JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 89, NO. B13, PAGES 11,261–11,272, DECEMBER 10, 1984

Geology and Geochronology of the Line Islands

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Geological and geophysical studies along the entire length of the Line Islands were undertaken in order to test the hot spot model for the origin of this major linear island chain. Volcanic rocks were recovered in 21 dredge hauls and fossiliferous sedimentary rocks were recovered in 19 dredge hauls. Volcanic rocks from the Line Islands are alkalic basalts and hawaiites. In addition, a tholeiitic basalt and a phonolite have been recovered from the central part of the Line chain. Microprobe analyses of groundmass augite in the alkalic basalts indicate that they contain high TiO_2 (1.0–4.0 wt %) and Al_2O_3 (3.4–9.1 wt %) and are of alkaline to peralkaline affinities. Major element compositions of the Line Islands volcanic rocks are very comparable to Hawaiian volcanic rocks. Trace element and rare earth element analyses also indicate that the rocks are typical of oceanic island alkalic lavas; the Line Islands lavas are very much unlike typical mid-ocean ridge or fracture zone basalts. Dating of these rocks by ^{40}Ar-^{39}Ar, K-Ar, and paleontological methods, combined with Deep Sea Drilling Project data from sites 165, 315, and 316 and previously dated dredged rocks, provide ages of volcanic events at 20 localities along the chain from 18°N to 9°S, a distance of almost 4000 km. All of these dates define mid-Cretaceous to late Eocene edifice or ridge-building volcanic events. Eocene volcanic events took place from 15°N to 9°S, and Late Cretaceous events took place from 18°N to 9°S. In the southern Line Islands both Cretaceous and Eocene events took place on the same edifice or ridge, indicating recurrent volcanism at a single locality. The irregular distribution of atolls in the chain, the fact that Late Cretaceous reefs flourished along a distance of approximately 2500 km in the central and southern Line Islands, and the observation that spatially closely related seamounts exhibit different subsidence histories are interpreted as indicating that large segments of the chain have not followed a $t^{1/2}$ related subsidence path. Magnetic surveys of 11 seamounts show that four of the seamounts, from the central Line chain, give virtual geomagnetic poles which fall well to the north of virtual geomagnetic poles of Cretaceous seamounts. These four poles agree with other paleomagnetic data of middle-late Eocene–early Oligocene age from the Pacific. One of these four seamounts yielded a ^{40}Ar-^{39}Ar total fusion age of 39 Ma. Because the poles of all four seamounts fall into a tight group we infer that they are probably of middle-late Eocene age to early Oligocene age. The other three seamounts as well as one seamont from the Line Islands analyzed previously all give virtual geomagnetic poles which agree with Late Cretaceous paleomagnetic data from the Pacific. Of these four seamounts, three give Late Cretaceous ^{40}Ar-^{39}Ar ages ranging from 71 to 85 Ma; another, in the southern Line Islands, is interpreted, on paleontological evidence, to be of Late Cretaceous age. The origin of the Line Islands has been ascribed by previous workers to the effects of a single hot spot and to the action of four hot spots. The single hot spot model cannot account for all of the volcanic edifices in the Line Islands, although it does explain a general age progression of 9.6 ± 0.4 cm/yr from north to south along the chain derived from a number of dated edifices. The four hot spot model accounts for more of the dated volcanic edifices but still does not explain all of the available data. The petrologic data argue against a mid-ocean ridge or transform fault origin proposed by earlier workers. The complex volcanic province represented by the Line Islands remains a challenge to existing models for the origin of midplate volcanism in the Pacific. An atoll drilling program which could determine edifice building histories, paleolatitudes of seamount formation, and subsidence rates and patterns in the Line Islands is needed.

INTRODUCTION AND BACKGROUND

The Line Islands geological province, capped by the atolls of Johnston, Palmyra, Washington, Fanning, Christmas, and Caroline islands, is made up of dozens of simple and composite seamounts and linear ridges that extend from Horizon Guyot and Johnston Island in the north to the northeast end of the Tuamotu Islands in the south (Figure 1). The Line Islands are a major bathymetric feature of the central Pacific comparable in size to the Hawaiian-Emperor chain to the north and the Marshall-Gilbert-Ellice chain to the west. *Morgan* [1972], arguing from the fact that the Line-Tuamotu geometric trends appear to parallel the Emperor-Hawaiian trends, postulated that the Line and Tuamotu chains were the temporal and genetic equivalents of the Emperor and Hawaiian chains, all four of these major features having developed through the actions of two hot spots fixed relative to each other for the past 70 Ma. *Jarrard and Clague* [1977] pointed out that geometric and paleomagnetic evidence argued against the proposition that the Line and Emperor chains were entirely coeval.

At the time the above arguments were put forward, reliable dates for volcanic activity over any significant portions of the

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Paper number 4B0781.
0148-0227/84/004B-0781$05.00

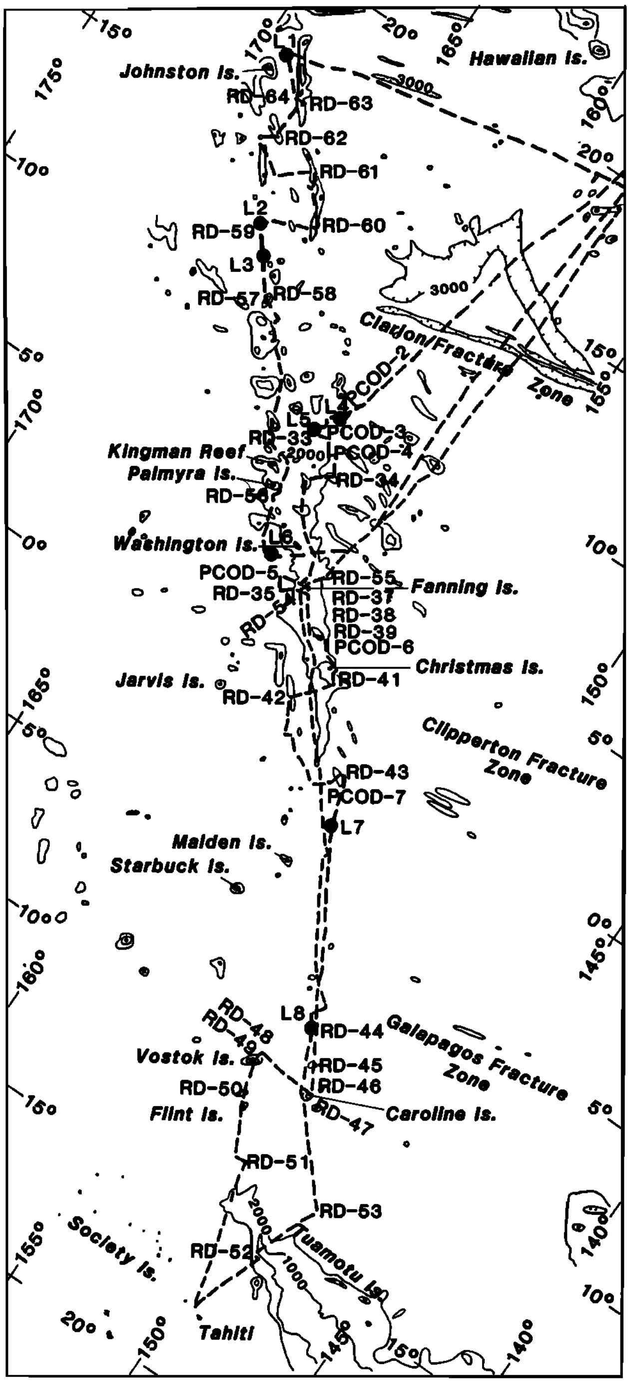

Fig. 1. Chart of the Line Islands showing the track of R/V *Kana Keoki* (dashed line) through the area. Dredge stations are indicated by RD numbers; piston core stations by PCOD numbers; seamount magnetization surveys by L numbers.

Line Islands were not available. Driling along the Line Islands on Deep Sea Drilling Project (DSDP) legs 17 and 33 (see *Winterer et al.* [1973] and *Schlanger et al.* [1976] for details) showed that volcanic episodes in the northern Line Islands at site 171 on Horizon Guyot and at sites 165, 315, and 316 in the central Line Islands were more temporally complex than could be accounted for by using the Emperor chain as a model for the development of the Line Islands. *Winterer* [1976] in an extensive review of the data relevant to the formation of the Line Islands emphasized the importance of the Line cross trend (Figure 2) and argued that repeated episodes of midplate volcanism along such cross trends were influenced by older Line Islands structures. He implied that several chains of volcanos on cross trends were formed by individual hot spots that crossed the main Line chain. Both DSDP drilling in the central Line Islands and the dating of rocks dredged from seamounts in the cross trend showed that both Late Cretaceous and Eocene volcanism had occurred there [*Lanphere and Dalrymple*, 1976; *Saito and Ozima*, 1977]. Further, paleontological studies of rocks dredged from seamounts in the southern Line Islands [*Haggerty et al.*, 1982] showed that both Late Cretaceous and Eocene volcanism had taken place in the vicinity of Caroline Island (Figure 1, RD-44 and RD-45). The wide geographic distribution of both Cretaceous and Eocene volcanism over a distance of several thousands of kilometers along the Line chain is regarded by us as establishing the fact that the Line Islands were not formed by the action of a single hot spot. That the southern Line Islands as well as the central Line Islands were formed by a complex overprinting of volcanic events was suggested by *Crough and Jarrard* [1981]. They showed that a depth and geoid anomaly extends from the Marquesas Islands into the southern Line Islands and ascribed this anomaly to the trace of a hot spot which transited the Line Islands in Eocene time. Vivid evidence that the Line chain has a complex history of volcanism as compared to that of the Emperor chain is contained in W. Haxby's geotectonic imagery map of the Pacific Basin [see *Francheteau*, 1983], a sketch map of which is shown here as Figure 2. In addition to the marked Line cross trend that cuts across the central Line Islands at 10°N a number of other linear ridges intersect the northern and central Line Islands; the southernmost of these extends toward the Marquesas Islands and lies along the depth and geoid anomaly of *Crough and Jarrard* [1981]. The en echelon appearance of much of the central Line Islands could be due to the presence of these short NW-SE trending features which intersect the main Line Islands trend. Bathymetrically then, the Line chain bears little resemblance to the relatively simple Emperor chain.

