes are blanketed by ice-rafted erratics.

6.4 cm/y

B. Line Islands

The Line Islands chain is a major bathymetric lineament composed of seamounts, atolls, and elongated submarine ridges. It extends 4200 km from the northwest end of the Tuamotu Archipelago to Horizon Guyot at the eastern end of the Mid-Pacific Mountains. The southern half of this lineament is subparallel to the Emperor Seamounts (Morgan, 1972), whereas the northern half has a more northwesterly bearing (Jarrard and Clague, 1977). Late Cretaceous basement ages (Santonian to Campanian) have been assigned at Deep Sea Drilling Project (DSDP) Sites 165, 315, 316 based on paleontological examination of lowermost sediments. Because these sites are separated by almost 1000 km, Schlanger *et al.* (1976) proposed that the central Line Islands were built by synchronous rather than age-progressive volcanism. Recently, Haggerty *et al.* (1982) reported dredged rocks from the southern Line Islands, 100 km northwest of Caroline Island, containing late Cretaceous fossils associated with volcanic debris that they interpret as evidence for a reef-bearing volcanic edifice of minimum age 70–75 m.y. Those authors extend the synchroneity of late Cretaceous volcanism from DSDP Site 165

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to Caroline Island, a distance of 2500 km, to argue against any hot spot origin for the Line Islands or any temporal equivalence with the Emperor Seamounts.

Radiometric ages (K–Ar and $^{40}Ar/^{39}Ar$) indicate, however, that no single mechanism may have produced this volcanic province. Volcanic rocks from the Line Islands, like other Cretaceous submarine volcanic rocks, are moderately to severely altered. Attempts to date these rocks by the conventional K–Ar method have produced scattered, irreproducible results (Davis *et al.*, 1980; Duncan, 1983; Schlanger *et al.*, 1984). In all cases the measured ages are minimum estimates. Both total fusion and incremental heating $^{40}Ar/^{39}Ar$ are more consistent, and we will restrict our discussion to these data (Table II). The majority of these age determinations support an age-progressive volcanic origin. From latitude 18°N (near Horizon Guyot) to 15°S (northwest end of the Tuamotu Archipelago) volcano ages decrease from 93 m.y. to 44 m.y., yielding a migration rate of volcanism of 8.5 ± 1.3 cm/yr. This compares rather favorably with age-progressive volcanism for the Emperor Seamounts. Eocene ages at the north-central Line Islands correspond to the position of the Marquesas–Line Swell (Crough and Jarrard, 1981) which is subparallel to the Hawaiian Ridge and may have been produced by the Marquesas hot spot. The alternative, that the young ages reflect rejuvenated eruptions better explained by "hot line" volcanism, seems less likely in view of the age progression seen in the few dated Eocene seamounts.

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The estimated basement age from fossil evidence at DSDP Site 165 agrees with radiometric ages of seamounts in the vicinity. Basement ages at DSDP Sites 315 and 316, and at the late Cretaceous seamounts of the southern Line Islands (Haggerty *et al.*, 1982) are older than the main hot spot trend by 10–30 m.y. They are about the age of the seafloor on which the Line Islands sit (Cretaceous magnetic quiet zone, 83–118 m.y.) and were probably erupted as seamounts or islands close to the Pacific–Farallon spreading ridge and later incorporated into the age-progressive swath. Similar occurrences are documented at Cretaceous seamounts in the Hawaiian Ridge (Clague and Dalrymple, 1975).

Most of the reliable radiometric age data from the Line Islands now seem to fit with age-progressive hot spot volcanism, as predicted by Morgan (1972). The northern Line Islands predate the Emperor Seamounts and give valuable information about the motion of the Pacific plate during the middle and latter part of the Cretaceous period. If we rotate the southernmost point of the Line Islands (44 m.y. old, also the approximate age of the Hawaiian–Emperor Bend) according to the rotation pole for the Hawaiian Ridge and the other parallel lineaments, we find the position of a hot spot which could have generated the Line Islands and younger portions of the Tuamotu Archipelago. This hot spot is at 23°S, 116°W, on the East Pacific Rise and northwest of Easter Island. Henderson and Gordon (1981) have proposed a more complex volcanic history involving several hot spots which leave overprinted traces in the Line Islands. The present age data do not permit us to distinguish between their model and Morgan's (1972) single hot spot model.

C. Louisville Ridge

Three volcanoes along the Louisville Ridge have been dated, although one yields a minimum age in view of seawater alteration. The others yield $^{40}Ar/^{39}Ar$ total-fusion ages of 53, 46 and 45 m.y. (Table II, Duncan, unpublished data from dredged samples collected by A. B. Watts), which places the Louisville Ridge in the Emperor Seamounts's phase of Pacific plate motion, in agreement with Jarrard and Clague's (1977) geometrical analysis. Osborn Seamount was dated at 30 to 36 m.y. by K–Ar methods (Ozima *et al.*, 1970) and we regard these as minimum age estimates.

No radiometric age data for the Marshall–Gilbert chain have been reported, but the azimuth of the chain suggests it is contemporaneous with the Line Islands and Emperor Seamounts (Morgan, 1972).

D. Musician Seamounts

The Musician Seamounts may be subdivided into four distinct provinces: a north-trending chain of volcanoes to the southwest; a northwest-trending chain of volcanoes to the northwest; a group of roughly westerly-oriented ridges to the southeast; and another group of westerly ridges to the northeast (Pringle, personal communication). Of these groups, only the northwest-trending chain of volcanoes appears to be an age-progressive chain. Clague and Dalrymple (1975) report ages of 87 and 65 m.y. for Rachmaninoff and Khachaturian Seamounts, respectively. Pringle (personal communication, 1983) reports an additional age of 95 m.y. for a previously uncharted volcano at the northwest end of the chain. These three seamounts decrease in age to the south-southeast and apparently formed at the same time as the northern Line Islands.

IV. PACIFIC PLATE MOTION IN THE HOT SPOT REFERENCE FRAME

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movement of the lithosphere over a thermal anomaly (hot spot, plume) that is fixed in the mantle. Previous estimates of inter-hot spot movement have varied (Burke *et al.*, 1973; Molnar and Atwater, 1973; Minster *et al.*, 1974; Molnar and Francheteau, 1975; Minster and Jordan, 1978), but most recent studies (Morgan, 1981; Duncan, 1981) conclude that hot spots move less than 0.5 cm/yr with respect to one another. On this basis, the resulting volcanic lineaments accurately record plate motions. From examination of island and seamount lineaments on the Pacific plate only, Jarrard and Clague (1977) and McDougall and Duncan (1980) found strong support for the Carey–Wilson–Morgan model of fixed hot spots.

