PETROLOGY, GEOCHEMISTRY, AND AGES OF VOLCANIC ROCKS FROM THE LINE ISLANDS, CENTRAL PACIFIC OCEAN

A THESIS SUBMITTED TO THE GRADUATE DIVISION OF THE
UNIVERSITY OF HAWAII IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

IN GEOLOGY AND GEOPHYSICS

DECEMBER 1986

By

Geoffrey Trevor Davis

Thesis Committee:

Michael O. Garcia, Chairman
John A. Philpotts
John M. Sinton

PETROLOGY, GEOCHEMISTRY, AND AGES OF VOLCANIC ROCKS FROM THE LINE ISLANDS, CENTRAL PACIFIC OCEAN

A THESIS SUBMITTED TO THE GRADUATE DIVISION OF THE
UNIVERSITY OF HAWAII IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

IN GEOLOGY AND GEOPHYSICS

DECEMBER 1986

By

Geoffrey Trevor Davis

Thesis Committee:

Michael O. Garcia, Chairman
John A. Philpotts
John M. Sinton

We certify that we have read this thesis and that, in our opinion, it is satisfactory in scope and quality as a thesis for the degree of Master of Science in Geology and Geophysics.

THESIS COMMITTEE

Michael O Garcia
Chairman

John A. Philpotts

John M. Sinton

ABSTRACT

The Line Islands chain is a major linear volcanic feature on the Pacific plate which, when combined with the Tuamotu Archipelago and the Gambier Islands, extends for over 6000 km from the Mid-Pacific Mountains southeast to Pitcairn Island, a recently active volcanic island. Comparison of the hot-spot origin for the Hawaii-Emperor chain to the origin for the Line-Tuamotu chain has been tentative, primarily due to the lack of sufficient petrologic and age data over the entirety of the chain. Three research cruises undertaken by the University of Hawaii R/V Kana Keoki in 1979 dredged and piston-cored volcanic rocks, volcanoclastic breccias, and reefal debris from along the entire chain, including one dredge in the northwestern Tuamotu Archipelago. Petrologic, geochemical, and age data are presented to characterize volcanism along the chain and to evaluate the hot-spot and other models for the origin of the Line Islands.

A variety of alkali basalts, alkali olivine basalts, and hawaiites, much like Hawaiian alkalic suite lavas, were recovered in nineteen rock dredges and one piston core. The rocks are slightly to moderately altered. Interstitial glass is replaced by smectite-group clays and olivine is completely replaced by iddingsite. The common phenocryst phases in the alkali basalts are replaced-olivine, plagioclase, and titaniferous augite, which are enclosed in a hypocrystalline to hypohyaline texture. The hawaiites are subtrachytic to intersertal in texture. Some contain either plagioclase or amphibole phenocrysts.

Whole rock chemical analyses, variably modified by seawater alteration, are similar to alkali basalt suite lavas of Hawaii. Microprobe analyses of fresh groundmass clinopyroxenes indicate they have high Ca, Al, Ti, and Na, confirming the alkalic nature of the original lavas. Nine Line Islands samples analyzed for rare-earth elements are all light rare-earth element enriched, typical of ocean island alkali basalts.

$^{40}Ar/^{39}Ar$ total fusion ages of volcanic rocks acquired during this study compare favorably with published radiometric and biostratigraphic age data along the chain. K-Ar ages determined are consistently younger than the total fusion ages due to basalt-seawater alteration and are considered unreliable. Volcanism has occurred along the chain from 93.4 my to 44-50 my. The bulk of available ages fit a 9.6 cm/yr rate of migration of hot-spot volcanism. However, both middle to late Cretaceous and early Tertiary ages are reported from along the entirety of the chain, with one seamount in the southern region exhibiting volcanism of both ages. No single hot-spot model of origin explains this age discrepancy, nor does the volcanism appear to be mid-ocean ridge, 'leaky' transform fault, or propagating fracture related. Although the volcanic rocks described in this and previous studies indicate petrologic and geochemical similarities between the Line and Hawaiian Islands, the widespread occurrence of Cretaceous through early Tertiary volcanism along the entirety of the chain indicates a more complex volcanic history for the origin of the Line Islands, not unlike that noted for many other Pacific plate volcanic provinces.

ACKNOWLEDGEMENTS

The cooperation and help of the captains and crew of the University of Hawaii research vessel Kana Keoki made possible the collection of data and samples for this study. Gratitude is also extended to the Republic of Kiribati, Ministry of the Line and Phoenix Groups, for permission to conduct research within their territorial waters.

Financial support for this study provided through the Hawaii Institute of Geophysics by the Office of Naval Research (Contract ONR N00014-75-C-0209), Dr. Michael O. Garcia and Dr. John A. Philpotts, co-investigators, is gratefully acknowledged.

The support and guidance of my committee, especially Dr. Michael O. Garcia, was greatly appreciated. Thanks are further extended to David M. Christie, William W. Sager, and Janet A. Haggerty for their thoughtful review and assistance in the preparation of this thesis.

Lastly, and most importantly, I wish to thank my wife, Ellen, for her encouragement and my parents, Wyn and Frank, for their unending confidence and support in all my life's endeavors.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (cont'd)

PREFACE

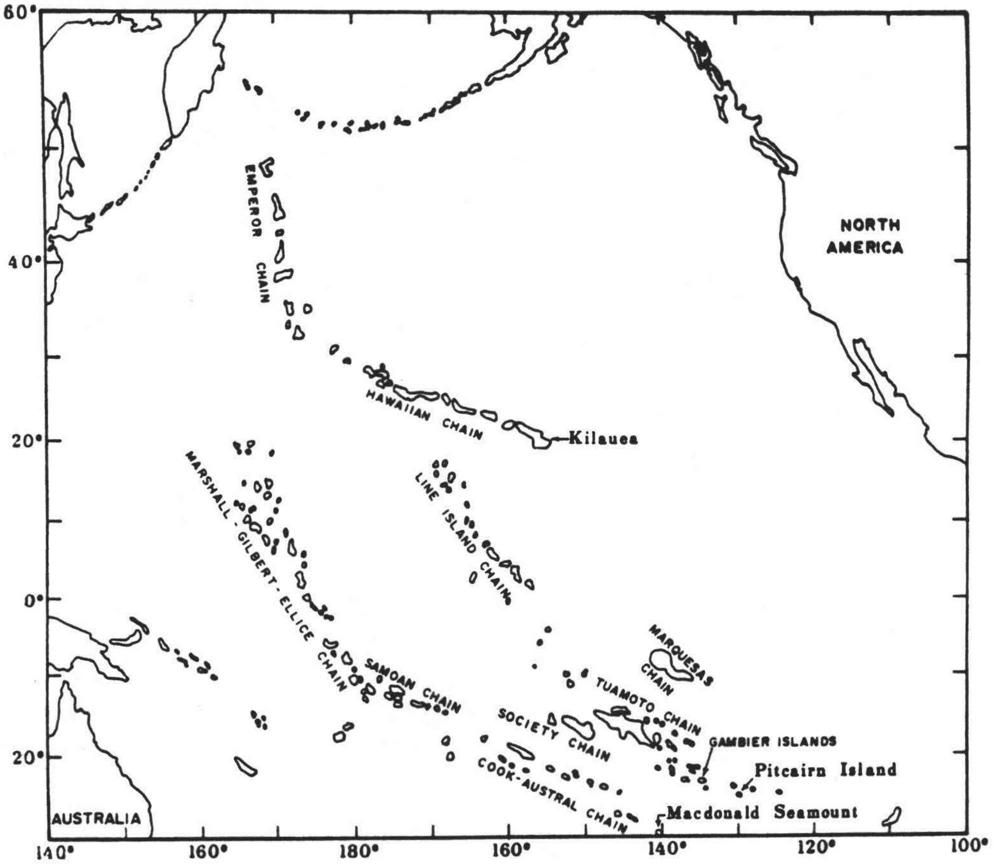
The written portion of this thesis was completed and approved in December 1986. The oral defense, however, was successfully completed in September, 1981. In the interim, several pertinent articles have been published on ocean island petrology, geochronology, and Pacific plate tectonics, including the research results of two doctoral candidates and co-investigators on the Line Islands Project at the University of Hawaii. With the permission of my committee, this thesis includes references to only those publications that resulted from research on samples and data collected during the same 1979 research cruises reported on in this study.

INTRODUCTION

The origin of linear volcanic chains in the Pacific Ocean, such as the Line-Tuamotu, Hawaii-Emperor, and Austral-Marshall chains, has been the focus of numerous geological and geophysical investigations since the early 1960's (Wilson, 1963a, 1963b; Morgan, 1971, 1972a, 1972b; Jackson, 1976; Sutton et al., 1976; Jarrard and Clague, 1977; Jackson et al., 1980). Aside from the spreading ridges from which the plates themselves are formed, these chains represent the major bathymetric expressions of volcanism on the Pacific plate. The recognition of their extent and magnitude calls attention to the large-scale processes inherent in their formation (FIGURE 1).