Henderson and Gordon [1982] and *Duncan* [1983] have addressed the complexity of the Line Islands and argue, based on plate motion reconstructions over the past 150 Ma, that several hot spots are needed to model the evolution of the Line Islands. If all linear volcanic features or chains of vol-

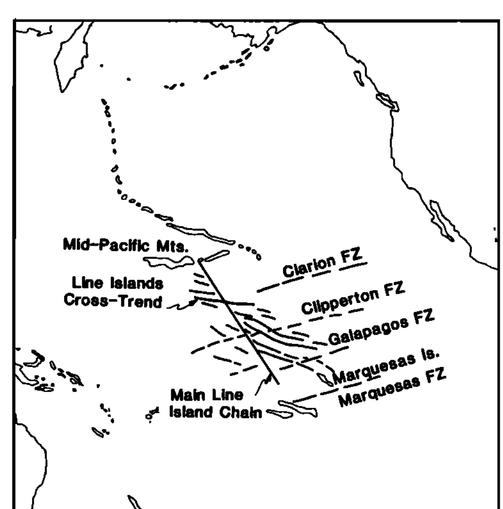

Fig. 2. Sketch map of major features in the Line Islands province (unlabeled linear trends are after the geotectonic imagery map of W. Haxby from *Francheteau* [1983]).

canic edifices originate solely by hot spot activity of the Hawaiian-Emperor style, then a number of hot spots must have contributed to the formation of the Line Islands. Other mechanisms for the linear localization of volcanic activity have been put forward. *Farrar and Dixon* [1981] postulated the presence of a long transform fracture zone that extended from the Emperor Trough through the Gardner Seamounts and the Line Islands. *Orwig and Kroenke* [1980] also proposed a fracture zone origin for the Line Islands. *Natland* [1976] considered that the petrology of rocks from the central Line Islands indicated their similarity to rift associated volcanism of the African type. *Winterer* [1976] also invoked fissures and fractures in the Line Islands to account for some of the volcanic activity there.

It is the purpose of this paper to present the geological, geochemical, and paleomagnetic data that will outline the constraints on any models proposed for the evolution of the Line Islands.

Cruise Operations

The geologic and geophysical studies of the Line Islands discussed here were undertaken during three cruises (of R/V *Kana Keoki*) to the area in the fall of 1979 (Figure 1). The objectives of these cruises were to dredge edifice volcanic rocks and capping limestone, take piston cores in submarine valleys incised into the sedimentary apron of the central Line Islands province, conduct seamount magnetization studies, and to collect magnetic, gravity, and bathymetric data relevant to the problem of the evolution of the Line Islands. Our bathymetric mapping showed that some existing bathymetry was incorrect and misleading. Among our discoveries were an unmapped seamount at 11°40′N, 160°40′W, a ridge which rises to 2700 m in depth connecting a seamount at 6°20′N, 158°W with a ridge at 6°20′N, 159°30′W; and a ridge nearly 300 km long consisting of eight peaks ranging from 3000 to 2150 m depth connecting Caroline Island at 10°S, 150°20′W with a seamount at 7°35′S, 151°35′W. In addition, Carol Guyot (9°N, 158°W) and Vostok Island (10°S, 152°3′W) were found to be incorrectly contoured.

A total of 21 dredges recovered volcanic rocks. Sedimentary rock samples were recovered in 19 dredges. In addition, sediments (and in one case basalt pebbles) were recovered from six piston cores. Underway gravity and magnetics were recorded over the entire length of the Line chain and over the margin of the Tuamotu Ridge. Eleven seamount magnetization surveys were conducted.

Petrology

Previous petrologic work on volcanic rocks from the Line Islands is almost entirely reported on in the DSDP initial reports of legs 17 and 33 [*Winterer et al.*, 1973; *Schlanger et al.*, 1976]. At DSDP site 315, six flow units of transitional basalt (intermediate in composition between Hawaiian tholeiitic and alkalic lavas) were recovered [*Jackson et al.*, 1976]. Hawaiites, some containing brown amphibole, were recovered at DSDP site 165 [*Bass et al.*, 1973]. A wide variety of rocks dredged from the northern and central portions of the Line Islands include tholeiites, alkalic basalts, hawaiites, phonolites, and potassic nephelinites. *Natland* [1976] considered the potassic nephelinites dredged at four locations in the Line Islands area as similar in composition and origin to potassic mafic lavas from African rift zones. He argued that the presence of such rocks in the Line cross trend indicated that the cross trend is the relic of a central Pacific rift system that underwent limited crustal extension.

Strontium isotopic ratios have been determined on some of these rocks using both untreated and HCl-leached material. Unfortunately, most of these samples are at least somewhat altered, and the values reported have very large uncertainties (e.g., 0.7030 ± 0.0009). Therefore it is difficult to interpret the values with any confidence. Nevertheless, the reported initial ^{87}Sr-^{86}Sr ratios for basalts vary from 0.7028 to 0.7039 (all but one between 0.7035 and 0.7039), virtually overlapping the reported range for Hawaiian volcanic rocks (0.7029–0.7041 [*Lanphere et al.*, 1980]) and generally higher than typical mid-ocean ridge basalts (MORB) ratios (0.7026–0.7035 [*Schilling et al.*, 1983]).

Previous petrologic studies have all been on samples recovered from the northern half of the Line chain; no samples had been recovered from the chain south of DSDP site 315 near Fanning Island at about 4°N. During the R/V *Kana Keoki* 1979 cruises, samples were dredged from along the entire length of the chain (Figure 1).

The rocks recovered from dredge stations and those previously reported from the Line Islands [*Bass et al.*, 1973; *Jackson et al.*, 1976; *Natland*, 1976] are almost entirely moderately to severely altered alkalic basalts and hawaiites. In addition, tholeiitic basalts and a phonolite have been recovered from the central part of the chain [*Natland*, 1976]. The alkalic basalts contain phenocrysts of plagioclase, olivine (replaced by iddingsite), and, rarely, augite. The hawaiites are generally aphyric, although some contain rare phenocrysts of plagioclase and/or brown hornblende. The matrix of both rock types consist predominantly of plagioclase, titaniferous augite, titaniferous magnetite, and, locally, clays replacing glass and olivine. Mineralogically, these rocks are typical of Hawaiian lavas.

Microprobe analyses of groundmass augite in the Line Islands lavas indicate that they contain high TiO_2 (1.0–4.0 wt %) and Al_2O_3 (2.0–9.1 wt %) [*Jackson et al.*, 1976]. A plot of SiO_2 versus Al_2O_3 shows the Line Islands lavas to be of alkaline to peralkaline affinities based upon the classification of *LeBas* [1962] (Figure 3), although two samples, RD-33-4 and RD-43-1 from the central Line Islands are of the nonalkaline type.

The freshest samples from each dredge haul were chemically analyzed (Table 1). All of the samples are moderately altered. Some samples have high Fe_2O_3/FeO ratios and P_2O_5 and H_2O contents. Nevertheless, the least altered samples are similar chemically to Hawaiian alkalic lavas. They plot in the Hawaiian alkalic lava field and span the range from alkalic olivine basalt to mugearite using the classification of *Coombs and Wilkinson* [1969].

Rare earth elements (REE) were determined by isotope dilution mass spectrometry on selected samples. One of the samples (RD-60-6) has the REE pattern of a typical Hawaiian tholeiite (Figure 4). The other samples shown have REE concentrations similar to those of Hawaiian alkalic lavas.