If the Pacific hot spots are fixed, or only very slowly moving, the volcanic trails emanating from them should be small circles of rotation about the finite rotation pole which describes the motion of the Pacific plate over the mantle. Also, the rates of migration of volcanism within these lineaments should vary as the sine of the angular distance from that rotation pole. This is analogous to the relation between relative-motion poles and transform-fault azimuths and half-spreading rates (Minster et al., 1974). The same methods of finite-rotation pole location can be applied to defining the Pacific plate over the mantle rotation pole.

Even a casual glance at the orientations of Pacific island and seamount chains would reveal abrupt changes in Pacific plate motion with respect to hot spots. In this review we will restrict our discussion to three phases of Pacific plate motion: 0–42 m.y., 42–100 m.y., and 100–150 m.y. Motion has been west-northwest along the trend of the Hawaiian Ridge in the most recent period. Between 42 m.y. and the middle Cretaceous (about 100 m.y.) motion was more northerly, following the trend of the Emperor Seamounts and Line Islands. From the late Jurassic to the middle Cretaceous the direction of Pacific plate motion was probably defined by west-trending volcanic lineaments such as the Mid-Pacific Mountains and the Magellan Seamounts.

Finer scale changes in plate motion are likely to have occurred. For example, the Marquesas Islands and the Hawaii to Kauai (0–5 m.y.) portion of the Hawaiian Ridge seem to have a slightly more southerly azimuth than the trends of island and seamount chains averaged over the past 42 m.y. (Jarrard and Clague, 1977; Epp, 1978). Other changes, in migration rate particularly, may have occurred in the late Tertiary (Dalrymple *et al.*, 1981). These departures are not large, however, and need to be better documented in more than one lineament before they can be used to add definition to plate motions.

Various finite-rotation poles for Pacific plate motion have been suggested for the period 0–42 m.y., the age of the most recent dramatic change

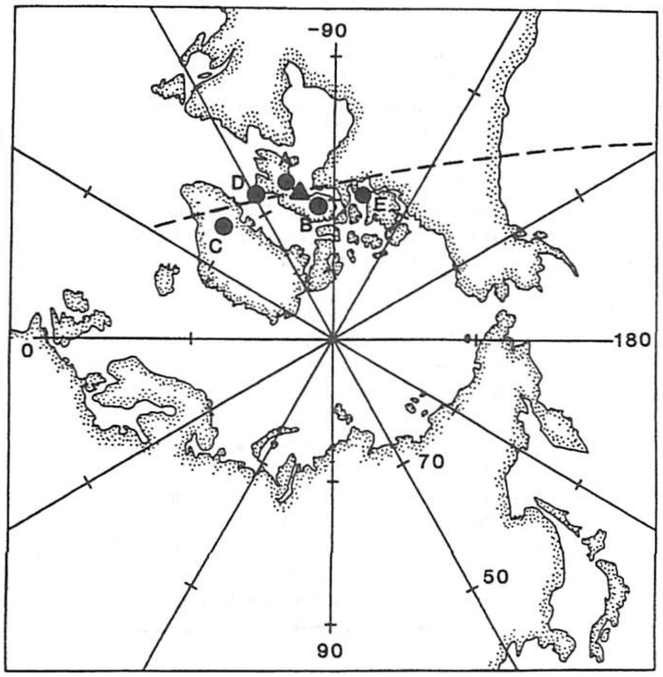

Fig. 3. Rotation poles for Pacific-plate motion from 0 to 42 m.y. Pole positions shown are those of Morgan (1972), A; Clague and Jarrard (1973b), B; Winterer (1973), C; Minster *et al.* (1974), D; and McDougall and Duncan (1982), E; The triangle denotes our preferred pole position at 68°N, 75°W.

in hot spot lineament azimuths (Morgan, 1972; Clague and Jarrard, 1973b; Winterer, 1973; Minster *et al.*, 1974; McDougall and Duncan, 1980). Figure 3 shows that these poles are quite close to one another, forming an elliptical group whose major axis (greatest variation) lies along a great circle passing from the cluster of poles into the central Pacific. This is so because most of the studied Pacific volcanic lineaments are close to the equator of this group of poles, where the sine function, and hence the volcano migration rate, is relatively insensitive to variations in the angular distance.

The rates found in the Gulf of Alaska seamount chains form an especially strong constraint in determining the distance from the pole to the Pacific hot spot lineaments. Therefore, McDougall and Duncan (1980) proposed a pole position closest to the Pacific region based on a 4.3 cm/yr rate of migration of volcanism for Pratt–Welker Seamount ages (Turner *et al.*, 1973). Recent additional age information (Table II) yields a faster rate of 6.7 cm/yr, which moves the best-fitting pole back away from the Pacific and closer to Morgan's (1972) original suggestion.

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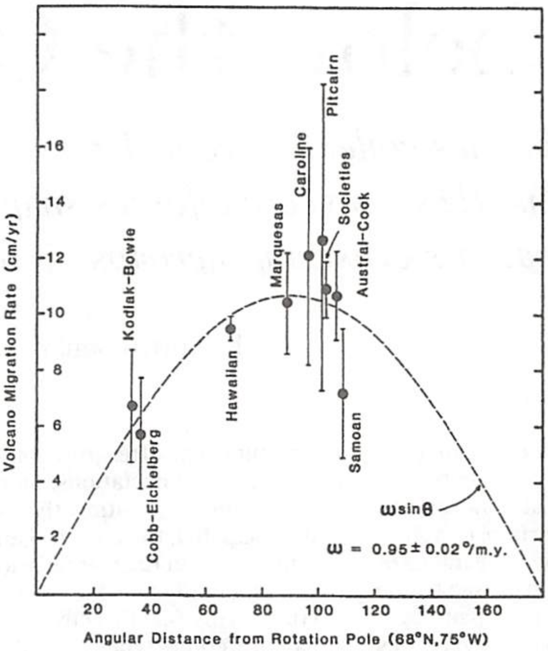

Fig. 4. Volcanic migration rate as a function of angular distance from the rotation pole located at 68°N, 75°W. The dotted curve is a least-squares best-fit with an angular rotation rate of 0.95 ± 0.02°/m.y. Volcano migration rates are from Table III.

In Figure 4 we plot the rate of migration of volcanism in nine hot spot lineaments (Table III) against angular distance from our preferred finite rotation pole at 68°N, 75°W. These data can be fitted to the theoretical relationship $v = \omega \sin \theta$, where v is the linear velocity at an angular distance θ, to estimate the angular velocity of rotation ω. By weighted least-squares linear regression of v on $\sin \theta$ the best-fit estimate of ω is 0.95 ± 0.02°/m.y. The correlation coefficient of the regression is 0.999, indicating a very close fit to the theoretical relationship, which is based on the model of fixed hot spots.