The Line-Tuamotu chain, including the Gambier Islands, is a nearly continuous chain of elongate ridges, seamounts, atolls, and a few volcanic islands extending for over 6000 km from Pitcairn Island northwest to Horizon Guyot near the Mid-Pacific Mountains. A bend in this chain of approximately 30^{o} from west to northwest separates the Line Islands to the northwest from the Tuamotu Archipelago. The Hawaii-Emperor chain is a linear chain of volcanic islands, atolls, and seamounts extending for nearly 6600 km from the Island of Hawaii northwest to Meiji Seamount near the Aleutian Trench. A bend in this chain of approximately 32^{o} separates the Emperor Seamounts to the northwest from the Hawaiian Ridge. The Austral-Marshall chain is a nearly continuous, 8600 km long, semi-linear chain of island groups including, from northwest to southeast, the Marshall, Gilbert, Ellice,

FIGURE 1. Generalized Mercator projection of major linear volcanic chains on the Pacific plate. Kilauea volcano and Macdonald seamount are currently active; Pitcairn Island has been dated at less than 1 my old (Duncan et al., 1974). Modified from Jackson, 1976.


60°
40°
20°
0°
20°
NORTH AMERICA
EMPEROR CHAIN
HAWAIIAN CHAIN
Kilauea
LINE ISLAND CHAIN
MARSHALL-GILBERT-ELLICE CHAIN
SAMOAN CHAIN
MARQUESAS CHAIN
TUAMOTO CHAIN
SOCIETY CHAIN
GAMBIER ISLANDS
Pitcairn Island
COOK-AUSTRAL CHAIN
Macdonald Seamount
AUSTRALIA
140°
160°
180°
160°
140°
120°
100°

Cook, and Austral Islands. Although broader and more discontinuous than either the Line-Tuamotu or Hawaii-Emperor chains, this belt of volcanic islands, atolls, and seamounts also bends conspicuously to the northwest at the southern end of the Ellice Islands. The Line-Tuamotu chain ends at Pitcairn Island, which has been dated at less than 1 my old (Duncan et al., 1974). The Hawaii-Emperor and Austral-Marshall chains end at active volcanic centers, the Mauna Loa, Kilauea, and Loihi volcanoes on the island of Hawaii and Macdonald Seamount, respectively.

Origins Of Linear Volcanic Chains

Several models have been proposed for the origin of linear volcanic chains. The Wilson-Morgan 'hot-spot' hypothesis proposed by Wilson (1963a, 1963b) and later modified by Morgan (1971, 1972a, 1972b) asserts that Pacific linear volcanic chains result from the passing of the Pacific Plate over relatively-fixed, deep-mantle melting anomalies or hot-spots. Dalrymple et al. (1974) proposed two corollaries to the hot-spot hypothesis: lavas from different volcanic centers along the chain should be petrographically and geochemically similar and the ages for volcanoes along the chain should increase in a direction parallel to plate motion away from the most active volcanic center.

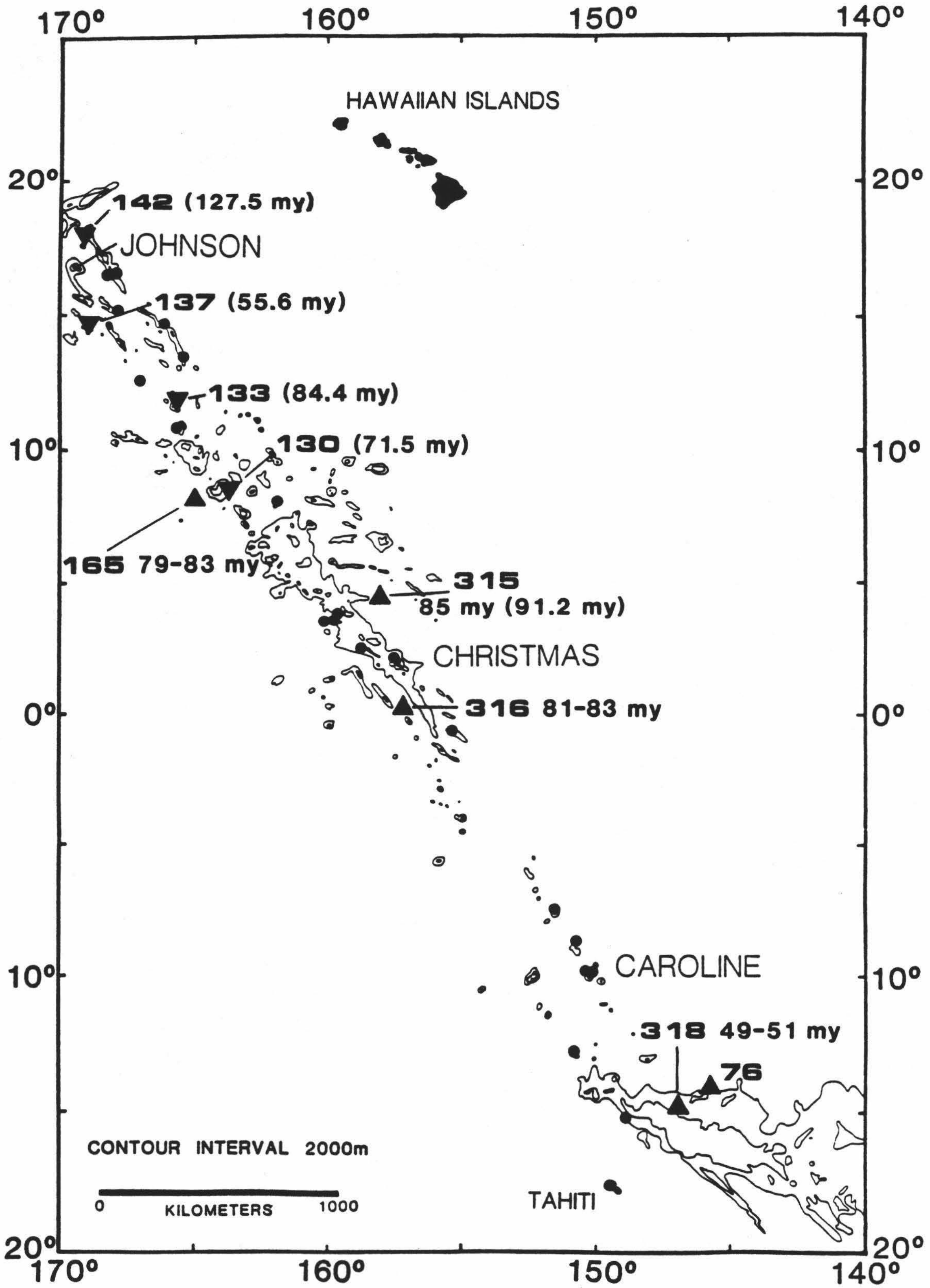
Several mechanisms for the origin of hot-spots have been suggested. Shaw (1973) proposed that the melting anomaly in the mantle was due to counterflow shear between the lithosphere and the asthenosphere as a result of asthenospheric convection, which provides thermal feedback to the heat source. This melting anomaly may remain fixed in the mantle by the gravitational downwelling of melt residuum (the gravitational anchor of Shaw and Jackson, 1973). Anderson (1975) described the melting anomaly as a chemical plume in the mantle resulting from original chemical inhomogeneities in the Earth.

In addition to the hot-spot hypothesis, the propagating fracture model provides another source of origin for linear volcanic chains. Initially introduced by Betz and Hess (1942) as tensional cracking of the ocean floor, the propagating fracture model proposes that linear volcanic chains form as fresh mantle material is extruded through a tensional fracture in the lithosphere (Jackson and Wright, 1970). Green (1971) and Turcotte and Oxburgh (1973) proposed that the lithospheric fracturing is caused by tensional stresses resulting from the movement of the Pacific Plate over an imperfect sphere and to changes in the radius of the plate's curvature, respectively. McDougall (1971) proposed that the fracturing and volcanism could result from the counterflow of material back to the East Pacific Rise along a narrow band in the aesthenosphere causing a degree of partial melting in the upper mantle coupled with diapiric upwelling from a thermal high in the low-velocitiy zone. Menard (1973) proposed that plates drifting over a bumpy aesthenosphere cause membrane stresses that may be sufficient to fracture the lithosphere. Anderson and Grew (1977) proposed that the fracturing is a result of stress corrosion due to the intrusion of magmas at elevated temperatures and corrosive action of associated gases with surrounding country rock in the lithosphere.

Models Proposed For The Origin Of The Line Islands Chain

Morgan (1971, 1972a, 1972b) proposed that the Line Islands represent a Pacific hot-spot trace equivalent in time to the Emperor Seamounts and the Marshall-Gilbert-Ellice chain. Morgan (1972b) noted that the azimuth of the Line Islands (320^{0}) differs from that of the Emperor Seamounts (348^{0}) and attributed this to slight wander of the mantle plume with time. Clague and Jarrard (1973), however, suggested that the Line Islands formed about a different, older pole of rotation than the Emperor Seamounts. Existing ages for the northern Line Islands indicate they are 5 to 50 my older than the northern Emperor Seamounts. Basement ages based on fossil evidence for the cessation of seamount volcanism at Deep Sea Drilling Project (DSDP) Sites 165, 315, and 316 (FIGURE 2) range from 79-83 my, 85 my, and 81-83 my, respectively (Scientific Staff-Leg 33, 1974) and a K-Ar age for plagiociase separates from a basalt drilled at Site 315A is 91.2 my (Lanphere and Dalrymple, 1976); ^{40}Ar-^{39}Ar ages from dredged rocks along and near the chain range from 55.6-127.5 my (Saito and Ozima, 1976, 1977). Data from DSDP drilling in the northern Emperor Seamounts gives a fossil age for Meiji Seamount (Site 192A) of 72 my (Worsley, 1973; Scholl and Creagar, 1973) and an ^{40}Ar-^{39}Ar age for basalt drilled on Suiko Seamount (Site 433) of 65 my (Dalrymple et al., 1980). Saito and Ozima (1977) used their 127.5 my, 84.4 my, and 71.5 my ages on the main trend to conclude that only the northern part of the Line Islands chain may have a hot-spot origin. Jarrard and Clague (1977) concluded that

FIGURE 2. Summary of previous ages along the Line Islands Chain: location of DSDP Sites 76, 165, 315, 316, and 318 (▲); basement ages based on fossil evidence for Sites 165, 315, and 316; a 'minimum' age for shallow-water sediments intercalated with volcanogenic breccias for Site 318; a K-Ar age, in parentheses, for DSDP Site 315; and four ^{40}Ar-^{39}Ar ages, in parentheses, for Scripps Institution of Oceanography dredges 130, 133, 137, and 142 (▼) from Saito and Ozima (1976, 1977) considered reliable by D. A. Clague (pers. comm., 1981).