Jackson et al. [1976], in addressing the suggestion that the Line Islands are an abandoned ridge crest, argue that the chemistry of the basalts drilled at DSDP sites 165 and 315 are inconsistent with a ridge crest origin. In their review of analyses in hand following leg 33 [*Jackson et al.*, 1976] they came to the conclusion that the Line Islands are made up of basaltic rocks that are similar to basalts of the Hawaiian chain. Analyses reported here support the argument that the main Line Islands chain was built of effusions of typical alkalic and tho-

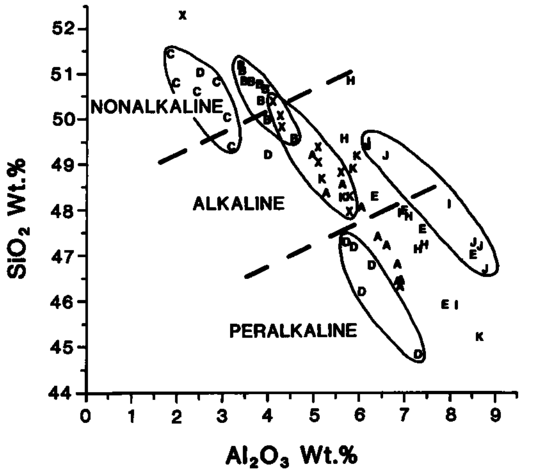

Fig. 3. SiO_2 and Al_2O_3 wt % in groundmass clinopyroxene grains from lavas from the Line chain. Fields for nonalkaline, alkaline, and peralkaline rocks are from *LeBas* [1962]. A, RD-41-1; B, RD-41-2; C, RD-44-2; D, RD-54-2; E, RD-59-1, H, RD-59-9; I, RD-59-10; J, RD-59-15; K, RD-63-7; X, RD-52-7.

leiitic Hawaiian type lavas and that there is no compelling evidence that a ridge crest origin is warranted for the Line Islands.

GEOCHRONOLOGY

The basic data set constraining discussions of the origin of linear island chains consists of determinations of the ages of volcanic edifice formation along the chain. The data used in this paper consist of dates derived from interpretation of volcanic and sedimentary sequences drilled on DSDP legs 17 and 33, edifice ages determined by dating of fossil assemblages dredged from seamounts, and radiometric ages determined by ^{40}Ar-^{39}Ar and K-Ar methods on dredged rocks collected by the Hawaii Institute of Geophysics (RD and PC prefix) and the Scripps Institution of Oceanography (D suffix) (Figures 5 and 6 and Tables 2 and 3). Because age determinations lie at the heart of any discussion on the origin of a chain such as the Line Islands, the data used are discussed below in the geological context of the various locations shown on Figures 1 and 5.

Three DSDP sites were drilled along the central Line chain in an attempt to reconstruct the history of edifice building

TABLE 1. Major Element Analyses of Volcanic Rocks From the Line Islands Chain

	Sample								
	63-7	61-1	60-6	59-13	41-2	43-1	44-3	45-1	52-2
SiO_2	41.70	45.20	46.45	42.90	45.20	42.75	41.75	38.65	44.55
TiO_2	3.48	3.88	2.02	2.78	2.88	2.60	3.22	2.34	2.93
Al_2O_3	13.53	17.02	16.20	17.64	13.74	17.97	15.80	15.72	15.87
Fe_2O_3	9.19	9.48	8.44	5.81	11.12	13.27	13.68	11.36	9.70
FeO	3.62	2.60	2.56	5.56	1.96	0.97	0.92	0.48	3.04
MnO	0.14	0.09	0.09	0.18	0.18	0.13	0.12	0.21	0.15
MgO	5.48	2.20	4.57	4.57	6.85	0.97	1.92	1.13	4.05
CaO	11.85	8.66	10.30	8.11	12.55	8.58	10.19	14.76	11.53
Na_2O	1.97	3.22	2.95	2.86	2.58	3.34	3.02	2.83	2.60
K_2O	1.21	2.46	1.03	1.94	0.91	1.75	1.29	1.71	0.92
P_2O_5	0.93	1.98	0.58	1.88	0.37	2.12	2.81	5.87	1.48
H_2O^+	3.29	1.95	2.43	3.60	0.62	3.39	2.54	2.51	1.50
H_2O^-	2.48	1.26	1.92	1.93	0.74	1.90	2.16	1.37	1.27
CO_2	1.05	0.02	0.08	0.17	0.16	0.29	0.37	0.83	0.24
Total	99.92	100.02	99.62	99.93	99.78	99.85	99.79	99.77	99.83

Analyst: K. Ramlal, University of Manitoba.

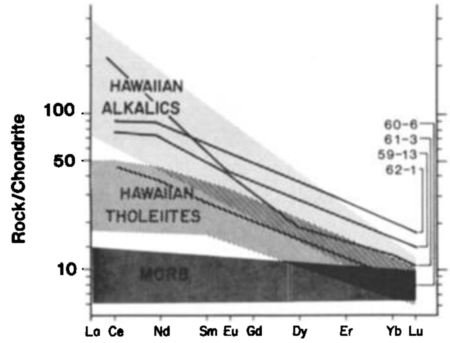

Fig. 4. Chondrite-normalized rare earth element patterns for some representative lavas from the Line Islands. Fields for Hawaiian tholeiites and alkalics and mid-ocean ridge basalt (MORB) from *Basaltic Volcanism Study Project* [1981].

[*Winterer et al.*, 1973; *Schlanger et al.*, 1976]. At DSDP site 165 a complex and long history of Cretaceous volcanism was revealed [*Lanphere and Dalrymple*, 1976; *Winterer et al.*, 1973]. Three basalt units interbedded with fossiliferous sediments were cored at the site. Between the two deepest basalt flows fossils of the *Eiffelithus eximus* zone were recovered. Taking the base of this zone to be at the Santonian-Campanian boundary dated at 83 Ma by *Harland et al.* [1982], we can deduce that volcanism was active at least 83 Ma. The age of the deepest basalt, based on sedimentation rate arguments could be as old as 93–101 Ma [*Lanphere and Dalrymple*, 1976]. Higher in the section at site 165 are thick volcanic breccia and sandstone beds which indicate that late-stage volcanism persisted into the *Tetralithus trifidus* zone of late Campanian age dated at 74 Ma by *Harland et al.* [1982]. A rock dredged from the large seamount just to the east of site 165 was dated at 72 Ma using the ^{40}Ar-^{39}Ar method [*Saito and Ozima*, 1977]. Thus major volcanism in the immediate vicinity of site 165 occurred over a time span of at least 11 Ma, from 72 to 83 Ma and possibly longer. At site 315 [*Schlanger et al.*, 1976] the east flank of the Fanning Island edifice was drilled. The basalt cored at the bottom of the hole

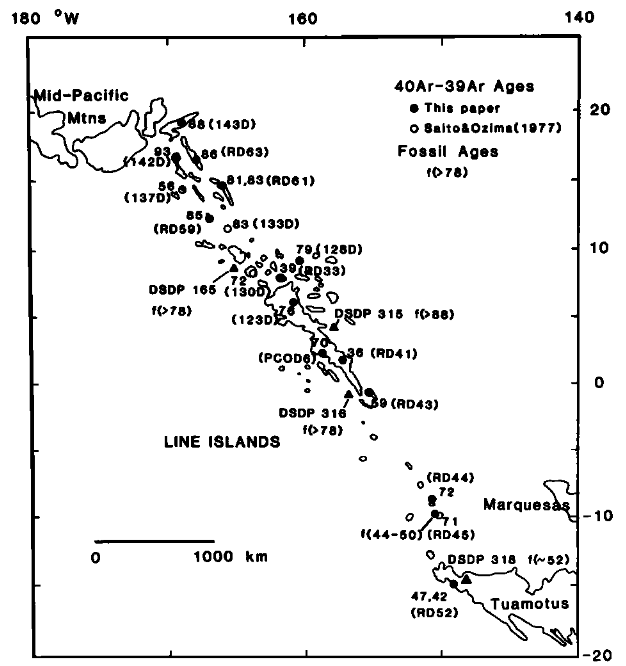

Fig. 5. Station locations and age determinations in the Line chain.