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This calculation uses the more rapid rate of migration of volcanism for the Hawaiian Ridge determined for the past 12 m.y., which is appropriate for the other Pacific volcanic chains (Table III). The average Hawaiian rate of migration from 42 m.y. to the present, 8.6 cm/yr, is not consistent with the faster rates shown in Figure 4. It seems that the plate has moved more rapidly since the end of the Oligocene (the precise timing will depend on further geochronological work on seamounts at the older end of the Hawaiian Ridge). But we suspect that the volcano migration rates for most chains are somewhat overestimated due to sampling bias wherein younger volcanoes have only the youngest surficial flows sampled and dated, while old volcanoes have relatively early lavas sampled and dated. The tendency then is to obtain ages older than the average age of the volcano on older volcanoes and ages younger than the average age of the volcano on young and active volcanoes. This sampling bias causes the calculated volcanic migration rates to be too rapid. In light of these difficulties, this phase of Pacific plate motion is remarkably well constrained.

Unfortunately, the same density of data is not available for earlier phases of Pacific plate motion. Jarrard and Clague (1977) proposed a rotation pole at 17°N, 107°W to form the Emperor Seamounts. We accept this estimate for the period 65–42 m.y. The rotation rate about this pole was 0.61°/m.y., calculated from radiometric ages of the Emperor Seamounts and southern Line Islands. The Musician Seamounts and the northern portion of the Line Islands have a more northwesterly trend, however, and require a different pole of rotation, close to 32°N, 84°W. From age determinations on northern Line Islands volcanoes, we find the rotation rate to have been about 0.63°/m.y. during this period.

At around 100 m.y. the Pacific plate changed direction dramatically, from westerly to northwesterly. No radiometric age information for sea-

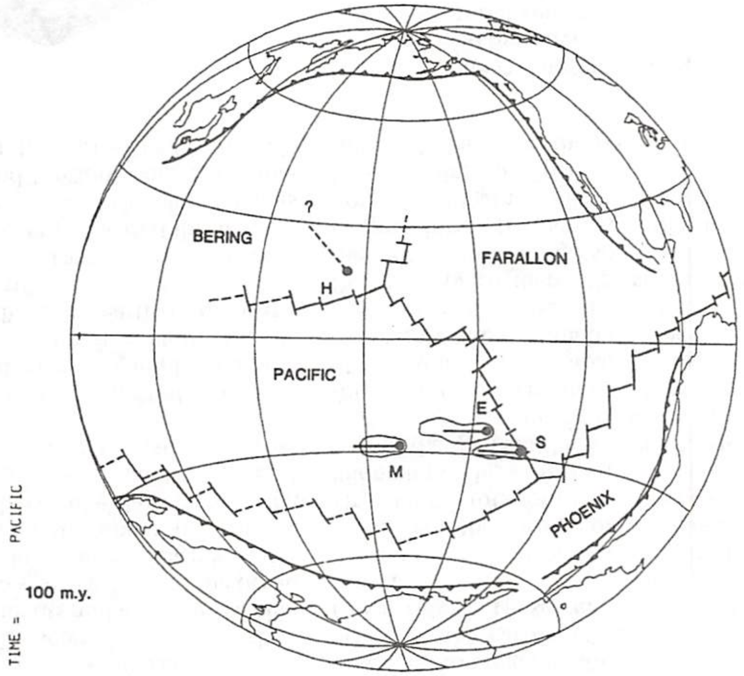

Fig. 5. Configuration of Pacific hot spots and spreading ridges at 100 m.y. Active hot spots include the Hawaiian (H), Macdonald (M), Easter (E), and Sala y Gomez (S).

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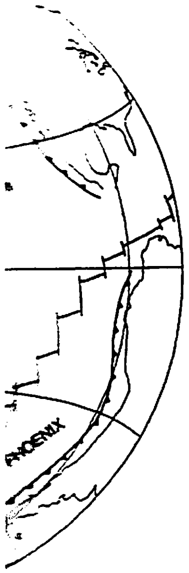

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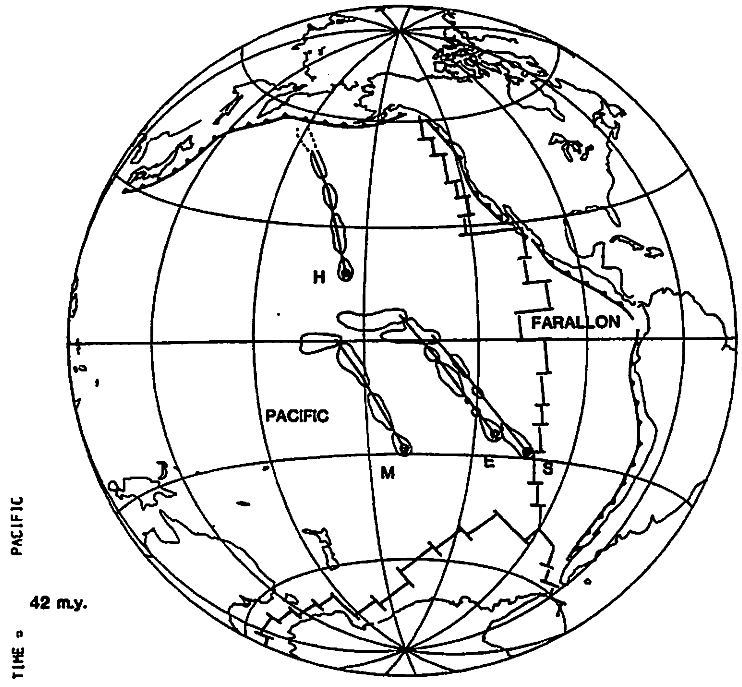

Fig. 6. Configuration of Pacific hot spots and spreading ridges at 42 m.y. Active hot spots include the Hawaiian (H), Macdonald (M), Easter (E), and Sala y Gomez (S).

mounts older than 100 m.y. is available, but minimum age estimates come from paleontologic examination of dredged material. Seamount ages in the Mid-Pacific Mountains seem to get younger from the west (Darwin Guyot) to the east (Horizon Guyot) between about 150 and 100 m.y. ago (Heezen *et al.*, 1973; Watts *et al.*, 1980). We pick a high-latitude pole of rotation for this period, reflecting westerly motion at a slow angular velocity of about

TABLE IV
Rotation Poles for the Pacific Plate over a Hot Spot Reference Frame

Time (m.y.)	Latitude (°N)	Longitude (°W)	Angle (°ccw)
0–42	68.0	75.0	34.0
42–65	17.0	107.0	14.0
65–74	22.0	95.0	7.5
74–100	36.0	76.0	15.0
100–150	85.0	−165.0	24.0