170°
160°
150°
140°
HAWAIIAN ISLANDS
20°
142 (127.5 my)
JOHNSON
137 (55.6 my)
133 (84.4 my)
10°
130 (71.5 my)
165 79-83 my
315
85 my (91.2 my)
CHRISTMAS
0°
316 81-83 my
10°
CAROLINE
318 49-51 my
76
CONTOUR INTERVAL 2000m
0 KILOMETERS 1000
TAHITI
20°

the bulk of the radiometric ages for the Line Islands contradict the simple volcanic age progression predicted by the Wilson-Morgan hot-spot hypothosis.

In addition to the trend of the Line Islands having a different azimuth than the Emperor chain, the bend in the Line-Tuamotu chain predates the Hawaii-Emperor bend by 7-12 my. Using an ^{40}Ar-^{39}Ar age of 127.5 my from the northern Line Islands (Saito and Ozima, 1976), a K-Ar age of 91.2 my for DSDP Site 315A (Lanphere and Dalrymple, 1976), and a minimum basement age of 81-83 my for DSDP Site 316 (Scientific Staff-Leg 33, 1974), a very tenuous rate of volcanic progression to the Line-Tuamotu bend would date the bend at 54 my (Jackson and Schlanger, 1976). The bend in the Hawaii-Emperor chain has been dated at 42 my (Dalrymple and Clague, 1976). Middle Eocene ages of 49-51 my for shallow-water sediments intercalated with volcanogenic breccias have been used as 'minimum' ages for the end of seamount volcanism at DSDP Site 318 in the northwestern Tuamotu Archipelago (Scientific Staff-Leg 33, 1974). Also, Solomon et al. (1977) noted that their predicted plate motions for 55 my ago, especially in the Pacific area, do not agree with 'fixed' hot-spots and seamount chain trends and postulated that either substantial relative motion of the roots of the hot-spots in the asthenosphere has occurred or that some seamount chains formed by other than a hot-spot origin. The collective results of these age relations studies indicates that the bend in the Line Islands-Tuamotu Archipelago may be interpreted as more of an intersection of two chains than a bend in this continuous, linear volcanic chain.

Malahoff (1971) noted that, although oceanic crust formation under the Line Islands occurred during the Cretaceous Quiet period, weak magnetic anomalies (<200 gammas) in the central portion of the chain parallel the trend of the chain and proposed that volcanism in the Line Islands occurred along narrow fissures within a 200 km wide rift zone. Considering the nearly coeval ages for the cessation of ocean island volcanism suggested by the DSDP data and noting that the Line Islands trend is approximately parallel to the M-1 anomaly of the Hawaiian magnetic lineations, Winterer (1976a) suggested that "this structural trend had its origin as a spreading ridge along Nova-Canton Trough, about 110 my ago" (in particular, see Figure 2, p.272). Winterer (1976b) further suggested that a Pacific-Farallon spreading ridge jump about 110 my ago left behind a structural weakness through which subsequent mid-plate volcanism occurred. Epp (1978) suggested that more than one mechanism was responsible for the origin of the chain. From a compilation of available ages and the tectonic relationships of Pacific linear volcanic chains, Epp noted that it appeared that volcanic activity followed a pre-existing structural weakness, possibly a residual structure parallel to a former ridge crest. In interpreting an observed free-air gravity anomaly profile across the central Line Islands ridge, Watts et al. (1980) ascribed the formation of the Line Islands to volcanism near the former ridge crest of the Pacific-Farallon plate boundary between 90-120 my ago. Two lines of evidence, however, suggest an origin at other than on or near a spreading ridge for the Line Islands chain.

First, the absence of transform fault offsets and fracture zones normal to the ridge crest, typical of modern and ancient spreading ridges, for a 4300 km long linear feature of ridge crest origin, is unlikely. Second, in petrologic descriptions of volcanic rocks from DSDP Sites 165 (Bass et al., 1973) and 315A and 316 (Jackson et al., 1976), and on dredged volcanic rocks from Line Islands seamounts and ridges (Natland, 1975, 1976a), only rocks of ocean island affinities have been recovered. These include rocks transitional between ocean island tholeiites and alkali basalts, alkali and alkali olivine basalts, hawaiites, mugearites, phonolites, and trachytes. Potassic nephelinites, more typical of continental extensional regimes (Carmichael et al., 1974), were also described by Natland (1975, 1976) from a cross-trend region of seamounts and ridges in the northern part of the chain. The validity of the occurrence of these potassic nephelinites along the Line Islands is discussed in the SUMMARY Chapter. Volcanic rocks exposed along mid-ocean spreading ridges are predominantly oceanic tholeiitic basalts, mostly emplaced by fissure eruptions into and along rift valleys and, to a lesser extent, as intrusions (Melson et al., 1968; Hekinian and Thompson, 1976). However, rare occurrences of alkali basalts have also been reported along the Mid-Atlantic Ridge (Muir and Tilley, 1964; Aumento, 1968; White and Schilling, 1978; Shibata et al., 1979). A weaker line of evidence for an origin at other than a ridge crest may come from the weak occurrence to absence of magnetic anomalies parallel to the chain as reported by Malahoff (1971), a magnetic pattern typical of modern and ancient spreading ridges (Larson and Chase, 1972).

In addition to hot-spot and spreading ridge origins for the chain, two different transform fault models have been proposed. Orwig and Kroenke (1980) proposed that the Line Islands formed coevally about 85 my ago along a transform fault of the Central Pacific Rise spreading ridge system. Farrar and Dixon (1981) proposed that a major transform fault propagated through up to 1700 km of Cretaceous crust on the Pacific plate between 67-40 my ago forming the Line Islands, the Gardner Seamounts, and the Emperor Trough. Active tectonic and volcanic processes in oceanic transform faults are indicated by exposed intrusive gabbroic and peridotitic rocks and fractionated mid-ocean ridge tholeiitic basalts (Thompson and Melson, 1972; Hekinian and Thompson, 1976). Exceedingly rare occurrences of alkali basalts have been reported from three fracture zones: St. Paul's Fracture Zone (Melson et al., 1967; Melson and Thompson, 1973), Romanche Fracture Zone (Bonatti et al., 1971), and Siqueiros Fracture Zone (Batiza et al., 1977). The validity of the Orwig and Kroenke (1980) and Farrar and Dixon (1981) 'leaky transform' origin for the Line Islands may be questioned from several directions. Although active volcanism has occurred along only a few modern transform faults (ie: St. Paul's, Romanche, and Siqueiros), no modern transform faults are of the enormous geographic extent or bathymetric magnitude of the elongate ridges and seamounts in the Line Islands chain. Nor have any erupted predominantly alkaline or more differentiated alkaline volcanic rocks similar to those of the Line Islands. There are no modern analogs of transform fault volcanism to explain the origin of the chain. Also, a 127.5 my age on a northern Line Islands ridge (Saito and Ozima, 1976), and a 55.6 my age on a seamount in a cross-trend lineation just off the main trend (Saito and Ozima, 1977) indicate that volcanism occurred along and near the chain for over 70 my and is not coeval around 85 my or limited to 67-40 my ago.

Four recent publications report the results of research on reefal material, debris-flow conglomerates, seamount magnetic and gravity data, petrologic data, and radiometric age data collected from along the entirety of the Line Islands chain. These samples and data were collected on the same Hawaii Institute of Geophysics Line Islands Project cruises as the volcanic rocks examined in this thesis.

Haggerty et al. (1982) report on the tectonic significance of two Late Cretaceous reef-bearing volcanic edifices, with 70-75 my 'minimum' ages, near Caroline Island in the southern Line Islands (dredges RD-44 and RD-45). These findings extend the known occurrences of Late Cretaceous volcanism in the Line Islands from Horizon Guyot at the southeastern end of the Mid-Pacific Mountains through DSDP Sites 165, 315, and 316 to near Caroline Island, a distance of just over 4000 km. Haggerty et al. (1982) proposed that the apparent synchronicity of Late Cretaceous volcanism argues against a single hot-spot model for the origin of the chain and, therefore, that the Line Islands are not the temporal equivalent of the Emperor Seamounts, as proposed by Morgan (1972a). Further, Haggerty et al. (1982) provide evidence at dredge RD-45 of alkali basalts extruded into unconsolidated middle Eocene sediments (~ 45 my old), indicating that the southern Line Islands have a history of recurrent volcanism, also difficult to reconcile with a single hot-spot. Other occurrences of Cretaceous mid-plate volcanism (Mid-Pacific Mountains, Marshall Islands, Geisha Guyots), some also with recurring volcanism as multiple events (Nauru Basin-Eniwetok area) similar to the southern Line Islands, were cited by Haggerty et al. (1982) as further evidence against single hot-spot models of origin for these features.