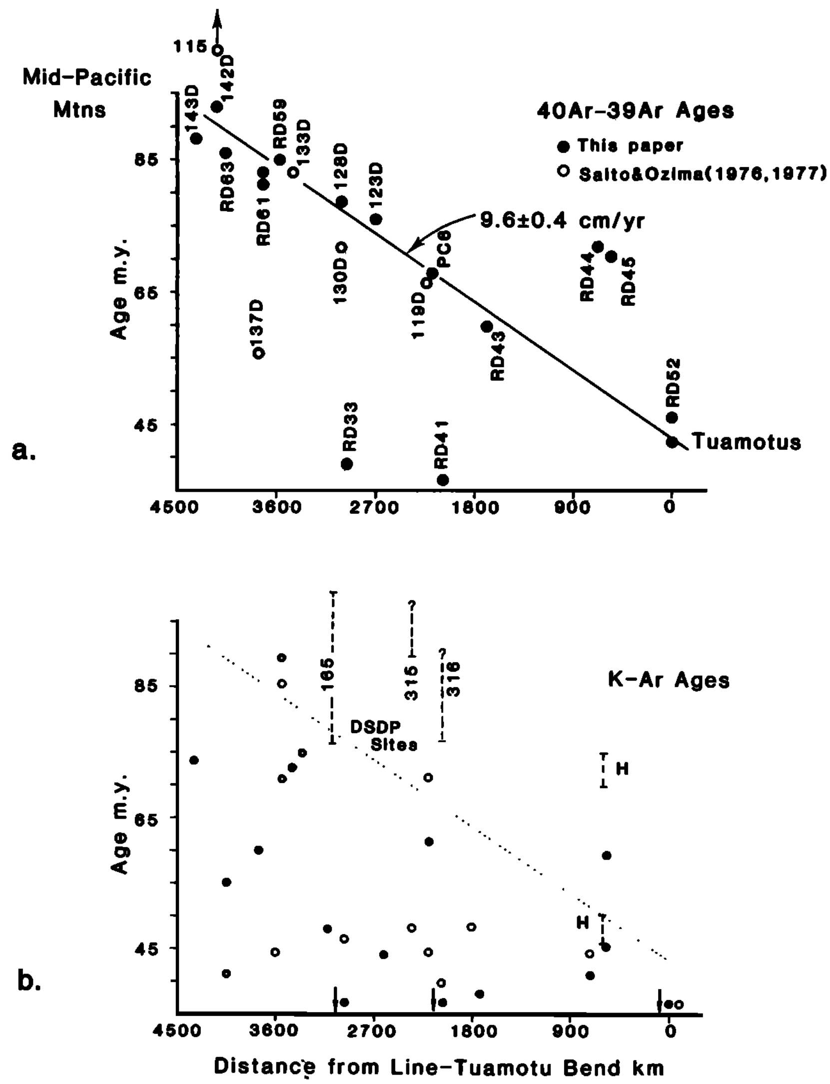

Fig. 6. Radiometric and paleontologic ages in the Line chain. (*a*) ^{40}Ar-^{39}Ar ages shown as solid circles were determined in this study; open circles are dates from *Saito and Ozima* [1976, 1977]. The solid line shows a rate of migration of volcanism of 9.6 ± 0.4 cm/yr which would account for many of the ages determined. (*b*) K-Ar ages and biostratigraphic age determinations (DSDP sites 165, 315, and 316 and seamounts (H) from *Haggerty et al.* [1982]).

yielded a feldspar fraction K-Ar age of 91.2 ± 2.7 Ma [*Lanphere and Dalrymple*, 1976]. Their age converts to 93.3 Ma upon using new constants [*Harland et al.*, 1982], the age used in this paper. Nannofossils of the *Marthasterites furcatus* zone were recovered 85 m above the basalt. These sediments are of Coniacian age, the *M. furcatus* zone being dated at 88 Ma [*Harland et al.*, 1982]. The correlation of the fossil age and the K-Ar age at site 315 argues for a cessation of major edifice building activity at ~93 Ma. Further, *Premoli-Silva and Brusa* [1981] record the presence of a mid-Cretaceous *Cuneolina* assemblage in turbidites at this site, implying the existence of a seamount in the photic zone in Cenomanian-Albian time, >90 Ma.

At site 316, basalt basement was not reached. The oldest sediments penetrated yielded foraminifera and nannofossils of early Campanian age (77–80 Ma) associated with basaltic breccias and volcanic sandstones. On the basis of the correlation of stratigraphic sections between sites 316, 315, and 165, basalt basement at 316 probably lies ~75 m below the deepest sediments recovered; the data of cessation of major edifice-building volcanism at 316 can be estimated at ~81–83 Ma [*Schlanger et al.*, 1976]. In summary the DSDP results from the main Line Islands system show the following:

1. Volcanism at site 165 and the nearby seamount from which dredge haul 130-D was taken occurred from 83 Ma (or possibly ealier) to 72 Ma.

2. At site 315, major edifice construction ceased by ~93 Ma; initiation of volcanism is undated but could be prior to ~95 Ma.

3. At DSDP site 316 the cessation of volcanic edifice building is estimated at 81–83 Ma; initiation of volcanism is undated.

In our study of rocks dredged from the Line Islands, both K-Ar and ^{40}Ar-^{39}Ar dating techniques were employed to examine the distribution of ages within this volcanic lineament (Figures 5 and 6 and Tables 2 and 3). Previous attempts at measuring reliable crystallization ages by the conventional K-Ar method [*Davis et al.*, 1980] have been frustrated by the effects of seawater alteration. Both K addition and Ar loss during low-temperature clay and zeolite formation, in the presence of seawater, will cause the measured age to be systematically lower than the rock crystallization age. Reconnais-

TABLE 2. The ^{40}Ar-^{39}Ar Total Fusion Age Data on Dredged Volcanic Rocks From the Line Islands Chain

Sample	Location	^{40}Ar-^{36}Ar	^{40}Ar-^{39}Ar	^{37}Ar-^{40}Ar*	Percent Radiogenic ^{40}Ar	Age $\pm 1\sigma$ $\times 10^6$ years
143D-102	19°30'N, 169°03'W	3011.	32.03	0.0538	90.0	88.1 ± 0.4
142D-11	18°00'N, 169°05'W	57028.	38.16	0.0092	99.4	93.4 ± 1.3
RD63-7	16°27'N, 168°13'W	1456.	35.36	0.1525	79.4	86.0 ± 0.9
RD59-12	12°31'N, 167°03'W	2463.	71.24	0.0106	88.0	85.0 ± 1.1
RD61-1	14°59'N, 166°27'W	965.9	86.32	0.0149	69.4	81.4 ± 1.1
RD61-5	14°59'N, 166°27'W	835.3	79.74	0.0221	65.1	82.6 ± 0.7
128D-11	9°15'N, 160°45'W	642.1	59.24	0.0089	53.8	78.7 ± 1.3
RD33-1	8°11'N, 161°55'W	379.8	128.84	0.0371	22.2	39.3 ± 1.5
123D-15	5°50'N, 160°45'W	2251.	28.74	0.1058	76.4	76.4 ± 0.5
PCOD-6-2	2°35'N, 158°30'W	2524.	58.05	0.0243	88.2	69.8 ± 1.0
RD41-1	2°06'N, 157°21'W	705.8	23.57	0.1929	57.7	35.5 ± 0.9
RD43-1	0°42'S, 155°17'W	702.4	33.15	0.0956	57.6	59.0 ± 0.8
RD44-3	7°35'S, 151°33'W	461.8	65.24	0.0445	35.9	71.9 ± 1.4
RD45-26D	9°04'S, 150°42'W	633.7	53.57	0.1238	53.1	70.5 ± 1.1
RD52-1	15°01'S, 149°02'W	544.1	75.62	0.0869	45.6	47.4 ± 0.9
RD52-2	15°01'S, 149°02'W	472.7	81.12	0.0914	37.4	41.8 ± 0.9

*Ar 37 corrected for decay since irradiation.

sance K-Ar ages determined in this study (Table 3) were similarly scattered and significantly lower than indirect age estimates based on paleontologic data [*Haggerty et al.*, 1982] or seamount magnetization studies [*Sager*, 1983*a*].

Recently, the application of the ^{40}Ar-^{39}Ar total fusion method to dating moderately altered submarine volcanic rocks has proven successful in determining consistent ages [*Dalrymple and Clague*, 1976; *Duncan*, 1978, 1982; *Dalrymple et al.*, 1981]. According to these studies it is probable that ^{39}Ar, derived from K-bearing alteration minerals or from K residing on grain boundaries, escapes from the sample during neutron irradiation or extraction line bake-out. Radiogenic ^{40}Ar was lost from precisely these sites during alteration, so the age signal from the low-temperature alteration phases is essentially erased prior to sample fusion. Thus the ^{40}Ar-^{39}Ar age commonly approaches the crystallization age because the predominant source of nonatmospheric argon is the primary crystalline phases.

Samples were selected from the Line Islands collections for K-Ar and ^{40}Ar-^{39}Ar geochronology on the basis of thin section examination. Petrographically, all samples show slight to moderate alteration. Augite and feldspar phenocrysts are generally fresh, particularly in the more trachytic-textured rocks (143D-102, 142D-11, RD-59-12, and PROD6-2). Olivine phenocrysts are commonly altered to iddingsite. The matrix phases such as feldspar and clinopyroxene are generally fresh, but where devitrified glass occurred, it has been altered to clays. Zeolites and calcite are common in vesicles and along microfractures. A further indication of the degree of alteration of these samples is the high-H_2O content in most samples (between 0.6 and 3.6 wt %) and in rare cases, high-CO_2 content (up to 1 wt %).

Argon isotopic compositions were measured using an AEI MS-10S mass spectrometer equipped with ^{38}Ar spike and air calibration pipette systems. For ^{40}Ar-^{39}Ar ages, split aliquots of crushed samples were irridiated at the U.S. Geological Survey TRIGA Reactor in Denver, Colorado, for 4 hours at 1 MW power. Operating conditions and isotope interference corrections have been described by *Dalrymple et al.* [1981].