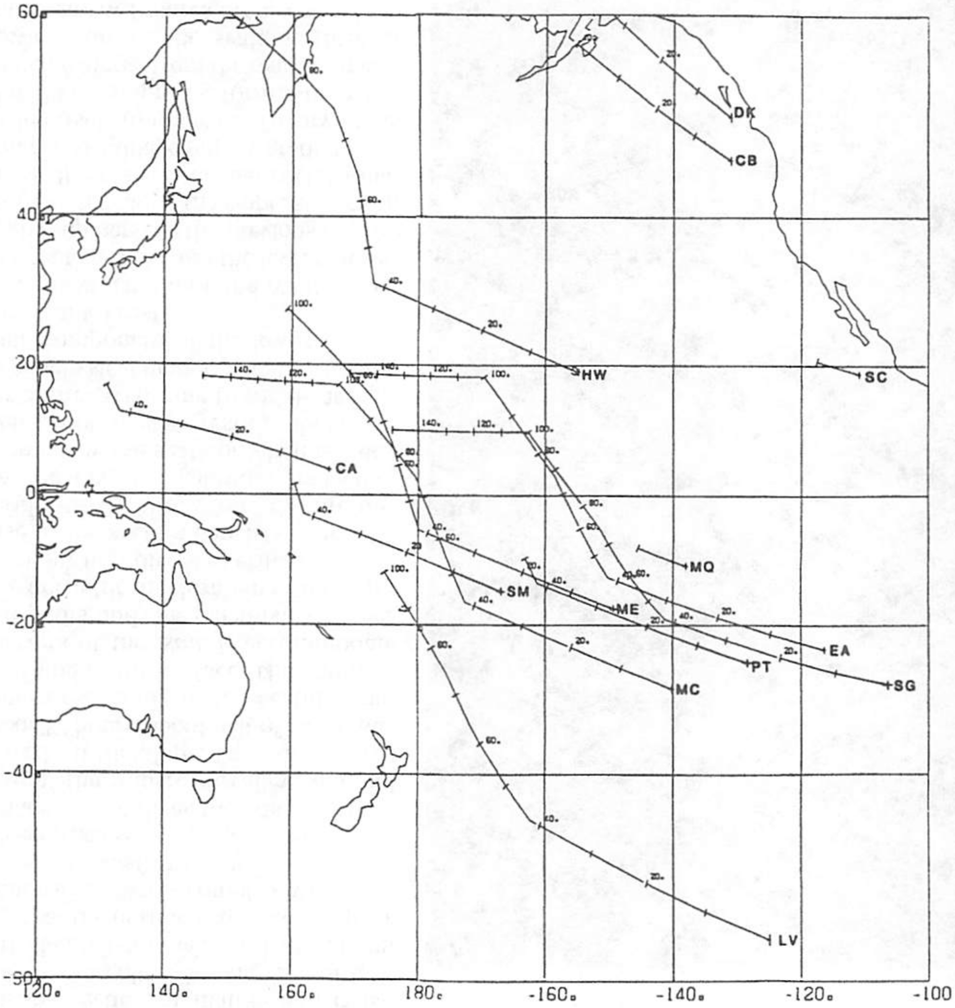

Fig. 7. Pacific plate at present time showing predicted hot spot lineaments and calculated ages in 10-m.y. increments for each volcanic chain assuming fixed hot spots. Hot spots include the Louisville Ridge (LV), Macdonald Seamount in the Austral Islands (MC), Pitcairn Island (PT), Mehetia in the Society Islands (ME), Samoa (SM), the Caroline Islands (CA), the Marquesas Islands (MQ), Easter Island (EA), Sala y Gomez (SG), Hawaii (HW), Socorro Island in the Revillagigedos Islands (SC), Cobb Seamont (CB) and Dellwood Knolls (DK).

0.48°/m.y. (Table IV). Henderson and Gordon (1981) have examined this early phase of Pacific plate motion and suggest that many of the submerged oceanic plateaus (Ontong Java, Manihiki, Hess, Shatsky) were formed at this time by slow plate motion away from hot spots lying beneath spreading ridges.

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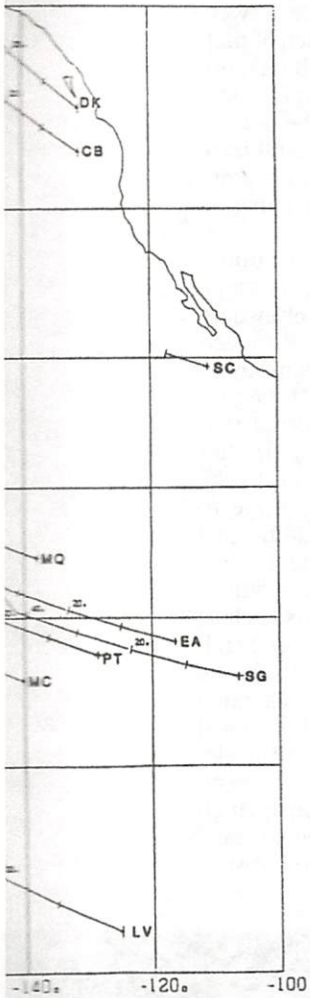

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To summarize, the Pacific plate has undergone two abrupt changes in direction relative to hot spots since Jurassic time: at about 100 m.y. and at 42 m.y. Also, the angular velocity of the plate has steadily increased. Other more subtle changes will be delineated as more age information becomes available. The cause of these dramatic plate motion changes is not clear. Undoubtedly they are related to global plate motion reorganizations, but the causative agent (e.g., new subduction zones, changes in mantle convection patterns, episodes of rapid true polar wander) is unknown. Dalrymple and Clague (1976) argue that the plate reorganization at 42 m.y. that resulted in the change of Pacific plate motion recorded as the Hawaiian–Emperor bend was ultimately caused by the closure of the Tethys seaway and collision of India with Eurasia.

In Figures 5 and 6 we show the position and boundaries of the Pacific plate in the hot spot reference frame at about 100 m.y. and 42 m.y. when changes in plate motion occur. The positions of the Pacific–Farallon, Pacific–Phoenix, and Pacific–Bering spreading ridges are reconstructed using identified magnetic anomalies (interpolated for 100 m.y.) on the Pacific plate (Hilde *et al.*, 1976). Figure 7 illustrates the predicted lineaments and volcano ages that would be left by fixed hot spots with the Pacific plate motions given in Table IV. The correlation with known bathymetric features and measured ages is remarkably good.

V. CONCLUSIONS

Several alternatives to the hot spot model have been proposed to explain age-progressive linear volcanism on the Pacific plate. Propagating fractures (Betz and Hess, 1942; Jackson and Wright, 1970; Green, 1971; McDougall, 1971) might develop in response to tensional stresses resulting from cooling of the plate away from spreading ridges or translatitude changes in the curvature of the earth's surface (Turcotte and Oxburgh, 1973; 1976). As has been pointed out (Jarrard and Clague, 1977; McDougall and Duncan, 1980), however, this hypothesis does not predict the observed congruent set of fractures that accurately reflect lithospheric plate motion over the mantle throughout a large plate like the Pacific. Green (1971) suggested that volcanic lineaments erupted from tensional stress resulting from movement of the plate over stationary bumps in the upper mantle. This model, however, is tantamount to a hot spot model in which the thermal anomaly is replaced by a topological one. Richter's (1973) longitudinal-roll model of upper mantle convection is consistent with observations from Pacific plate island and seamount chains with the advantage that recurrent or simultaneous volcanism along lineaments is allowed. On the other hand, the irregular distribution of parallel volcanic chains does not seem to reflect a regular spacing of upper mantle convection cells.