Sager et al. (1982) detailed the magnetic modeling and petrology of Nagata Seamount (RD-59 dredge site) in the northern Line Islands. Alkali olivine basalts, amphibole-phyric alkali basalts, and hyaloclastite breccias were dredged from the western flank of the seamount. K-Ar ages for samples 59-7 and 59-13 clustered around 86 my, in close agreement with a $^{40}Ar/^{39}Ar$ age of 85 my determined from RD-59 samples. A younger K-Ar age for sample 59-2 of 70 my was attributed to basalt-seawater alteration effects which lower the K-Ar ages. The virtual magnetic pole (VGP) determined for Nagata Seamount at 61.6°N, 4.0°E was also consistent with a Middle to Late Cretaceous age of seamount formation.

Sager and Keating (1984) report the results of seamount magnetic anomaly studies on eight Line Islands seamounts to determine paleomagnetic pole positions. Four seamounts gave paleomagnetic pole positions consistent with other Pacific plate Cretaceous pole positions. Radiometric ages of volcanic rocks dredged from three of these seamounts ranged from 72-85 my. Sager and Keating (1984) also point out the apparent inadequacy of a single hot-spot to explain Cretaceous volcanism along the entirety of the chain. The other four seamounts, grouped from 8^{o}N to 3^{o}S along the central portion of the chain, gave geomagnetic pole positions consistent with other Pacific plate Eocene-Early Oligocene pole positions. A radiometric age from one of these seamounts was 39 my. Sager and Keating (1984) suggest that the Eocene volcanic event in the Line Islands was contemporaneous with the change in Pacific plate motion recorded at 43 my ago by the bend in the Hawaii-Emperor chain and that resurgent Tertiary volcanism occurred along a zone of lithospheric weakness caused by the original formation of the chain.

Schlanger et al. (1984) reports the cumulative evaluation of all the data obtained to date from the Line Islands Project cruises. Volcanic rocks recovered from seamount and elongate ridge dredges and piston cores are predominantly alkali basalts and hawaiites, with one tholeiitic basalt and phonolite recovered. Major, trace, and rare-earth element compositions indicate that the volcanic rocks are much more typical of oceanic island alkalic lavas than mid-ocean ridge or fracture zone basalts. Further, microprobe analyses of groundmass clinopyroxenes in the alkali basalts indicate that they are of alkaline to peralkaline affinity (high TiO_2 and Al_2O_3). $^{40}Ar/^{39}Ar$ and K-Ar radiometric ages and paleontological age determinations from these dredges and previous DSDP Sites and Scripps Institiution of Oceanography (Scripps) dredges indicate a range of mid-Cretaceous to Late Eocene ages for volcanic edifice and elongate ridge volcanism throughout the Line Islands.

Cretaceous volcanism is recorded from Scripps dredge 142-D (127.5 my; Saito and Ozima, 1976, 1977) to dredge RD-45 (70.5 my; Schlanger et al., 1984), a distance of 3600 km. Tertiary volcanism is recorded from Scripps dredge 137-D (55.6 my; Saito and Ozima, 1976, 1977) to dredge RD-45 (middle Eocene; Haggerty et al., 1982).

Schlanger et al. (1984) discuss the tectonic implications of the petrologic and age data in terms of the origin of the chain by the hot-spot model of Morgan (1971, 1972a, 1972b) and by the action of four hot-spots as proposed by Henderson and Gordon (1982) and Duncan (1983). The extent of Cretaceous and Tertiary volcanism along the entirety of the chain argues heavily against a single hot-spot origin. As for a multiple hot-spot origin, Schlanger et al. (1984) recognize that a majority of the age dated edifices may be interpreted as defining an age-progression volcanic trend from 93 my (Scripps dredge 142-D) to 44-50 my (dredge RD-45), supporting an origin by a hot-spot currently active in the vicinity of Easter Island. However, a 9.6 cm/yr plate motion rate calculated over this single hot-spot does not account for the volcanic ages determined a DSDP Sites 165, 315, and 316 and dredges RD-44 and RD-45. Further, three edifices in the northern, cross-trend, and islands portions of the chain (Scripps dredge 137-D, dredge RD-33, and dredge RD-41, respectively) range in age from 60-38 my and may be interpreted to be related to volcanic overprinting by a second hot-spot along the Line-Marquesas Swell (Crough and Jarrard, 1981).

Schlanger et al. (1984) suggest that the age dates available to date along the Line Islands chain fail to support the four hot-spot model of Henderson and Gordon (1982) and Duncan (1983). Further, they propose that the complex mechanism for linear and coeval volcanism along the Line Islands chain in terms of a multiple hot-spot origin, as opposed to a ridge crest or transform fault origin, might be more clearly illuminated by an atoll drilling program to determine edifice building histories, paleolatitudes of seamount formation, and subsidence rates and patterns

Purpose

In 1979, three cruises on the University of Hawaii research vessel Kana Keoki attempted a total of 31 rock dredges and 6 oriented piston cores covering the entire Line Islands Chain and one rock dredge from the northwestern Tuamotu Archipelago. Volcanic rocks were recovered from 19 rock dredges and one piston core. The rocks vary in nature from pillow fragments to massive basalts with vesicularity ranging from 0-50 volume percent. These basalts are slightly to severely altered and are variably oxidized. The vesicles in many samples are lined or filled with clay minerals, carbonate, or phosphate. Most samples are partially manganese-oxide covered.

This study presents new petrologic and geochemical data on these Line Islands volcanic rocks and, utilizing these data, evaluates current hypotheses for the origin of the chain. Submarine basalt alteration generally prevents the classification of original magma types solely by petrography or whole-rock, major element chemistry (Hart et al.,

1974). Several trace elements, including the rare-earths, are believed to remain relatively immobile during sea water alteration and may provide an indication of both original magma type and tectonic setting (Philpotts et al., 1969; Thompson, 1973; Hart et al., 1974). According to Hekinian and Thompson (1976), hot-spot volcanic rocks may be chemically distinguished from basalts erupted along mid-ocean ridges and transform faults on the basis of TiO_2, total iron, Cr, and Ni contents. In addition, the chemical composition of clinopyroxene phenocrysts and matrix grains have been used to distinguish original magma types for a number of geologic environs (Kushiro, 1960; LeBas, 1962; Vallance, 1974; Fodor et al., 1975; Garcia, 1975).

The specific objectives of this thesis are twofold:

1) to present new petrographic, whole rock and mineral composition, and age data for volcanic rocks recovered from the Line Islands chain and Tuamotu Archipelago and

2) to characterize volcanism along the Line Islands chain and evaluate the models proposed for the origin of the chain.