That conventional K-Ar analyses underestimate the ages of Line Islands volcanic rocks is particularly apparent in the scattered ages of samples from the same seamount (RD-45-1, RD-45-26D) or neighboring seamounts (Table 3 and Figure 6). Where indirect age estimates are available, K-Ar age determi-

TABLE 3. K-Ar Age determinations From Dredged Volcanic Rocks From the Line Islands Chain

Sample	Location	Percent K	Radiogenic ^{40}Ar $\times 10^{-5}$ cm^3/g	Percent Radiogenic Ar	Age* $\pm 1\sigma$ $\times 10^6$ years
143D-102	19°30'N, 169°03'W	2.097	0.6128	88.8	73.7 ± 0.8
RD63-7	16°27'N, 168°13'W	1.194	0.2589	78.6	55.0 ± 0.6
RD61-1	14°59'N, 166°27'W	2.098	0.4840	67.3	59.8 ± 0.6
133D-9	12°04'N, 165°50'W	1.666	0.4808	65.8	72.8 ± 1.3
128D-11	9°15'N, 160°45'W	0.725	0.1370	56.6	48.0 ± 0.6
RD33-1	8°11'N, 161°55'W	0.695	0.0625	44.8	23.5 ± 0.3
123D-15	5°50'N, 160°45'W	1.996	0.3478	86.6	44.3 ± 0.5
PCOD-6-2	2°35'N, 158°30'W	1.601	0.3783	90.2	61.2 ± 0.6
RD41-1	2°06'N, 157°21'W	1.016	0.1005	75.6	25.3 ± 0.3
RD43-1	0°42'S, 155°17'W	1.411	0.2047	53.8	37.8 ± 0.4
RD44-3	7°35'S, 151°33'W	1.120	0.1780	32.8	41.4 ± 0.5
RD45-1	9°04'S, 150°42'W	1.301	0.2259	34.4	45.2 ± 0.6
RD45-26D	9°04'S, 150°42'W	0.915	0.2133	58.4	59.0 ± 0.7
RD52-2	15°01'S, 149°02'W	0.742	0.0712	35.9	25.1 ± 0.4

*Ages calculated from the following decay and abundance constants: $\lambda_\varepsilon = 0.581 \times 10^{-10}$ yr^{-1}; $\lambda_\beta = 4.962 \times 10^{-10}$ yr^{-1}; $^{40}K/K = 1.167 \times 10^{-4}$ mol/mol.

nations are always younger, by 9–30 Ma, and are not reliable indicators of sample crystallization age, despite generally high proportions of radiogenic argon.

The ^{40}Ar-^{39}Ar total fusion ages are much more consistent, however (Table 2 and Figure 6). Where multiple samples from the same seamount were analyzed (RD-61-1, RD-61-5, RD-52-1, and RD-52-2), age agreement was good. Samples from neighboring seamounts (143D-102, 142D-11, and RD-63-7; RD-44-3 and RD45-26D) gave similar ages. Further, the concordance of our radiometric dates with age determinations based on paleontological and seamount magnetization data indicate that the ^{40}Ar-^{39}Ar ages are reliable. *Haggerty et al.* [1982] determined a minimum age of 70–75 Ma, based on the occurrence of Late Cretaceous shallow water fossils, for the seamount from which RD-45 was taken; as shown on Table 2, RD-45-26D yielded a ^{40}Ar-^{39}Ar age of 70.5 ± 1.1 Ma. Seamount L8 has a virtual geomagnetic pole which lies close to a Maestrichtian pole of both *Gordon* [1982*a*] and *Sager* [1982*a*]; RD-44-3 from this seamount yielded a ^{40}Ar-^{39}Ar age of 71.9 ± 1.4 Ma, within the 65–73 Ma span of the Maestrichtian stage according to *Harland et al.* [1982]. The majority of sample ages falls along a linear array, from older seamounts in the north (~93 Ma) to younger seamounts in the south (~44 Ma at the Line-Tuamotu bend). The overall consistency of this data set encourages confidence in these estimates of volcano ages. It is difficult to imagine, for instance, a process which would produce progressively greater alteration to the south to yield the observed pattern. A rate of migration of volcanism of 9.6 ± 0.4 cm/yr best fits the linear array of seamount ages. A number of ages, however, do not fall on the main linear trend, these are also considered reliable and are discussed below.

Earlier studies have reported ^{40}Ar-^{39}Ar age determinations from a number of seamounts in the northern and central Line Islands [*Saito and Ozima*, 1976, 1977]. Where both ^{40}Ar-^{39}Ar total fusion and incremental heating ages were reported, we have plotted the total fusion ages considered to be reliable by Saito and Ozima (shown as open circles) for comparison with the ages determined in the present study (shown as solid circles) in Figure 6. Two seamounts, 130D and 133D, yield Cretaceous ages which fall along the main linear trend. Another is Eocene in age. *Saito and Ozima* [1977] reported an isochron age of 127.5 ± 5.0 Ma and a total fusion age of 114.8 ± 1.3 Ma for 142D dredged from the northern end of the Line Islands. We determined an age of 93.4 ± 1.3 Ma for this site. The reason for this discrepancy is unknown. Other ages from neighboring seamounts support our younger age determinations, however.

SEAMOUNT PALEOMAGNETISM

Measurement and analysis of the magnetic field of a seamount can yield information on the paleoazimuth and latitudinal transport of a seamount subsequent to its formation and on the location of its virtual geomagnetic pole (VGP); the location of its VGP allows inferences to be drawn as to the age of the seamount. In this paper the implications of the paleomagnetic results for periods of volcanism along the Line chain are stressed. The details of the surveys and data reduction methods are described by *Sager and Keating* [this issue] and *Sager* [1983*a*].

To these ends, 11 seamounts in and around the Line chain were surveyed for paleomagnetic analysis; of these, seven gave apparently reliable results. Previous to our work, eight seamounts in and around the chain had been paleomagnetically studied, but a useful result was obtained from only one, L3 in Figure 1 [*Harrison et al.*, 1975]. The magnetization parameters and virtual geomagnetic poles (VGP's) derived from the eight seamount magnetic models that yielded apparently reliable results are given along with ^{40}Ar-^{39}Ar ages determined for them in Table 4.

The goodness of fit ratio (GFR) [*Richards et al.*, 1967], measuring the match between the observed and calculated anomalies, is high for all of the seamounts analyzed in this study, ranging from 3.1 to 5.2. The larger the GFR the better the agreement between the observed and calculated anomalies; usually a GFR of 1.8–2.0 is considered to be the minimum acceptable value for a reliable magnetic inversion [*Harrison et al.*, 1975; *Sager*, 1983*a*]. Not only do the GFR's of the Line seamounts indicate excellent results, but the paleomagnetic poles derived from these seamounts are consistent among themselves and with other Pacific seamount VGP's. Moreover, the VGP's of the reliably dated seamounts from the chain that have been studied paleomagnetically are in close agreement with other Pacific paleomagnetic data of the same age, as is discussed below.

Four of the Line seamounts gave VGP's closer to the geographic pole than any VGP derived from a Cretaceous Pacific seamount (Figure 7) implying that these four seamounts are younger than Cretaceous age. These four VGP's are located close to the VGP's of three Pacific seamounts that probably formed during the late Eocene or early Oligocene. Of the three, one is inferred to be approximately 41–42 Ma of age by its position in the Hawaiian seamount chain and by its magnetic polarity [*Sager*, 1984]. The other two seamounts are located in the eastern Pacific on seafloor 45 and 37 Ma old as indicated by magnetic lineations [*Sager*, 1983*b*]. In addition to this data, a DSDP sediment paleolatitude (site 166) calculated from samples spanning the late Eocene and early Oligocene records a paleopole locus in agreement with the four Line Islands VGP's as does a paleoequator transit determined from sediment facies examined at DSDP site 163 [*Sager*, 1983*b*].

Of the four seamounts that give high-latitude VGP's, only one has been dredged and dated. Seamount L4 (RD-33) has an ^{40}Ar-^{39}Ar total fusion age of 39.3 ± 1.5 Ma. Seamount L5 is directly adjacent (and possibly connected to) to seamount L4 [*Sager and Keating*, this issue] and is thus likely to be the same age, particularly considering the nearness of their VGP's (Figure 7). Neither L6 nor L7 have been dated, but the proximity of their VGP's to the other Eocene-Oligocene paleomagnetic poles coupled with the fact that a significant number of Eocene ages have been determined for seamounts in the Line Islands (Table 3) [*Saito and Ozima*, 1977; *Haggerty et al.*, 1982] suggests that these two seamounts are also likely to be the same age.

The other four Line Islands seamounts studied paleomagnetically produced VGP's that are located among the VGP's of Pacific seamounts of Cretaceous age. Both L1 and L8 have VGP's located near the Maastrichtian paleomagnetic poles calculated by *Gordon* [1982*a*] and *Sager* [1983*a*] (Figure 8). L1 is undated, but a rock from L8 yielded an ^{40}Ar-^{39}Ar total fusion age of 71.9 ± 1.4 Ma (RD-44) which agrees well with the age inferred for the volcano from fossils [*Haggerty et al.*, 1982] and from its reversed polarity [*Sager and Keating*, this issue].