The Carey–Wilson–Morgan hot spot model for age-progressive linear volcanism seems to explain the geometry and distribution of ages within Pacific island and seamount chains extremely well. This is best documented for the latest phase of Pacific plate motion, 42 m.y. to the present, but older lineaments seem to support the model as well. As more age data become available from late Jurassic, Cretaceous, and early Tertiary seamounts, more precise limits of inter-hot spot motion may be possible. At present, there is no evidence that these thermal anomalies move significantly with respect to one another.

This conclusion is important because the population of hot spots can then be used as a reference frame for precisely reconstructing plate positions through time. If, as Morgan (1972) suggested, hot spots are the tops of narrow, upwelling plumes of deep-mantle material, their stationary nature implies an extremely stable pattern of mantle convection. In addition, volcanic chains of islands and seamounts record the motion of lithospheric plates with respect to the mantle, which constitutes the major portion of the earth (aside from the outer and inner core).

Paleomagnetic and paleoclimatic data record plate motions (latitude only) with respect to the Earth's spin axis. Thus, any difference in plate paleolatitudes between the two reference frames will reveal true polar wander, that is, a motion of the figure of the earth (i.e., mantle) relative to its spin axis. Estimates of the northward late Cretaceous and Cenozoic component of Pacific plate motion from seamount magnetization (Sager, 1983), skewness of seafloor magnetic anomalies (Gordon, 1982; Jarrard and Cande, 1982) and analysis of equatorial sediment facies (van Andel *et al.*, 1975; Hammond *et al.*, 1979; Gordon and Cape, 1981) are significantly less than that determined from the hot spot reference frame during the same period. The difference is on the order of 10° to 15° and is seen also in similar comparisons for other plates (Hargraves and Duncan, 1973; Jurdy, 1981; Morgan, 1981). Whether this inferred true polar wander was rapid or gradual may be determined in the near future with more detailed paleomagnetic polar wander curves.

Much information, then, can be gleaned from Pacific island and seamount chains regarding the direction and velocity of plate motions relative to the Earth's mantle. Many questions remain, and we raise just a few. As noted previously the Pacific plate has changed its direction of motion abruptly at about 100 m.y. and 42 m.y. Is the cause of these sudden changes to be found in plate tectonic processes (i.e., confined to the lithosphere) or in more deep-seated processes? What is the characteristic lifetime of Pacific

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REFERENCES

Bargar K. E., and Jacks
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Batiza, R., 1980, Origin
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Betz, F., Jr., and Hess, H
p. 99–116.
Bonatti, E., and Harrison
402–404.
Bonhommet, N., Beeson
ology and petrology
1286.
Brousse, R. and Bellon, H
Marquises (Ocean Pa
Brousse, R., Phillippet, J
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Bryan, W. B., 1966, Hist
Socorro Island, Mexic
Bryan, W. B., 1967, Geol
v. 78, p. 1461–1476.
Burke, K., Kidd, W. S. F.
hot spots, *Nature*, v.
Carey, S. W., 1958, A tect
(Carey, S. W., ed. Ho
Chevallier, J. P., 1973, Ge
Biology and Geology
York: Academic, p. 1
Clague, D. A., 1982, Petrol
Am. Geophys. Union
Clague, D. A. and Dalrymp
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ACKNOWLEDGMENTS

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REFERENCES

Bargar K. E., and Jackson, E. D., 1974, Calculated volumes of individual shield volcanoes along the Hawaiian–Emperor chain, *J. Res. U. S. Geol. Surv.*, v. 2, p. 545–550.

Batiza, R., 1980, Origin and petrology of young oceanic volcanoes: Are most tholeitic rather than alkalic?, *Geology*, v. 8, p. 477–483.

Betz, F., Jr., and Hess, H. H., 1942, The floor of the north Pacific Ocean, *Geogr. Rev.*, v. 32, p. 99–116.

Bonatti, E., and Harrison, C. G. A., 1976, Hot lines in the earth's mantle, *Nature*, v. 263, p. 402–404.

Bonhommet, N., Beeson, M. H., and Dalrymple, G. B., 1977, A contribution to the geochronology and petrology of the island of Lanai, Hawaii, *Geol. Soc. Am. Bull.*, v. 88, p. 1282–1286.

Brousse, R. and Bellon, H., 1974, Age du volcanisme de lile d'Eiao, au Nord de l'Archipel des Marquises (Ocean Pacifique), *C. R. Acad. Sci. Paris*, v. 278, p. 827–830.

Brousse, R., Phillippet, J.-C., Guille, G., and Bellon, H., 1972, Geochronometrie des iles Gambier (Ocean Pacifique), *C. R. Acad. Sci. Paris*, v. 274, p. 1995.

Bryan, W. B., 1966, History and mechanism of eruption of soda rhyolite and alkali basalt, Socorro Island, Mexico, *Bull. Volcanol.*, v. 29, p. 453–479.

Bryan, W. B., 1967, Geology and petrology of Clarion Island, Mexico, *Geol. Soc. Am. Bull.*, v. 78, p. 1461–1476.

Burke, K., Kidd, W. S. F., and Wilson, J. T., 1973, Relative and latitudinal motion of Atlantic hot spots, *Nature*, v. 245, p. 133–137.

Carey, S. W., 1958, A tectonic approach to continental drift, in: *Continental Drift, a Symposium* (Carey, S. W., ed. Hobart: Univ. of Tasmania, p. 177–355.

Chevallier, J. P., 1973, Geomorphology and geology of coral reefs in French Polynesia, in: Biology and Geology of Coral Reefs, Volume 1. Jones, O. A., and Erdean, R., eds. New York: Academic. p. 113–141.

Clague, D. A., 1982, Petrology of tholeiitic basalt dredged from Hualalai volcano, Hawaii, *Tran. Am. Geophys. Union*, v. 63, p. 1138.

Clague, D. A. and Dalrymple, G. B., 1973, Age of Koko Seamount, Emperor Seamount chain, *Earth Planet. Sci. Lett.*, v. 17, p. 411–415.

Clague, D. A. and Dalrymple, G. B., 1975, Cretaceous K–Ar age of volcanic rocks from the Musician Seamounts and the Hawaiian Ridge, *Geophys. Res. Lett.*, v. 2, p. 305–308.

Clague, D. A., and Jarrard, R. D., 1973a, Tertiary Pacific plate motion deduced from the Hawaiian–Emperor chain, *Geol. Soc. Am. Bull.*, v. 84, p. 1135–1154.