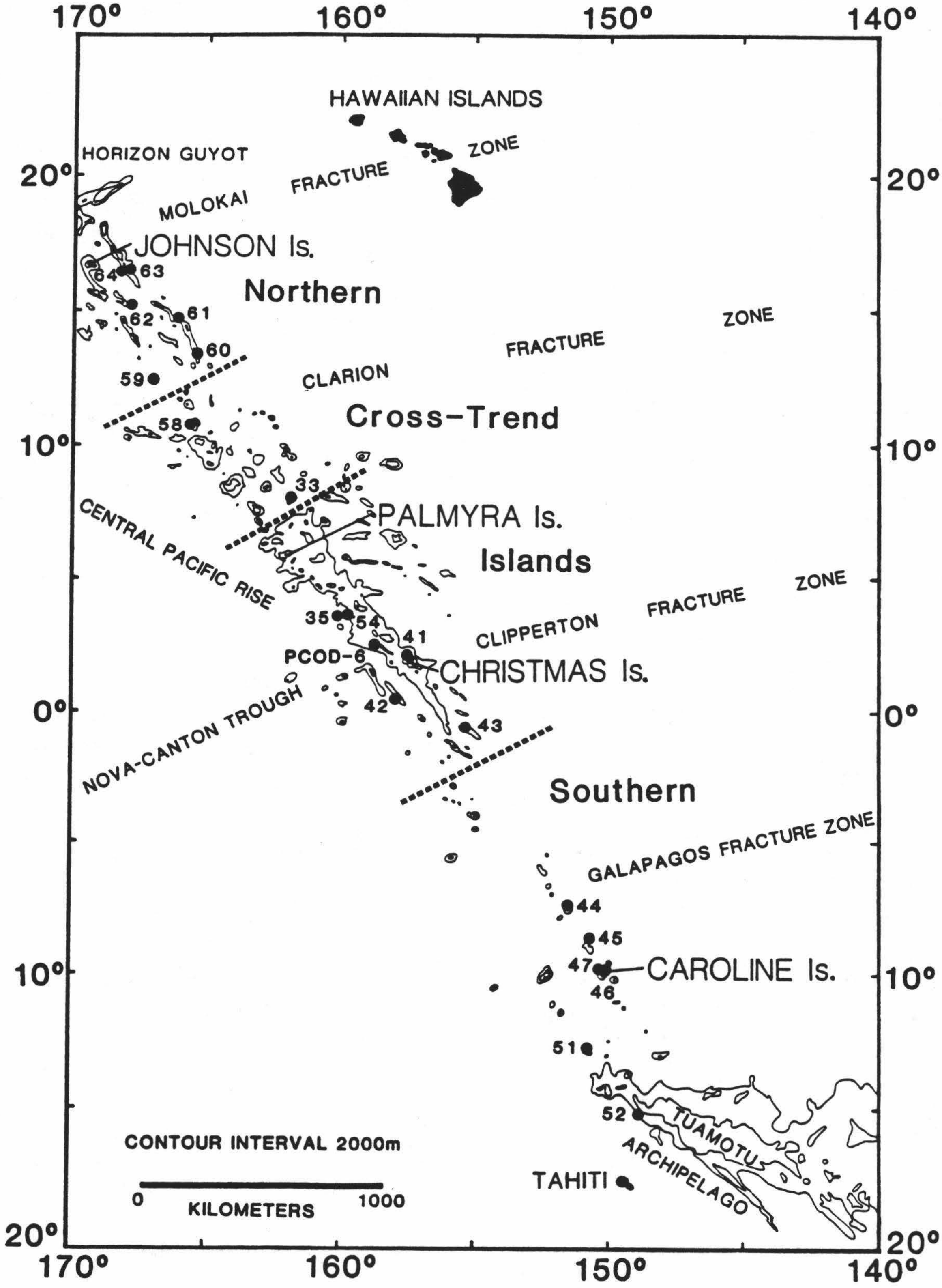
REGIONAL GEOLOGIC SETTING

Chain Morphology

The Line Islands are a morphologically complex linear chain of elongate ridges, seamounts, and atolls stretching for over 4300 km across the central Pacific basin (FIGURE 3). Trending approximately 320^o , the chain extends from Horizon Guyot southeast to the Tuamotu Archipelago. The gross morphology of the chain varies along its length and can be subdivided into roughly four geographic regions: northern, cross-trend, islands, and southern. Winterer (1976b) has previously described the bathymetry of the northern, cross-trend, and islands portions of the Line Islands (Winterer's Northern, Central, and Islands Provinces).

The northern region extends from Horizon Guyot to about 13^oN and consists of en echelon ridges aligned parallel to the trend of the chain. Long, narrow, straight to slightly arcuate ridges on the eastern side and shorter sub-parallel ridges in a broad zone 150-200 km wide to the west characterize the en echelon structure. These ridges vary in length from less than 100 km to nearly 400 km and are generally less than 100 km wide. They rise above a sea floor about 5000-5500 m deep to narrow summits 1500-2000 m below sea level. Johnson Island, the only island in this region, is a coral atoll at the northern extension of a ridge on the western side of the chain. Compared to about 300 m of sediments on the ocean floor on either side of the northern region, the

FIGURE 3. Map showing the Line Islands Chain and its relationship to nearby Pacific plate structural features. Dredge sites from which volcanic rocks were recovered and are discussed in this study are indicated. Dashed lines separate northern, cross-trend, islands, and southern regions. Modified from base chart printed in Deep Sea Drilling Project, v. 33, 1976.

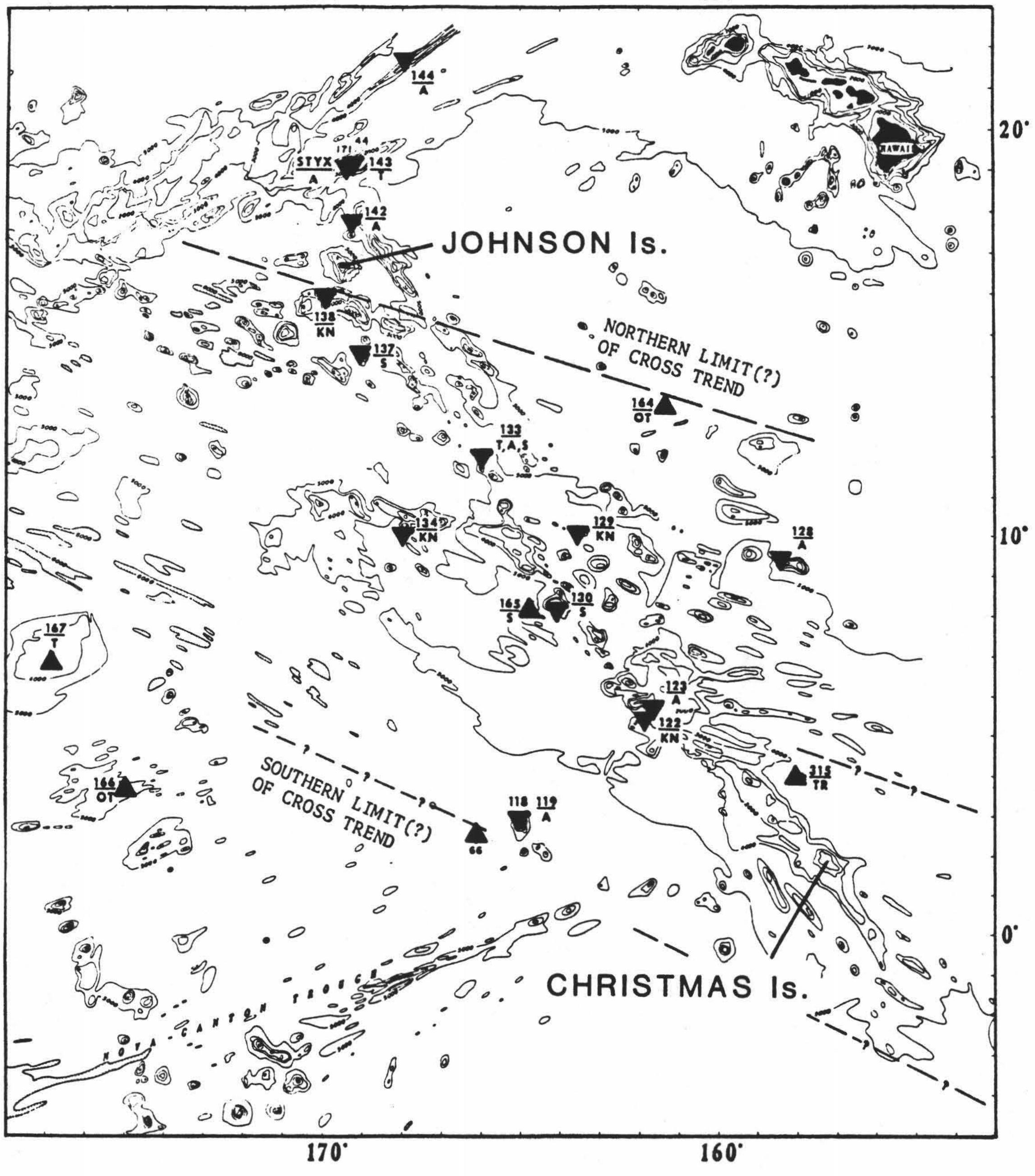

170°
160°
150°
140°
HAWAIIAN ISLANDS
HORIZON GUYOT
MOLOKAI FRACTURE ZONE
20°
JOHNSON Is.
64
63
Northern
62
61
60
59
CLARION FRACTURE ZONE
58
Cross-Trend
10°
33
PALMYRA Is.
CENTRAL PACIFIC RISE
Islands
35
54
41
CLIPPERTON FRACTURE ZONE
PCOD-6
CHRISTMAS Is.
42
NOVA-CANTON TROUGH
43
0°
Southern
GALAPAGOS FRACTURE ZONE
44
45
47
CAROLINE Is.
46
51
52
TUAMOTU ARCHIPELAGO
TAHITI
CONTOUR INTERVAL 2000m
0
KILOMETERS
1000

valleys between these ridges are filled with up to 700 m of sediments, suggesting extensive turbidite deposits of shallow-water origin (Winterer, 1976b).

The cross-trend region extends from 13^{o}N to Kingman Reef at $6^{o}30'$N. The bathymetric expression of the Line Islands in this region changes from elongate ridges to variably-sized, isolated seamounts. Most of these seamounts rise to within 1000-1500 m of sea level, a few rise to within 700 m. They are generally 40-60 km in diameter, but may exceed 100 km across. The seamounts in the cross-trend region are also aligned in roughly en echelon rows parallel to the main trend, possibly up to five rows in a broad band over 400 km wide (Winterer, 1976b).

Two sets of WNW-trending bands of ridges and seamounts intersect the main trend of the chain from the northwest; one at 15^{o}-16^{o}N marking the northern boundary of the cross-trend region and one at 9^{o}-10^{o}N (FIGURE 4). A third, less continous cross-trend lineation intersects the western Line Islands at 0^{o}-1^{o}N, also from the northwest, and marks the southernmost lineation to intersect the chain. Neither the 15^{o}-16^{o}N or the 0^{o}-1^{o}N cross-trend lineations can be traced through the main trend of the chain and both extend to the northwest for up to 800 km. The 15^{o}-16^{o}N lineation does not appear to alter the shapes or trends of the elongate ridges in the northern region, but this intersection forms the boundary between the northern and cross-trend regions. The 9^{o}-10^{o}N lineations can be traced across the Line Islands to the southeast for nearly 800 km and to the northwest for at least 500 km, but may possibly extend for an additional 2200 km to the northwest (Winterer, 1976b).