Seamounts L2 and L3 are located close to one another in the Line chain (Figure 7) and have ^{40}Ar-^{39}Ar total fusion ages that are virtually identical, 85.0 ± 1.1 Ma (L2, RD-59) and

TABLE 4. Magnetization Parameters for Line Islands Seamounts

		Location		VGP							
Name	ID	Latitude N	Longitude E	Latitude N	Longitude E	Inclination (+Down)	Declination (+East)	Intensity, A/m	GFR	Age, m.y.	Reference
Watkins	L1	17.5	190.8	68.8	33.5	−4.3	352.0	5.8	5.2		1
Nagata	L2	12.5	193.0	61.6	4.0	−29.0	4.4	3.8	3.7	85.0 ± 1.1	2
Kapsitotwa	L3	12.0	194.2	47.5	333.5	−36.6	28.0	5.1	3.7	82.7 ± 3.6	3
Stanley	L4	8.2	198.1	75.6	356.5	−10.5	5.3	3.2	4.7	39.3 ± 1.5	4
Willoughby	L5	7.9	198.1	78.2	14.6	−7.8	0.7	3.5	4.4		4
Chapman	L6	3.4	199.9	75.7	37.8	−19.7	355.6	4.7/8.0	4.3		4
Clarke	L7	−3.3	206.0	80.0	20.4	−25.3	1.0	3.3	4.0		4
Uyeda	L8	−7.5	208.5	68.5	345.6*	40.1	195.7	6.9	3.1	71.9 ± 1.4	4

GFR, goodness of fit ratio. References: 1, *Keating and Sager* [1980]; 2, *Sager et al.* [1982]; 3, *Harrison et al.* [1975]; 4, *Sager and Keating* [this issue].
*Reversely polarized, south pole given.

82.7 ± 3.6 Ma (L3, 133D) [*Saito and Ozima*, 1977], yet their VGP's are separated by over 22°. This phenomenon was puzzling until it was noted that apparent polar wander just prior to 80 Ma was very rapid (Figure 8) [*Gordon*, 1983; *Sager*, 1983*a*], so that a difference of only a few million years in the age of two samples could result in a larger separation of their paleopoles. Consequently, we hypothesize that L2 is slightly younger than L3, which is allowed within the analytical uncertainty of their ^{40}Ar-^{39}Ar total fusion ages.

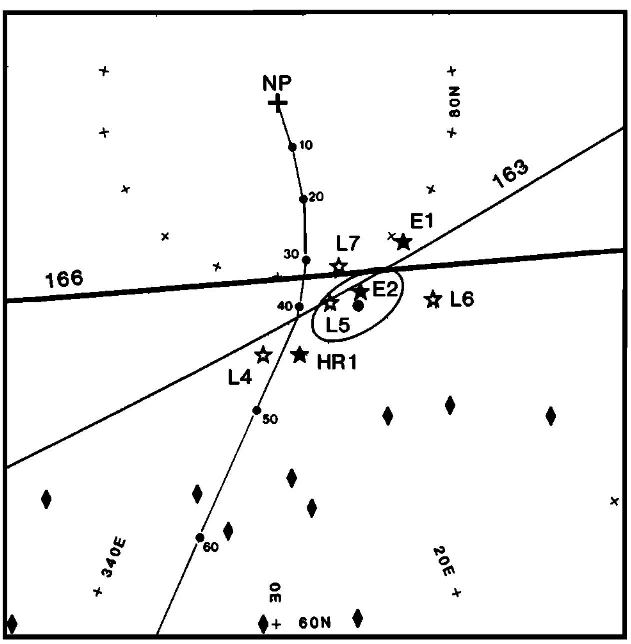

Fig. 7. Comparison of high-latitude seamount paleopoles and Pacific Eocene paleomagnetic data. The VGP's of seamounts L4-L7 are shown by open stars. L4 has a total fusion age of 39 ± 1.5 Ma. Seamounts E1, E2, and HR1 have VGP's shown by the solid stars. HR1 has been assigned an age of 41–42 Ma by its position in the Hawaiian chain [*Sager*, 1984] and E1 and E2 have maximum ages of 45 and 37 Ma, respectively, determined by the age of the seafloor upon which they rest [*Sager*, 1984]. The heavy line is a segment of the small circle that is the locus of the paleomagnetic poles measured from sediment samples from DSDP site 166. These samples range in age from Oligocene to Eocene [*Jarrard*, 1973]. The thin line is a similar segment of the polar circle estimated from the identification of equatorial sediments in the cores from DSDP site 163. It was determined that this site crossed the equator 43 ± 6 Ma [*Suarez and Molnar*, 1980]. The large dot is the mean position of the Eocene seamount VGP's and the ellipse is the 95% confidence region of the mean paleomagnetic pole [*Sager*, 1984]. The small dots connected by the dashed lines are positions of the paleopole predicted by the Pacific plate/hot spot rotation model of *Jarrard and Clague* [1977] (with rotation rate corrected by *Dalrymple et al.* [1977]) labeled at 10-Ma intervals. The diamonds are the VGP's of Cretaceous seamounts from *Harrison et al.* [1975]. Map projection is polar equal area.

VOLCANIC EVENTS

The above described DSDP results, radiometric ages, biostratigraphic ages, and paleomagnetic results determined for seamounts and linear ridges in the Line Islands reveal the complexity of volcanic events in this province. Figures 5 and 6 summarize the relevent radiometric and fossil age determinations from the site of Horizon Guyot south to the Tuamotu Islands. Table 2 lists the data referred to in this section. For the purposes of this discussion the well-defined Line chain is taken to extend from Horizon Guyot and the northern end of the linear ridge from which dredge 142-D was taken to the southern end of the line of seamounts from which RD-45 was

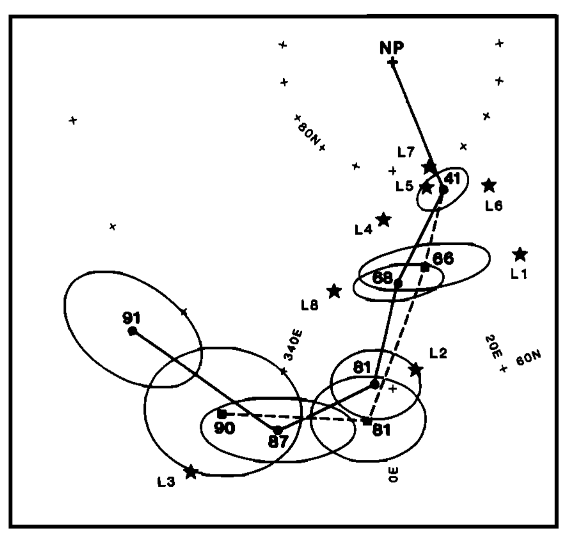

Fig. 8. Comparison of Line Islands seamount paleomagnetic poles with Pacific apparent polar wander paths. The Line Islands VGP's are shown by solid stars. Solid circles show the locations of the mean paleomagnetic poles calculated by *Sager* [1983*a*, 1984], whereas the solid squares represent the mean pole positions of *Gordon* [1982*a*, 1983]. The solid line is the apparent polar wander path of *Sager* [1983*a*]; the dashed line, the path of *Gordon* [1983]. The 95% confidence regions surrounding the mean paleomagnetic poles are shown as ellipses, and the numbers within the ellipses are the mean ages of the poles in millions of years. Seamounts L2, L3, L4, and L8 have total fusion ages of 85.0 ± 1.1, 82.7 ± 3.6, 39.3 ± 1.1, and 71.9 ± 1.4 Ma, respectively. Map projection is polar equal area.

taken that extend north from Caroline Island. The sequence of volcanic events at both the northern and southern boundaries of the Line chain are also complex. Drilling on Horizon Guyot [*Winterer et al.*, 1973] showed this ridge to have a history of two Cretaceous volcanic events separated by a period of Cenomanian reef growth. Further, dates obtained in our study from the northeast end of the Tuamotu Islands of 41.8 ± 0.9 and 47.4 ± 0.9 Ma (RD-52) complicate the generally accepted argument that the Line-Tuamotu elbow is coeval with the Emperor-Hawaiian elbow dated at 43 Ma. On the basis of fossil evidence derived from drilling at DSDP site 318 in the Tuamotu chain [*Schlanger et al.*, 1976], where late early Eocene shallow water fossils in turbidites overlie the presumed basalt basement, it was argued that the volcanic edifices of the Tuamotu ridge could have formed more than 51 Ma. Also, *Haggerty et al.* [1982] determined, paleontologically, that Eocene volcanism, ~44–50 Ma, took place in the southern Line chain at the site of RD-45. Therefore the data available at this time show that volcanism in the area of the Line-Tuamotu elbow took place from more than 51 to 42 Ma.