Clague, D. A., and Jarrard, R. D., 1973b, Hot spots and Pacific plate motion (abstract), *Trans. Am. Geophys. Union*, v. 54, p. 238.

Clague, D. A., Dalrymple, G. B., and Moberly, R., 1975, Petrography and K–Ar ages of dredged volcanic rocks from the western Hawaiian–Emperor chain, *Geol. Soc. Am. Bull.*, v. 84, p. 991–998.

Clague, D. A., Dao-Gong, C., Murnane, R., Beeson, M. H., Lanphere, M. A., Dalrymple, G. B., and Holcomb, R. T., 1982, Age and petrology of the Kalaupapa basalt, Molokai, Hawaii, *Pac. Sci.*, v. 36, 411–420.

Crough, S. T., and Jarrard, R. D., 1981, The Marquesas–Line swell, *J. Geophys. Res.*, v. 86, p. 11,763–11,772.

Dalrymple, G. B., and Clague, D. A., 1976, Age of the Hawaiian–Emperor Bend, *Earth Planet. Sci. Lett.*, v.. 31, p. 313–329.

Dalrymple, G. B., and Garcia, M. O., 1980, Age and chemistry of volcanic rocks dredged from Jingu Seamount, Emperor Seamount chain, in: *Initial Reports of the Deep Sea Drilling Project*, Jackson, E. D. and Koizumi, I., eds., v. 55, Washington, D. C.: U. S. Government Printing Office, p. 685–594.

Dalrymple, G. B., Clague, D. A., and Lanphere, M. A., 1977, Revised age for Midway volcano, Hawaii volcano chain, *Earth Planet Sci. Lett.*, v. 37, p. 107–116.

Dalrymple, G. B., Jarrard, R. D., and Clague, D. A., 1975, K–Ar ages of some volcanic rocks from the Cook and Austral Islands, *Geol. Soc. Am. Bull.*, v. 86, p. 1463–1467.

Dalrymple, G. B., Lanphere, M. A., and Clague, D. A., 1980a, Conventional and ^{40}Ar–^{39}Ar ages of volcanic rocks from Ojin (site 430), Nintoku (site 432), and Suiko (site 433) seamounts and the chronology of volcanic propagation along the Hawaiian–Emperor chain, in: *Initial Reports of the Deep Sea Drilling Project*, Jackson, E. D. and Koizumi, I., eds., v. 55, Washington, D. C.: U. S. Government Printing Office, p. 659–676.

Dalrymple, G. B., Lanphere, M. A., and Jackson, E. D., 1974, Contributions to the petrography and geochronology of volcanic rocks from the leeward Hawaiian Islands, *Geol. Soc. Am. Bull.*, v. 85, p. 727–738.

Dalrymple, G. B., Lanphere, M. A., and Natland, J. H., 1980b, K–Ar minimum age for Meiji Guyot, Emperor Seamount chain, in: *Initial Reports of the Deep Sea Drilling Project*, Jackson, E. D. and Koizumi, I., eds., v. 55, Washington, D. C.: U. S. Government Printing Office, p. 677–684.

Davis, G. T., Naughton, J. J., and Philpotts, J. A., 1980, Petrology, geochemistry, and ages of Line Islands basaltic rocks, central Pacific Ocean, *Trans. Am. Geophys. Union*, v. 61, p. 1144.

Delaney, J. R., Johnson, H. D., and J. Karsten, 1981, The Juan de Fuca Ridge hot spot-propagating rift system: New tectonic, geochemical, and magnetic data, *J. Geophys. Res.*, v. 86, p. 11,747–11,750.

Doell, R. R., and Dalrymple, G. B., 1973, Potassium–argon ages and paleomagnetism of the Waianae and Koolau series, Oahu, Hawaii, *Geol. Soc. Am. Bull.*, v. 84, p. 1217–1242.

Duncan, R. A., 1981, Hot spots in the southern oceans—an absolute frame of reference for motion of the Gondwana continents, *Tectonophysics*, v. 74, p. 29–42.

Duncan, R. A., 1983, Overprinted, age-progressive volcanic chains in the Line Islands and Pacific plate Motion since 100 m.y., *Trans. Am. Geophys. Union*, v. 64, p. 345.

Duncan, R. A., 1985, Radiometric ages from volcanic rocks along the New Hebrides–Samoa lineament, in: *Geological Investigations of the Northern Melanesian Borderland, Circum-Pacific Council for Energy and Mineral Resources: Earth Science Series*, Brocher, T. M., ed, *Am. Assoc. Pet. Geol. Mem.* (in press).

Duncan, R. A., and Clague, D. A., 1984, The earliest volcanism on the Hawaiian Ridge, *Trans. Am. Geophys. Union*, v. 65, p. 1076.

Duncan, R. A., and McDougall, I., 1974, Migration of volcanism with time in the Marquesas Islands, French Polynesia, *Earth Planet. Sci. Lett.*, v. 21, p. 414–420.

Duncan, R. A. and McDougall, I., 1976, Linear volcanism in French Polynesia, *J. Volcanol. Geotherm. Res.*, v. 1, p. 197–227.

Duncan, R. A., McDougall, I., Carter, R. M., and Coombs, D. S., 1974, Pitcairn Island—another Pacific hot spot? *Nature*, v. 251, p. 679–682.

Dymond, J., 1975, K–Ar ages of Tahiti and Moorea, Society Islands, and implications for the hot-spot model, *Geology*, v. 3, p. 236–240.

Dymond, J. R., Watkins, N. D., and Nayudu, Y. R., 1968, Age of Cobb Seamount, *J. Geophys. Res.*, v. 73, p. 3977–3939.

Epp, D., 1978, Age and tectonic relationships among volcanic chains on the Pacific plate, Ph.D. Dissertation, Honolulu: Univ. of Hawaii, 235 pp.

Gordon, R. G., 1982, The late Maastrichtian paleomagnetic pole of the Pacific plate, *Geophys. J. R. Astr. Soc.*, v. 70, p. 129–140.

Gordon, R. G., and Cape, C. D., 1981, Cenozoic latitudinal shift of the Hawaiian hot spot and its implications for true polar wander, *Earth Planet. Sci. Lett.*, v. 55, p. 37–47.

Green, D. H., 1971, Composition of basaltic magmas as indicators of origin: application to oceanic volcanism, *Phil. Trans. R. Soc. London, Ser. A.*, v. 267, p. 707–725.

Grooms, D. G., 1980, Contributions to the petrography, geochemistry and geochronology of volcanic rocks along and near the western Hawaiian ridge and Kaula Island, Hawaiian Islands, M. S. Thesis, Honolulu: Univ. of Hawaii, 97 pp.

Haggerty, J. A., Schlanger, S. O., and Premioli-Silva, I., 1982, Late Cretaceous and Eocene volcanism in the southern Line Islands and implications for hot spot theory, *Geology*, v. 10, p. 433–437.