FIGURE 4. Map of the Central Basin of the Pacific showing the limits of the cross-trend region proposed by Natland, 1976a. Locations of DSDP drill sites (▲) and Scripps Institution of Oceanography 7 TOW Leg 6 and Aries Leg 5 dredge sites (▼) indicated and lava types labeled. OT = oceanic tholeiitic basalt; TR = island edifice transitional basalts; T = tholeiitic basalts; A = alkalic series lavas; S = strongly alkalic series lavas; KN = potassic nephlenite. Modified from Natland, 1976a.


170°
160°
20°
10°
0°
144
A
HAWAII
STYX
A
171 44
143
T
142
A
JOHNSON Is.
138
KN
137
S
NORTHERN LIMIT(?) OF CROSS TREND
164
OT
133
T,A,S
134
KN
129
KN
128
A
165
S
130
S
167
T
123
A
122
KN
315
TR
166
OT
SOUTHERN LIMIT(?) OF CROSS TREND
118
119
A
66
CHRISTMAS Is.
NOVA-CANTON TROUGH
170°
160°

Seamounts on the eastern side of this lineation in the vicinity of 8^{o}-10^{o}N and 159^{o}-161^{o}W are elongated parallel to the cross-trend rather than the main trend. The shapes and trends of seamounts in the main trend at the intersection of this cross-trend lineation also do not appear to be affected by the intersection. Ridges in the central and eastern side of the main trend in the vicinity of the 0^{o}-1^{o}N intersection are elongated parallel to the cross-trend lineation, while ridges on the western side are parallel to the main trend.

The Islands region extends from Kingman Reef to about 2^{o}S and includes the coral atolls of Palmyra, Washington, Fanning, and Christmas Islands. The expression of the chain changes from rows of isolated seamounts to a 150-200 km wide band of atolls and smaller seamounts with a thick apron of sediments between the peaks. This broad, continuous plateau of a thick sediment apron is everywhere shallower than 3500 m and is within 300 m of sea level between Kingman Reef and Christmas Island. DSDP Site 315A, 93 km east of Fanning Island in 4150 m of water, penetrated nearly 100 m of volcanoclastic sands and silts and ferruginous clays before reaching basement lavas (Shipboard Scientific Party-Leg 33, 1976). Site 316, 210 km south of Christmas Island in 4450 m of water, penetrated 837 m of volcanogenic sands, breccias, and nannofossil oozes without reaching basement (Shipboard Scientific Party-Leg 33, 1976). The en echelon structure of elongate ridges and seamount rows in the northern and cross-trend regions becomes more diffuse in this region, partly because of the extensive sediment cover and partly because both sides of the chain become less continuous and more widely spaced (especially between 2^{o}-5^{o}N). Narrow elongate ridges replace the main trend seamounts and atolls south of Christmas Island on the western side and south of the equator on the eastern side and end about 2^{o}S. The ridges are up to 170 km long, 60 km wide, and have average elevations of 1500-2000 m below sea level. A broad arch, above abyssal depths (approximately 6150 m) to about 4000 m water depth, intersects the main trend from the northwest just south of Palmyra Island and trends roughly parallel to the cross-trends. Orwig and Kroenke (1980) have named this broad rise, traceable for over 800 km to the northwest, the Central Pacific Rise (note FIGURE 3). The lineation of the Central Pacific Rise does not affect the Line Islands trend or appear to carry through to the eastern side.

The southern region stretches for over 1300 km between the elongate ridges at 2^{o}S and the Tuamotu Archipelago at about 13^{o}S. A few, isolated, widely spaced seamounts and coral atolls, including Malden, Vostok, Flint, and Caroline Islands, occur in two rows about 200 km apart and further delineate the main trend. A possible third row, including Starbuck Island and a very few seamounts, parallels these two rows 200 km off to the west. Long gaps in the eastern and western rows of seamounts and atolls, upwards of 450 km in the east and 600 km in the west, mark extensive discontinuities in the chain. Two ship tracks during this study confirmed the discontinuous nature of the eastern row between 2^{o}-5^{o}S. The western rows remain poorly surveyed.

Five flat-topped seamounts and ridges in the cross-trend and islands regions were previously surveyed and dredged (Natland et al., 1972; Natland, 1976b). Although the dredge stations were on the upper flanks of these features, evidence for an erosional or reef-building history, such as beach or stream deposits and coral, was markedly absent. Only manganese-oxide encrusted volcanic rocks (aquagene tuffs) and foraminiferal sands were recovered. The dredged materials and bathymetry of these features suggest that submarine caldera collapse shaped these volcanoes, either during post-subsidence volcanism or as entirely submarine volcanism (Natland, 1976b).

Regional Setting

The Line Islands appear to lie on oceanic crust which displays no linear magnetic anomalies (Larson and Chase, 1972). DSDP Legs 17 and 33 failed to drill into mid-ocean ridge tholeiites, so the age of the crust could not be determined. The Phoenix magnetic lineations to the southwest (Larson et al., 1972) and the Hawaiian magnetic lineations to the northwest (Larson and Chase, 1972) have been used by Jackson and Schlanger (1976) to estimate the youngest age of the crust in the Line Islands to be between 110-130 my. Baldwin et al. (1974) estimated the age of the Phoenix M-1 anomaly off to the southwest of the Line Islands Chain to be 119-127 my. The Line Islands terminate and, possibly ,cut across the Nova-Canton Trough, which intersects from the southwest at about 3°N. The Phoenix magnetic lineations north of and roughly parallel to the Nova-Canton Trough are traceable east to the Line Islands, but are unrecognizable on the eastern side of the chain

(Winterer, 1976b). Winterer (1976b) suggested that either the underlying crust was formed during a Middle to Late Cretaceous magnetic quiet period or that the ocean crust magnetic patterns were obscured by later volcanic activity.

In addition to the cross-trend lineations, the Central Pacific Rise, the Nova-Canton Trough, and four East Pacific Rise fracture zones (the Molokai, Clarion, Clipperton, and Galapagos Fracture Zones) intersect the Line Islands chain. The fracture zones all intersect at oblique angles from the east, become more diffuse to the west and truncated (?) at their intersection with the chain. They do not appear to have influenced the trend or bathymetric expression of the Line Islands chain.

Previous Petrologic Work

Previous studies of volcanic rocks from the Line Islands chain involve samples recovered during DSDP Legs 17 and 33 and from rock dredges from Scripps Institution of Oceanography Expedition 7-TOW, Leg 6. Reviews of the geophysical studies and tectonic considerations for the Line Islands region were presented in the INTRODUCTION. Bass et al. (1973) described volcanic rocks recovered from DSDP Site 165 as differentiated flows or shallow sill intrusions of hawaiite, possibly one mugearite, and amphibole-bearing volcanic rocks resembling Hawaiian post-erosional basanites and nephelinites. Bass et al. (1973) concluded that these ocean island volcanic rocks were unlikely to be flows from mid-ocean ridge eruptions and suggested that the lavas cored at Site 165 may be direct sill intrusions from the mantle.

Jackson et al. (1976) described six distinguishable flow units of basalts transitional between Hawaiian tholeiites and alkalic lavas from Site 315A. These volcanics were believed to be related to the Fanning Island edifice 93 km to the west. A combination of trace, rare-earth, and pyroxene mineral composition data from Site 315A were used by Jackson et al. (1976) to infer that the Line Islands are comprised of basalts similar to those of the Hawaiian Islands. Jackson et al. (1976) also described basalt clasts in volcanoclastic breccia beds with weak affinities to ocean island alkali basalts from Site 316.

Natland (1975, 1976a) studied volcanic rocks dredged from seamounts and ridges in the northern, cross-trend, and islands regions of the Line Islands chain during Scripps Expedition 7-TOW, Leg 6. Based on whole rock chemical analyses and petrography, these samples are a diverse mixture of basalts transitional between tholeiitic and alkali basalts, and alkali basalts, hawaiites, mugearites, trachytes, and phonolites. Natland concluded that these volcanics are dominantly ocean island tholeiitic to strongly alkalic in character, precluding a typical spreading ridge crest or abandoned ridge crest origin for the chain. Further, rocks described by Natland as potassic nephelinites, previously undescribed in ocean basins, were recovered in four widely separated dredges (122, 129, 134, and 138), including amphibole and biotite-bearing samples. These volcanics appear to be restricted to the cross-trend region. Natland noted their similarity to potassic mafic lavas of the East African Rift and suggested that they also formed in an area of slow, extensional tectonics. Xenoliths in these lavas contain brown amphibole or biotite with clinopyroxene. Natland suggested that these xenoliths were derived from a shallower source (<20 Kb) than were the aluminous orthopyroxene or garnet-bearing xenoliths found in SiO_2-undersaturated Hawaiian lavas (Jackson and Wright, 1970). Again, the validity of the occurrence of these potassic nephelinites is discussed further in the SUMMARY Chapter.

^{40}Ar-^{39}Ar age determinations were performed on samples previously analyzed by Natland (1975, 1976a) and on samples from DSDP Sites 66 and 165 (Saito and Ozima, 1976, 1977). The ages of Line Islands chain samples range from 55-128 my for the 10 samples analyzed. D. A. Clague (pers. comm., 1981) reviewed the analyses, in particular, the ^{40}Ar-^{39}Ar y-intercept from the isochron diagrams used to calculate the ages presented. Several samples intercept at significantly higher values than the atmospheric ratio of 295.5, leaving the determined isochron ages in question. Clague considered three averaged ages of 55.6 my for plagioclase mineral separates from sample 137D (an aegerine phonolite from a cross-trend seamount) to be very reliable. Clague also considered main trend ages for sample 142D (mugearite) of 127.5 my and for sample 133D (alkali olivine basalt) of 84.4 my to be reliable. However, the 71.5 my age for sample 130D (alkali basalt) may be reliable, according to Clague (note FIGURE 2). Other ages for Line Islands samples were considered by Saito and Ozima (1977) and Clague (1981, pers. comm.) to be less reliable.