Within the Line chain the following chronologic data needs to be taken into account. As shown on Figures 5 and 6, the majority of dated volcanic edifices define an overall age progression along the Line chain from the location of dredge 142-D (93.4 ± 1.3 Ma) to the Line-Tuamotu elbow. Watkins Seamount (L1 of this paper; Figure 1) is also considered to be of Late Cretaceous age. A rate of migration of volcanism of 9.6 ± 0.4 cm/yr best fits this trend. However, deviations from the progressive trend exist. The cluster of ages represented by RD-63 (86.0 ± 0.9 Ma), RD-61 (81.4 ± 1.1 Ma, 82.6 ± 0.7 Ma), RD-59 (85.0 ± 1.1 Ma), and 133-D (84.4 ± 0.9 Ma) are associated with 137D dated at ~57 Ma by *Saito and Ozima* [1977]. The elongate ridge from which 137-D was dredged exactly parallels the ridges from which RD-63 and RD-61 were taken; RD-59 is from an isolated seamount lying off the southern end of the ridge from which 137-D was taken. It is difficult to reconcile this parallelism of ridges with the path of a single hot spot to account for both the Cretaceous and Paleocene ages in this short sector of the Line Islands. Further, 137-D lies to the north of the well-defined Line cross trend (Figure 1). Seamounts L2 and L3 of this paper (Table 4 and Figure 1) yielded Cretaceous ages based on paleomagnetics which are in accord with the radiometric age determinations of RD-59 and 133-D. In the Line cross trend itself (Figure 2), which has a geometric trend distinct in the province, the only radiometric age obtained at 128D (78.7 ± 1.3 Ma) plots in the main trend line shown in Figure 6 even though the seamount from which the rock was taken lies far to the east of the main Line chain.

Further, the long time span of volcanism at site 165 and the age of 39.3 ± 1.5 Ma obtained for RD-33 argue against a straightforward age progression along the Line cross trend, although both of these locations, it could be argued, lie to the south of the well-defined cross trend and may represent volcanic activity of Cretaceous age along the 9.6 ± 0.4 cm/yr progression shown in Figure 6 complicated by Eocene volcanism along one of the SE trending ridges which intersects the Line Islands chain. Seamounts L4 and L5 of this paper are of Tertiary age based on paleomagnetic data. In the central Line Islands the date of 76.4 ± 0.5 Ma for dredge 123-D falls on the line of age progressions shown on Figure 6. However, at site 315 major edifice building ceased by 93.3 Ma and a nearby seamount, L6 of this study, is probably of Eocene age. At the southern end of the central Line Islands the cluster of dates represented by PCOD-6 (69.8 ± 1.0 Ma), RD-41 (35.5 ± 0.9 Ma), RD-43 (59.0 ± 0.8 Ma), and DSDP site 316 (minimum age of cessation of volcanism at 81–83 Ma) presents further complications for a single hot spot linear progression model. Sample PCOD-6 consisted of a relatively fresh cobble of plagioclase-rich basalt in a piston core taken in a turbidite-filled basin which lies downslope from the site of RD-41. This basalt cobble must represent debris from a seamount. Thus we see in a very close geological conjunction edifice ages of 69.8 ± 1.0 and 35.5 ± 0.9 Ma. The PCOD-6 and RD-43 dates fit on the linear progression line of Figure 6. The cessation of volcanism at DSDP site 316 greatly predates both PCOD-6 and RD-43; three distinct periods of volcanism are seen in this region. Seamount L7 of this paper, of Eocene age, could also be ascribed to the main age-progressive trend linear ridge.

The final set of dates to be discussed are those from the southern Line Islands, dredge hauls RD-44 and RD-45. Prior to the determination of radiometric age dates from these dredge hauls, *Haggerty et al.* [1982] had determined on fossi evidence that the seamount from which RD-45 was obtained had a minimum age of 70–75 Ma. This seamount is capped by coarse-grained bioclastic limestone of reefal origin which contains rudists, calcareous algae, and volcanic rock fragments. Further, volcanic peperite was dredged from the RD-45 seamount. Tests of planktonic foraminifera incorporated into this volcanic rock have been dated as middle Eocene in age, 44–50 Ma [*Haggerty et al.*, 1982]. The ages of 71.9 ± 1.4 and 70.5 ± 1.1 Ma reported here are consistent with the Maestrichtian age of shield-building volcanism at these seamounts which must have been above sea level in Late Cretaceous time as determined by the fossil evidence of *Haggerty et al.* [1982]. These Cretaceous dates fall far above the postulated line of progression shown on Figure 6 and argue persuasively against the formation of the Line Islands by a single hot spot. In fact, when considered together with the DSDP results from 165, 315, and 316, one could argue that an older progressive trend existed which paralleled the trend line defined in Figure 6. The phase of Eocene volcanic activity at RD-45 can be explained by hot spot volcanism along the main trend. We wish to emphasize the following points concerning volcanic events:

1. The majority of dated volcanos can be interpreted as defining an age-progressive volcanic trend from 93 (142-D) to 44–50 Ma (RD-45 southward along the Line chain, which supports an origin by hot spot volcanism now active in the vicinity of Easter Island. During this period the Pacific plate moved at 9.6 ± 0.4 cm/yr across this hot spot.

2. Three volcanos exhibit Eocene and Paleocene volcanism (between 38 and 60 Ma) which does not fit this main trend: 137-D at 15°N, RD-33 in the Line Islands cross trend, and RD-41 at 2°N. This small group of ages possibly shows an age progression which could be related to volcanic overprinting by hot spot volcanism along the Line-Marquesas Swell [*Crough and Jarrard*, 1981]. Alternatively, these volcanos represent a period of rejuvenescence not related to hot spot volcanism but part of a Pacific-wide Eocene volcanic event [*Haggerty et al.*, 1982]. In either case, the Eocene and Paleocene edifices and ridges sampled are in close proximity to older Cretaceous edifices and ridges, as in the case of RD-45 and the pair of ages shown by PCOD-6 and RD-41. The same edifices may be composites of both Cretaceous and Eocene volcanic episodes and clearly require a volcanic history requiring more than a single hot spot.

3. The Cretaceous ages determined at DSDP sites 165,

315, and 316 and from RD-44 and RD-45 do not fit 9.6 ± 0.4 cm/yr trend and could be interpreted as representing a progressive age trend that is systematically 10–20 Ma older than the linear trend shown in Figure 6 which connects the Tuamotu elbow with the northernmost Line Islands. It is particularly difficult to fit the 93.3 Ma age of volcanism at DSDP site 315, which is concordant with the age of the *Cuneolina* assemblage there, to the 9.6 ± 0.4 cm/yr trend.

REEF GROWTH AND SUBSIDENCE

One of the major implications of the hot spot model for the development of a linear island chain is that the history of reef growth along the chain should reflect the progressive chronology of volcanism along the chain, provided that the volcanic edifices built from the seafloor into the photic zone in latitudes amenable to vigorous reef growth. The thickness of the reef cap on an edifice would depend on the subsidence path of the edifice. Along a hot spot path the edifices and the seafloor would be expected to sink along an age-depth curve such as one of those proposed by *Parsons and Sclater* [1977], *Heestand and Crough* [1981], and *Crough* [1983] where depth is equal to a function of $t^{1/2}$.

The Emperor-Hawaiian chain is the best documented hot spot trace in the Pacific Basin; along this chain the history of reef growth and development follows a classical Darwinian pattern [see *Jackson et al.*, 1980]. Around the island of Hawaii, now over the hot spot, only Recent reefs are known. At Midway Island, drilling revealed that reef growth has been continuous since Miocene time [*Ladd et al.*, 1970]. Drilling along the Emperor chain showed that Paleocene reefal carbonates cap seamounts in that part of the chain. Failure of atolls to maintain themselves at sea level in the Emperor chain can be ascribed to the transport of the Emperor edifices into colder, northern waters as these edifices moved NW atop the Pacific plate. Moreover, an almost continuous chain of closely spaced atolls extends from Midway Island SE along the chain to Gardner Pinnacle where the volcanic edifice breaks sea level.

Therefore, if the Line chain formed through the action of a single hot spot, we would expect to see a history of reef growth and subsidence along the chain somewhat parallel but older than that seen in the Emperor-Hawaiian chain. However, in the case of the Line chain, two kinds of data needed for a detailed reconstruction of a subsidence history are largely lacking. First, the age of the seafloor in the vicinity of the Line chain is poorly known, and second, the history of reef growth can only be inferred from data from DSDP sites 165, 315, and 316 in the central part of the chain and dredge haul sites RD-44, 45, 46, and 47 in the southern part of the chain.

The oldest known reefs in the main Line chain were in the vicinity of Fanning Island as shown by data from DSDP site 315. There *Premoli-Silva and Brusa* [1981] report a mid-Cretaceous *Cuneolina* assemblage of Cenomanian-Albian age in turbidites of both late Campanian–middle Maestrichtian and Oligocene age. The presence of this mid-Cretaceous fauna is in concordance with the K-Ar age of 93.3 Ma reported for the basal basalt at DSDP site 315. If we consider Horizon Guyot to be the northern extension of the Line chain, then we must consider the *Cuneolina*-bearing reef limestone drilled there at DSDP site 171 [*Winterer et al.*, 1973] to be coeval with the mid-Cretaceous reef reported at DSDP site 315. During late Campanian through early-middle Maestrichtian time (70–75 Ma) reefs existed in the vicinity of Kingman Reef (DSDP site 165), Fanning Island (DSDP site 315), south of Christmas Island (DSDP site 316), and on seamounts just north of Caroline Island (dredge hauls 44 and 45). The existence of reefs of late Campanian to early-middle Maestrichtian age along a 2500-km length of the Line chain from DSDP site 165 to RD-45 shows reef development over this distance between 70 and 75 Ma.