Halunen, A. J., Jr., 1979, Tectonic of the Fiji Plateau, Ph.D. Dissertation, Honolulu: University of Hawaii.

Hammond, S. R., Epp., D., and Theyer, F., 1979, Neogene relative motion between the Pacific plate, the mantle, and the earth's spin axis, *Nature*, v. 278, p. 309–312.

Hargraves, R. B. and Duncan, R. A., 1973, Does the mantle roll? *Nature*, v. 245, p. 361–363.

Hawkins, J. W., 1976, Petrology and geochemistry of basaltic rocks of the Lau Basin, *Earth Planet. Sci. Lett.*, v. 28, p. 283–297.

Heezen, B. C., MacGregor, I. D., *et al.*, 1973, *Initial Reports of the Deep Sea Drilling Project*, v. 20, Washington, D. C.: U. S. Government Printing Office.

Henderson, L. J. and Gordon, R. G., 1981, Oceanic plateaus and the motion of the Pacific plate with respect to the hot spots, *Trans. Am. Geophys. Union*, v. 62, p. 1028.

Herzer, R. H., 1971, Bowie Seamount, a recently active flat-topped seamount in the northeast Pacific Ocean, *Can. J. Earth Sci.*, v. 8, p. 676–687.

Hilde, T. W. C., Uyeda, S., and Kroenke, L., 1976, Tectonic history of the western Pacific, in: *Geodynamics: Progress and Prospects*, Drake, C. L., ed. Washington, D. C.: American Geophysical Union, p. 1–15.

Jackson, E. D., 1976, Linear volcanic chains on the Pacific plate, in: *The Geophysics of the Pacific Ocean Basin and its Margin*, Sutton, G. H., Manghani, M. H., and Moberly, R., eds. *Geophys. Mon.* 19, Washington, D. C.: American Geophysical Union, p. 319–335.

Jackson, E. D., and Wright, T. L., 1970, Xenoliths in the Honolulu volcanic series, Hawaii, *J. Petrol.*, v. 11, p. 405–430.

Jackson, E. D., Koizumi, I., Dalrymple, G. B., Clague, D. A., Kirkpatrick, R. J., and Greene, H. G., 1980, Introduction and summary of results from DSDP Leg 55, the Hawaiian–Emperor hot spot experiment, in: *Initial Reports of the Deep Sea Drilling Project*, Jackson, E. D., Koizumi, I., *et al.* eds., Washington: U. S. Government Printing Office, p. 5–31.

Jarrard, R. D., and Cande, S.C., 1982, A Pacific polar wandering curve based on the skewness of marine magnetic anomalies, *Trans. Am. Geophys. Union*, v. 63, p. 916.

Jarrard, R. D. and Clague, D. A., 1977, Implications of Pacific Island and seamount ages for the origin of volcanic chains, *Rev. Geophys. Space Phys.*, v. 15, p. 57–76.

Johnson, R. H., and Malahoff, A., 1971, Relation of Macdonald volcano to migration of volcanism along the Austral chain, *J. Geophys. Res.*, v. 76, p. 3282–3290.

Jurdy, D. M. 1981, True polar wander, *Tectonophysics*, v. 74, p. 1–16.

Keating, B. H., Mattey, D. P., Naughton, J., and Helsley, C. E., 1983b, Age and origin of Truck Atoll, eastern Caroline Islands; geochemical, radiometric age, and paleomagnetic evidence, *Geol. Soc. Am. Bull.*, v. 95, p. 350–356.

Keating, B. H., Mattey, D., Naughton, J., Epp, D., and Helsley, C. E., 1981, Evidence for a new Pacific hot spot, *Trans. Am. Geophys. Union*, v. 62, p.381.

Klitgord, K. D., and Mammerickx, J., 1982, Northern East Pacific Rise: Magnetic anomaly and bathymetric framework, *J. Geophys. Res.*, v. 87, p. 6725–6750.

Krummenacher, D. and Noetzlin, J., 1966, Ages isotopiques K–Ar de roches prélevées dans les possessions francaises du Pacifique. *Bull. Soc. Geol. France.*, v. 8, p. 173–175.

Larson, R. L., Moberly, R., *et al.*, 1975, *Initial Reports of the Deep Sea Drilling Project*, v. 32, Washington, D. C.: U. S. Government Printing Office.

Mattey, D. P., 1981, Secular geochemical variations in lavas from Truk, Ponope and Kusaie, eastern Caroline Islands, *Trans. Am. Geophys. Union*, v. 62, p. 1068

Mattey, D. P., 1982, Minor and trace element geochemistry of volcanic rocks from Truk, Ponape, and Kusaie, eastern Caroline Islands: evolution of a young hot spot trace across old oceanic crust, *Contr. Min. Petrol.* (in press).

McDougall, I., 1964, Potassium–argon ages from lavas of the Hawaiian Islands, *Geol. Soc. Am. Bull.*, v. 75, p. 107–128.

McDougall, I., 1971, Volcanic island chains and sea-floor spreading, *Nature*, v. 230, p. 141–144.

McDougall, I., 1979, Age of shield-building volcanism of Kauai and linear migration of volcanism in the Hawaiian Island Chain, *Earth Planet. Sci. Lett.*, v. 46, p. 31–42.

McDougall, I., and Aziz-ur-Rahman, 1972, Age of the Gauss–Matuyama boundary and of the Kaena and Mammoth events. *Earth Planet Sci. Lett.*, v. 14, p. 367–380.

McDougall, I., and Duncan, R. A., 1980, Linear island chains—recording plate motions? *Tectonophysics*, v. 63, p. 275–295.

McDougall, I. and Swanson, D. A., 1972, Potassium–argon ages of lavas from the Hawi and Pololu volcanic series, Kohala volcano, Hawaii, *Geol. Soc. Am. Bull.*, v. 83, p. 3731–3738.

Minster, J. B., and Jordan, T. H., 1978, Present-day plate motions, *J. Geophys. Res.*, v. 83, p. 5331–5354.

Minster, J. B., Jordan, T. H., Molnar, P., and Haines, E., 1974, Numerical modeling of instantaneous plate motions, *Geophys. J. R. Astron. Soc.*, v. 36, p. 541–576.

Molnar, P., and Atwater, T., 1973, Relative motions of hot spots in the mantle, *Nature*, v. 246, p. 288–291.

Molnar, P., and Francheteau, J., 1975, The relative motion of hot spots in the Atlantic and Indian oceans during theh Cenozoic, *Geophys. J. R. Astr. Soc.*, v. 43, p. 763–774.

Moore, J. G., Clague, D. A., and Normark, W. R., 1982, Diverse basalt types from Loihi Seamount, Hawaii, *Geology*, v. 10, p. 88–92.

Morgan, W. J., 1971, Convection plumes in the lower mantle, *Nature*, v. 230, p. 42–43.