Strontium isotopic ratios were determined by Matsuda (1980) on many of the same Scripps' dredge samples analyzed by Saito and Ozima and for samples from DSDP Sites 165 and 315A. Matsuda (1980) reported up to three $^{87}Sr/^{86}Sr$ ratios for several samples: the measured value, the calculated initial value, and a value after a 6 Normal HCl acid leach treatment (removing altered plagioclase and olivine). Initial $^{87}Sr/^{86}Sr$ ratios for samples 142D (mugearite) and 130D (alkali basalt) along the chain's main trend were 0.7028 and 0.7033, respectively, with both HCl leach ratios at 0.7031. The initial ratio of an alkali basalt from DSDP Site 165 was 0.7038, with an HCL leach ratio of 0.7033. Two cross-trend region alkali basalts, samples 128D and 129D, had initial ratios of 0.7034 and 0.7035 and HCl leach ratios of 0.7030 and 0.7036, respectively. Both the DSDP Site 165 alkali basalt and the cross-trend lavas had ratios similar to the main trend lavas and to the observed $^{87}Sr/^{86}Sr$ ratio range of 0.7029-0.7039 in Hawaii-Emperor chain alkali basalts (Lanphere et al., 1980). However, two phonolite samples from dredge 137D, also on the main trend, had higher initial and HCl leach ratios, 0.7039-0.7047 and 0.7041-0.7044, respectively, than the other main trend lavas reported. Matsuda (1980) considered these lavas to be from a different magma source since they are younger rocks than the other main trend lavas reported (note ages on FIGURE 2). Further, Matsuda (1980) reported initial ratios of two basalts from DSDP Site 315A of 0.7038-0.7039, similar to other main trend lavas and typical Hawaiian alkali basalts, but noted that the HCl leach ratio for one of the samples dropped to 0.7027, which is more typical of mid-ocean ridge basalts. Matsuda (1980) concluded that the low initial $^{87}Sr/^{86}Sr$ ratio of sample 130D (0.7028) and low HCl leach ratio of a sample from DSDP Site 315A (0.7027) implied that magma sources for many Line Islands and Hawaiian lavas were shallow in the mantle and are low or depleted in K, Rb, and Rb/Sr ratio, hence the low $^{87}Sr/^{86}Sr$ ratios, as the magma source for mid-ocean ridge basalts.

Little information is available for the Tuamotu Archipelago. Drilling at DSDP Sites 76 and 318, both in the northwestern Tuamotu chain (FIGURE 2), failed to reach volcanic basement, but sediments containing basalt pebbles of oceanic island affinity were penetrated at Site 318 (Jackson and Schlanger, 1976). 'Minimum' ages from fossil debris for five western Tuamotu Archipelago localities, including Sites 76 and 318, range from 37.5-53.5 my (Jarrard and Clague, 1977). Two southern atolls, Mururoa and Fangataufa, have been drilled. Mururoa contains an alkali basalt to trachyte differentiated alkaline series with the most recent extrusions being Ne-normative, while more extreme differentiates (D. I. from 50-67) and Ne-normative volcanics are reported from Fangataufa (Demange et al., 1979).

METHODS OF STUDY

Volcanic rocks from the Line Islands were recovered from dredge hauls taken by the University of Hawaii research vessel KANA KEOKI during Hawaii Institute of Geophysics cruises KK79080801 (Leg 1, 1979, Co-Chief Scientists: S. O. Schlanger and B. Keating), KK79080802 (Leg 2, 1979, Chief Scientist: B. Keating), and KK791029 (1979, Chief Scientist: B. Keating). Site locations and major lithologies for nineteen rock dredges and one piston core from which volcanic rocks were recovered appear in TABLE 1.

A representative suite of volcanic rocks from each dredge was selected for petrographic study as determined by hand specimen examination. Two volcanic pebbles from a piston core (PCOD-6) were also selected, on the basis that they were of sufficient size for both petrographic and geochemical analyses.

The freshest volcanic rocks were selected for both chemical analysis and K-Ar dating after careful petrographic examination for alteration. For the geochemical analyses, an attempt was made to analyze each major rock lithology from each dredge. The samples were cut into 0.5 cm thick slabs with a water-lubricated, diamond bit saw and broken into smaller chips (2-3 mm diameter). Most of the altered olivine phenocrysts, inclusions, vesicle linings, and manganese-oxide stained chips were removed by sieving and hand-picking and were rinsed in an ultrasonic bath with deionized-distilled water. The cleaned chips were then dried for 4-6 hours at approximately 90°C, crushed to a fine

TABLE 1

DREDGE SITE LOCATIONS AND VOLCANIC ROCK LITHOLOGIES RECOVERED BY THE R/V KANA KEOKI FROM THE LINE ISLANDS IN 1979

ROCK DREDGE	LAT. LONG.	WATER DEPTH RANGE	FEATURE AND LITHOLOGIES
33	8° 10.9'N 161° 55.1'W	3875-3900m	Ridge; 210 kg of pillow and angular fragments of alkali basalt.
35	3° 31.9'N 160° 14.6'W	2125-2150m	Seamount; 20 g of angular pebbles of hawaiite.
41	2° 05.5'N 157° 20.6'W	1350-1520m	Christmas Island; 40 kg of angular clasts of alkali and alkali olivine basalt in volcanoclastic breccia.
42	0° 32.6'N 157° 53.9'W	1750-1900m	Ridge; 175 kg of angular clasts of alkali olivine basalt in volcanoclastic breccia.
43	0° 42.4'S 155° 17.2'W	2300-3000m	Ridge; 10 kg of angular fragments of alkali olivine basalt.
44	7° 35.3'S 151° 32.6'W	1800-2100m	Seamount; 175 kg of angular fragments of transitional to alkali basalt and hawaiite.
45	9° 03.8'S 150° 41.6'W	1300-1450m	Seamount; 22 kg of angular fragments of alkali olivine basalt.
46	9° 53.1'S 150° 12.1'W	1400-1500m	Caroline Island; 7 kg of angular fragments of amphibole-bearing alkali basalt.
47	9° 53.3'S 150° 09.1'W	2400-2750m	Caroline Island; 4 kg of angular fragments of alkali olivine basalt.
51	12° 52.5'S 150° 45.8'W	3000-3200m	Seamount; 875 kg of pillow fragments of alkali olivine basalt in volcanoclastic breccia.

TABLE I (Continued)

DREDGE SITE LOCATIONS AND VOLCANIC ROCK LITHOLOGIES RECOVERED BY THE R/V KANA KEOKI FROM THE LINE ISLANDS IN 1979

ROCK DREDGE	LAT. LONG.	WATER DEPTH RANGE	FEATURE AND LITHOLOGIES
52	15° 00.8'S 149° 02.3'W	3350- 3400m	Tuamotu Archipelago; 500 kg of pillow fragments of alkali olivine basalt.
54	3° 38.4'N 159° 31.4'W	2800m	Seamount; 90 kg of angular fragments alkali basalt and hawaiite.
58	10° 48.8'N 165° 32.6'W	1150- 1325m	Seamount; one 15 g clast of hawaiite in volcanoclastic breccia.
59	12° 31.0'N 167° 03.3'W	3000- 3750m	Seamount; 440 kg of rounded and angular fragments of alkali olivine basalt, amphibole-bearing alkali basalt, and ankaramite.
60	13° 27.7'N 165° 25.1'W	3850m	Ridge; 220 kg of pillow and angular fragments of alkali basalt.
61	14° 58.9'N 166° 26.9'W	2800m	Ridge; 110 kg of pillow and angular fragments of alkali basalt.
62	15° 09.4'N 168° 06.1'W	2700m	Ridge; 110 kg of angular fragments of alkali basalt.
63	16° 26.1'N 168° 06.8'W	2325m	Ridge; 165 kg of angular fragments of alkali olivine basalt.
64	16° 25.9'N 168° 08.8'W	2400m	Ridge (same as RD-63); 33 kg of angular fragments of severely-altered basalt.
PCOD-6*	2° 34.6'N 158° 30.1'W	2930m	Turbidite fan; two 15 g pebbles of hawaiite.

*Piston Core with Orientation Device

powder in a boron carbide mortar, and stored in glass vials. Samples for K-Ar analyses were prepared as above, except they were dried at room temperature (approximately 25^{o}C) for 12-15 hours prior to analyses.

Whole-rock major element and Cr, Ni, V, and Zr chemical analyses were performed by K. Ramlal at the Department of Earth Sciences of the University of Manitoba, Canada. A summary of the analytical techniques and precision for the analyses appears in APPENDIX A. An internal control basalt standard was used from the Hawaii Institute of Geophysics collection (HIG-8, Macdonald et al., 1973).

Li, K, Rb, Sr, and Ba and the rare-earth elements Ce, Nd, Sm, Eu, Gd, Dy, Er, Yb, and Lu have been determined at the Hawaii Institute of Geophysics by mass spectrometric, stable isotope dilution techniques (Schnetzler et al., 1967a, 1967b). BCR-1 and a blank were run as internal standards using the same spike and acid solutions as for the unknowns (see Flanagan, 1976, for BCR-1 analyses).