Evidence for post-Cretaceous reef growth is only recorded from DSDP site 165, where late Eocene reef-derived fossil debris was cored in Oligocene turbidites [*Premoli-Silva and Brusa*, 1981] and at Caroline Island (RD-46 and 47) where dredge hauls recovered reef limestones of Eocene through Plio-Pleistocene age; Caroline Island is an atoll today [*Haggerty et al.*, 1982]. At the site of dredge haul RD-44, late Cretaceous reefs were succeeded by a late Paleocene neritic-shelf carbonate unit, but by middle Eocene time, pelagic sedimentation prevailed at this site. We can assume that there are sections of post-Cretaceous reefs below the atolls of the central Line chain. It is important to note that dredge hauls RD-57 through 64 recovered no reefal limestone debris between Johnston Island and Kingman Reef. The morphology of the chain and the pattern of reef growth along it contrasts with the Emperor-Hawaiian chain. Long sections of the Line chain lack atolls, i.e., from Johnston Island to Kingman Reef and from Christmas Island to Caroline Island. This lack of atolls, considering that the Line chain was in latitudes amenable to reef growth throughout its history from Late Cretaceous to the present day, argues against a hot spot model that would produce a chain capped by a more regularly disposed chain of atolls. Further, the irregular distribution of atolls argues for a subsidence history along the chain at variance with one predicted by a regular age-depth relationship related to $t^{1/2}$. Where reefing history is known from closely spaced edifices such as the sites of RD-44, RD-45, and Caroline Island (RD-46 and 47), the subsidence history appears to have been complex. At RD-44 the apparent succession of Late Cretaceous reefs followed by late Paleocene neritic shelf carbonates and then by middle Eocene pelagic sediments suggests that the edifice subsided too quickly for the maintenance of reef growth; subsidence at this site amounted to 1500 m since Late Cretaceous time. At RD-45, reef growth ceased by Maestrichtian time, and the edifice has subsided 1200 m since that time. At Caroline Island, reef growth has persisted at least from Eocene time to the present day. We note that *Epp* [this issue] estimated subsidence rates at DSDP sites 165 and 316 and at the sites of the seamounts from which dredge hauls RD-44 and RD-45 were taken (see also *Haggerty* [1982] for original data) and came to the conclusion that each of these sites underwent different subsidence histories no one of which fit the subsidence paths predicted by the age-depth curves of *Parsons and Sclater* [1977], *Heestand and Crough* [1981] and *Crough* [1983].

DISCUSSION

The purpose of the research carried out by the present authors was the testing of the various models put forward to account for the Line chain. Beginning with *Morgan*'s [1972] proposition that the Line chain was generated by a single hot spot other models followed. *Natland* [1976] argued that the petrologic character of several basaltic rocks recovered from the Line chain and the cross trend indicated that at least parts of the chain were part of a central Pacific rift system of limited crustal extension. *Winterer* [1976] postulated a ridge crest origin for the main Line chain at ~110 Ma followed by ridge jumps; he recognized the importance of the NW-SE trending cross ridges and proposed that they were younger than the main Line trend and that the complexity of the chain was due to the passage of several hot spots across the chain. *Crough and Jarrard* [1981] proposed that one such cross trend continued into the Line chain from the Marquesas Islands. *Farrar and Dixon* [1981] proposed fracture zone volcanism as a major factor in the formation of the Lines. *Henderson and Gordon* [1982] have attempted to explain the complex volcanic history of the Line chain through the action of four hot spots that traversed the area of the present chain at different times. Finally, *Epp* [this issue] proposed two models, each of which employs a single hot spot, for the evolution of the Line chain. He argues that perturbations of the signal, i.e., the surface expression of volcanism, of the hot spot account for the complex chronology of the volcanic events along the chain.

The purpose of this section then is to present arguments against certain models that tend to invalidate them and that place constraints on other models. This section might be viewed as constructed after the Popperian argument that while it may not be logically possible to validate an hypothesis by discovering new confirming data, it is possible to invalidate an hypothesis by discovering even a single new piece of evidence that contradicts that hypothesis.

The ridge crest model set is difficult to justify on paleomagnetic grounds inasmuch as the magnetic anomaly patterns implicit in such models are not known in and around the Line chain. A stronger argument against the ridge crest model lies in the petrologic character of the basalts from the chain as discussed above. Our data and that of *Jackson et al.* [1976] show that the basalts in the Line chain are similar to those found in the Emperor-Hawaiian chain, the classic hot spot trace; the basalts are largely normal oceanic island basalts.

The fracture zone model is attractive in that it would account for the simultaneity of much of the Cretaceous volcanism along the Line chain. However, a fracture zone origin would imply large amounts of strike-slip displacement along the axis of the chain. *Farrar and Dixon* [1981] proposed 1700 km of strike-slip motion along a fracture zone that extended from the Emperor Trough through the Gardner Seamounts and through the entire Line chain. *Gordon* [1982*b*], based on a review of available paleomagnetic data has effectively refuted the Farrar-Dixon model.

Models that ascribe the Line chain to the action of a single hot spot run into difficulties in the face of the distribution along the entire chain of radiometric and biostratigraphic data relevent to the timing of volcanic edifice formation and periods of reef growth. If we take the Emperor-Hawaiian chain [see *Jackson et al.*, 1980] as the example of a single hot spot trace, we see that individual edifices in that chain built up from the seafloor to sea level in 1–2 m.y. and the reefs immediately formed on and around these edifices. This example cannot be applied to the Line chain. A single hot spot moving through the Line chain cannot account for (1) the formation of Cenomanian or older reefs at both Horizon Guyot and in the vicinity of Fanning Island (DSDP site 315), (2) the Late Cretaceous and Eocene volcanism recorded at site RD-45, (3) the simultaneous appearance of reefs of late Campanian to early-middle Maestrichtian age from near DSDP site 165 to the site of RD-45, and (4) the irregular subsidence history of at least parts of the Line chain.

Further, as shown on Figure 6, the trace of a single hot spot which may have caused the progressive volcanism along the chain at a plate motion rate of 9.6 ± 0.4 cm/yr does not account for the ages of volcanism seen at DSDP sites 165, 315, and 316 and at sites RD-44 and RD-45.

If we adhere to the generally accepted idea that significant volcanism in the oceanic basins is due to hot spots, leaky transform faults, or activity at ridge crests and we do not, for the Line chain, accept ridge crest or transform fault associated volcanism as a major factor, then we are drawn, ineluctably, to the hot spot mechanism to account for the chain. Our data can be interpreted to show that two hot spots traversed the present chain. However, both of these would have had to follow parallel paths with a time interval of from 10 to 20 m.y. between them. One would expect that a second hot spot passing so closely along an earlier hot spot trace would have produced a more morphologically coherent chain with many more atolls than we now see in the Line chain. The geotectonic imagery map of W. Haxby [see *Francheteau*, 1983] certainly indicates that many possible hot spot traces pass into the Line chain, at least one of which coincides with the hot spot track between the Line chain and the Marquesas as proposed by *Crough and Jarrard* [1981]. *Henderson and Gordon* [1982] propose that four hot spots formed the Line chain, although their model does not account for many of the dated edifices in the chain.

Before completely accepting the efficacy of multiple hot spot models in explaining individual island chains we wish to emphasize that complex volcanic chronologies are not restricted to the Line chain but characterize the entire Pacific Basin from the Line Islands to the western subduction zone boundaries of the present Pacific plate [*Schlanger and Premoli-Silva*, 1981; *Schlanger et al.*, 1981; *Haggerty*, 1982; *Haggerty et al.*, 1982]. Both Cretaceous and Eocene volcanism blanketed this western part of the Pacific Basin; Cretaceous volcanism took place over a vast area between ~110 and ~70 Ma [*Watts et al.*, 1980; *Menard*, 1964; *Larson and Schlanger*, 1981; *Rea and Vallier*, 1983]. Indeed, mid-Cretaceous volcanism is a global phenomenon [*Schlanger et al.*, 1981]. We propose that a mechanism exists that would allow the surface expression of coeval volcanism over wider areas than that allowed for in necessarily laterally restricted hot spot models.

Acknowledgments. This research was supported by the Office of Naval Research. We especially thank the captain and crew of the R/V *Kana Keoki* for their efforts during three cruises of the ship in atoll-studded waters. The government of the Republic of Kiribati kindly allowed us to conduct research in their territorial waters. Also we appreciate the help and hospitality of the people of Fanning Island while R/V *Kana Keoki* lay disabled off the island. Discussions on the geology of linear island chains with R. Gordon and L. Henderson were enlightening and helpful. R. Gordon kindly reviewed the manuscript. Over the past decade, as a shipmate on cruises to the Line Islands and in the course of many fruitful discussions, E. L. Winterer has contributed greatly to our efforts. Analyses of reefal faunas in the Line Islands province by I. Premoli-Silva showed the extent of Cretaceous reef growth. We thank J. Morgan and R. Jarrard for critical reviews and helpful suggestions for the improvement of the original manuscript. Hawaii Institute of Geophysics contribution 1486.

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(Received January 5, 1984;
revised May 2, 1984;
accepted May 25, 1984.)