Morgan, W. J., 1972, Deep mantle convection: plumes and plate motions, *Am. Assoc. Petrol. Geol. Bull.*, v. 56, p. 203–213.

Morgan, W. J., 1981, Hot spot tracks and the opening of the Atlantic and Indian oceans, in: *The Sea, Emiliani, C., ed. v. 7-Wiley-Interscience, New York: p. 443–475.*

Natland, J. H., 1980, The progression of volcanism in the Samoa linear volcanic chain, Am. J. Sci., v. 280-A, p. 709–735.

Naughton, J. J., Macdonald, G. A., and Greenberg, V. A., 1980, Some additional potassium–argon ages of Hawaiian rocks: the Maui volcanic complex of Molokai, Maui, Lanai, and Kahoolawe, *J. Volcanol. Geotherm. Res.*, v. 7, p. 339–355.

Ozima, M., Kaneoka, I., and Aramaki, S., 1970, K–Ar ages of submarine basalts dredged from seamounts in the western Pacific area and discussion of oceanic crust, *Earth Planet. Sci. Lett.*, v. 8, p. 237–249.

Porter, S. C., Stuiver, M., and Yang, I. C., 1977, Chronology of Hawaiian glaciations, *Science*, v. 195, p. 61–63.

1983b. Age and origin of
age, and paleomagnetic
E., 1981. Evidence for a
Rise: Magnetic anomaly
-6750.
roches prélevées dans
v. 8, p. 173–175.
Sea Drilling Project, v.
Truk, Ponope and Kusaie,
p. 1068
rocks from Truk, Pon-
hot spot trace across old
Islands, *Geol. Soc. Am.*
Nature, v. 230, p. 141–
linear migration of volcanism
p. 31–42.
yama boundary and of the
p. 367–380.
cording plate motions? *Tec-*
of lavas from the Hawi and
Bull., v. 83, p. 3731–3738.
J. Geophys. Res., v. 83,
Numerical modeling of in-
p. 541–576.
the mantle, *Nature*, v. 246,
spots in the Atlantic and
v. 43, p. 763–774.
basalt types from Loihi
v. 230, p. 42–43.
motions, *Am. Assoc. Petrol.*
lantic and Indian oceans, in:
p. 443–475.
linear volcanic chain, *Am.*
Some additional potassium–
of Molokai, Maui, Lanai, and
submarine basalts dredged from
anic crust, *Earth Planet. Sci.*
Hawaiian glaciations, *Science*,

Richter, F. M., 1973, Convection and the large-scale circulation of the mantle, *J. Geophys. Res.*, v. 78, p. 8735–8745.

Sager, W. W., 1983, A late Eocene paleomagnetic pole for the Pacific plate, *Earth Planet. Sci. Lett.*, v. 63, p. 408–422.

Saito, K., and Ozima, M., 1975, ^{40}Ar–^{39}Ar isochron age of a mugearite dredged from Suiko Seamount in the Emperor chain, *Rock Magn. and Paleogeophysics*, v. 3, p. 81–84.

Saito, K., and Ozima, M., 1976, ^{40}Ar–^{39}Ar ages of submarine rocks from the line Islands: implications on the origin of the Line Islands, *Am. Geophys. Union, Geophys. Mon.*, v. 19, p. 369–374.

Saito, K. and Ozima, M., 1977, ^{40}Ar–^{39}Ar geochronological studies on submarine rocks from the western Pacific area, *Earth Planet. Sci. Lett.*, v. 33, p. 353–369.

Schlanger, S. O., Jackson, E. D., *et al.*, 1976, *Initial Reports of the Deep Sea Drilling Project*, v. 33, Washington, D. C.: U. S. Government Printing Office.

Schlanger, S. O., Garcia, M. O., Keating, B. H., Naughton, J. J., Duncan, R. A., Haggerty, J., and Philpotts, J., 1984, Geology and geochronology of the Line Islands, *J. Geophys. Res.* (in press).

Silver, E. A., von Huene, R., and Crouch, J. K., 1974, Tectonic significance of the Kodiak–Bowie Seamount chain, northeastern Pacific, *Geology*, v. 2, p. 147–150.

Steiger, R. H. and Jager, E., 1977, Subcommission on geochronology: convention on the use of decay constants in geo- and cosmo-chronology, *Earth Planet. Sci. Lett.*, v. 36, p. 359–362.

Talandier, J. and Kuster, G. T., 1976, Seismicity and submarine volcanism in French Polynesia, *J. Geophys. Res.*, v. 81, p. 939–948.

Turcotte, D. L. and Oxburgh, E. R., 1973, Mid-plate tectonics, *Nature*, v. 244, p. 337–339.

Turcotte, D. L. and Oxburgh, E. R., 1976, Stress accumulation in the lithosphere, *Tectonophysics*, v. 35, p. 183–199.

Turner, D. L., and Jarrard, R. D., 1982, K–Ar dating of the Cook–Austral Island chain: a test of the hot spot hypothesis, *J. Volcanol. Geotherm. Res.*, v. 12, p. 187–220.

Turner, D. L., Forbes, R. B., and Naeser, C. W., 1973, Radiometric ages of Kodiak Seamount and Giacomini Guyot, Gulf of Alaska: implications for circum-Pacific tectonics, *Science*, v. 182, p. 579–581.

Turner, D. L., Jarrard, R. D., and Forbes, R. B., 1980, Geochronology and origin of the Pratt–Welker Seamount chain, Gulf of Alaska: a new pole of rotation for the Pacific plate, *J. Geophys. Res.*, v. 85, p. 6547–6556.

Van Andel, Tj. H., Heath, G. R., and Moore, T. C., 1975, Cenozoic history and paleoceanography of the central equatorial Pacific Ocean, *Geol. Soc. Am. Mem.*, v. 143, p. 1–134.

Watts, A. B., Bodine, J. H. and Ribe, N. M., 1980, Observations of flexure and the geological evolution of the Pacific Ocean basin, *Nature*, v. 283, p. 532–537.

Wilson, J. T., 1963, A possible origin of the Hawaiian Islands, *Can J. Phys.*, v. 41, p. 863–870.

Winterer, E. L., 1973, Sedimentary facies and plate tectonics of equatorial Pacific, *Am. Ass. Pet. Geol. Bull.*, v. 57, p. 265–282.

Winterer, E. L., Ewing, J. I., *et al.*, 1973, *Initial Reports of the Deep Sea Drilling Project*, v. 17, Washington, D. C.: U. S. Government Printing Office.

Worsley, J. R., 1973, Calcareous nannofossils: leg 19 of the Deep Sea Drilling Project, in Initial Reports of the Deep Sea Drilling Project, Creager J. S., and Scholl, D. W., *et al.*, eds., v. 19, Washington, D. C.: U. S. Government Printing Office, p. 741–750.