Mineral analyses have been performed at the Hawaii Institute of Geophysics using a CAMECA-MBX electron microprobe, with natural mineral standards. Both internal and external standards were used, consisting of well-analyzed clinopyroxenes, olivine, plagioclase, hornblende, chromite, ilmenite, and garnet. Instrument operating conditions were usually 15 kV and 12-15 nA sample current. Each analysis reported is an average of three to six points per grain, with at least five grains analyzed per sample. Core and rim analyses were made to check for chemical zoning and overall homogeneity. Raw data were corrected for dead time of detectors and spectrometer background. Mineral analyses were then obtained using a ZAF correction method (Henoc and Tong, unpub. manus.). Accuracy is estimated to be 1-2% for major elements and 5-10% for minor elements, on the basis of replicate microprobe analyses compared with wet chemical analyses.

Conventional K-Ar measurements were performed in the laboratory of J. J. Naughton at the Hawaii Institute of Geophysics using isotope dilution mass spectrometry methods described by Dalrymple and Lanphere (1969, 1971) and Gramlich (1970). Ultrasonically cleaned rock chips were split into two separates; the separates were leached in 6 Normal nitric acid or 6 Normal sulfuric acid prior to analyses.

$^{40}Ar/^{39}Ar$ total fusion age determinations were performed in the laboratory of R. A. Duncan at Oregon State University using an AEI MS-10S mass spectrometer equipped with ^{38}Ar spike and air calibration pipette systems. Sample selection criteria and preparation and irriadiation conditions for fourteen Line Islands and two Tuamotu Archipelago samples were described in Schlanger et al. (1984).

RESULTS

Volcanic rocks were recovered in eighteen rock dredges and one piston core from along the entire Line Islands chain and in one Tuamotu Archipelago rock dredge. Since most features were dredged only once, no clear view of the stratigraphic relationships and variations of the lavas is possible. The locations of each dredge site, listed in TABLE 1, are shown in FIGURE 3. Dredge site morphology and petrographic descriptions of volcanic rocks from each dredge appears in APPENDIX B.

Petrography

One-hundred and eighteen thin-sections were made of volcanic rocks recovered during the three Kana Keoki cruises. From this suite, twenty-eight samples were chosen for detailed petrographic study and major element geochemical analyses. Modes for the twenty-eight samples studied were determined by point counting 500 points per section (TABLE 2). Dredge site morphology and petrographic descriptions of volcanic rocks from each dredge appears in APPENDIX B. Modes for other thin-sections were estimated by visual inspection.

The rocks occur as angular to rounded fragments and pillow fragments, commonly variably manganese-oxide coated (0-2 cm thick), and as clasts embedded in volcanoclastic breccias. On average, vesicularity ranges from 5-20%, with extremes of 0% (44-3) and 48% (61-4). The vesicles are commonly small (0-2 mm diameter), round to irregular

TABLE 2

MODAL POINT COUNTS FOR ANALYZED SAMPLES FROM THE LINE ISLANDS AND TUAMOTU ARCHIPELAGO. OLIVINE IS COMPLETELY REPLACED BY IDDINGSITE. BASED ON 500 POINTS COUNTED PER SAMPLE.

	33-1	33-4	41-2	43-1	44-2	44-3	45-1	46-1	52-1	52-2	52-4	52-7	54-2	58-1
PHENOCRYSTS														
Olivine	13	18	12	15	1	0	7	0	14	17	13	7	0	0
Plagioclase	5	3	0	1	4	1	4	2	5	8	5	11	0	0
Clinopyroxene	0	0	9	0	0	0	0	0	1	3	1	1	0	0
Amphibole	0	0	0	0	0	0	0	3	0	0	0	0	0	6
Opaque	0	0	0	0	0	0	0	1	0	0	0	0	0	0
GROUNDMASS														
Plagioclase	39	29	32	46	39	29	33	32	26	29	25	26	29	38
Olivine	8	4	6	20	19	20	17	7	4	3	6	11	8	10
Clinopyroxene	2	0	13	0	1	1	0	0	16	10	11	16	5	0
Amphibole	0	0	0	0	0	0	0	0	0	0	0	0	0	12
Opaque	14	12	16	9	11	11	6	12	16	11	9	4	14	17
Altered Interstitial Material	19	34	12	9	25	38	33	43	18	19	30	24	44	17
DOMINANT TEXTURE	Hyalopilitic porphyry	Hyalopilitic porphyry	Porphyritic	Variolitic	Subtrachytic	Aphyric	Hyalopilitic porphyry	Hypohyalline	Porphyritic	Porphyritic	Porphyritic	Subophitic	Aphyric	Aphyric
VESICULARITY	10	14	18	18	1	0	18	32	23	22	20	19	4	0

ANALYST : G. Davis, University of Hawaii

TABLE 2 (continued)

MODAL POINT COUNTS FOR ANALYZED SAMPLES FROM THE LINE ISLANDS AND TUAMOTU ARCHIPELAGO. OLIVINE IS COMPLETELY REPLACED BY IDDINGSITE. BASED ON 500 POINTS COUNTED PER SAMPLE.

	59-1	59-2	59-7	59-10	59-12	59-13	60-6	61-1	61-3	61-4	62-1	63-7	PC6-1	PC6-2
PHENOCRYSTS														
Olivine	5	7	0	4	0	0	3	0	0	0	0	5	0	0
Plagioclase	1	3	0	5	1	2	1	0	0	0	14	0	1	2
Clinopyroxene	4	1	1	18	0	0	0	0	0	0	0	2	0	0
Amphibole	0	0	2	0	2	16	0	0	0	0	0	0	0	0
Opaque	0	0	0	1	0	0	1	0	0	0	0	0	0	0
GROUNDMASS														
Plagioclase	27	30	37	27	33	28	29	36	38	37	42	18	41	47
Olivine	19	16	5	8	4	0	24	23	23	37	2	19	15	19
Clinopyroxene	17	1	0	3	2	1	9	13	0	0	1	23	1	0
Amphibole	0	0	34	9	37	11	1	0	0	0	0	0	0	0
Opaque	12	12	9	8	10	18	2	5	13	11	14	8	13	8
Altered Interstitial Material	15	30	12	17	11	24	30	23	26	15	27	25	29	24
DOMINANT TEXTURE	Porphyritic	Porphyritic	Trachytic	Hypocrystalline	Subtrachytic	Subtrachytic	Hyalopilitic	Aphyric	Aphyric	Aphyric	Intersertal	Hypocrystalline Porphyry	Trachytic	Trachytic
VESICULARITY	22	32	10	21	18	7	7	25	23	48	29	7	0	2

ANALYST : G. Davis, University of Hawaii shaped, and are commonly lined with a thin coating of yellow to pale brown clay minerals (celadonite and smectite, respectively). Calcite, zeolites (natrolite or phillipsite), and Mn oxides are also present in the vesicles of some samples. A few samples contain flattened and elongate vesicles aligned with groundmass plagioclase microlites (59-7, 12, 13; PC6-2).

The majority of the basalts are porphyritic with olivine as the major phenocryst phase. In all cases, phenocryst and groundmass olivine are replaced by reddish-brown iddingsite with the relict crystal boundaries, mostly euhedral to subhedral, remaining intact. Plagioclase is present in most samples as subhedral tabular phenocrysts, commonly concentric zoned and partially resorbed, which may contain altered glass and very fine-grained opaques. Clinopyroxene phenocrysts, augite to titanaugite, generally occur as subhedral to anhedral fragments and are not a common phase for many of these samples. Euhedral to subhedral crystals and anhedral fragments of brown amphibole are the only phenocryst phase in a few samples (46-1; 59-7, 12, 13). These phenocrysts are medium brown pleochroic and may be zoned, resembling the brown amphiboles described by Natland (1975, 1976a) in the potassic nephelinites of the Line Islands cross-trend region. Rare, groundmass amphibole occurs in small, irregular patches in sample 58-1 and as very fine-grained needles in sample 59-10.

Groundmass textures are commonly hypocrystalline to hypohyaline in the alkali and alkali olivine basalts, but may vary from porphyritic to aphyric. The sub-trachytic to intersertal textures of the amphibole-

bearing alkali basalts from RD-59 and the aphyric pebbles from PCOD-6 resemble the hawaiites and mugearites of Natland (1975, 1976a). The groundmass phases are commonly plagioclase microlites and iddingsite-replaced olivine and clinopyroxene fragments and microphenocrysts, opaques as fine-grained clots of magnetite and needles of titanomagnetite (both as randomly oriented needles and as overlapping trellice-patterns), and rare amphibole as fibrous laths and very fine-grained needles (samples 58-1, 59-10, 60-6). The presence of trellice-patterned opaque needles in these basalts is a common characteristic of rapid growth, most likely formed during quenching in a submarine environment (Natland, 1975, 1976a; see description of sample 122D). The remaining groundmass, up to 40%, consists of devitrified interstitial glass, commonly oxidized to a dull reddish-brown color. Other replacement minerals include Mn-stains with minor zeolites and calcite as very thin vesicle-linings (<0.5 mm thick) and very minor alkali feldspar.

On the basis of petrography and texture, these volcanic rocks are predominantly alkali and alkali olivine basalts, some hawaiites, and rare ankaramite (sample 41-2). The presence of phenocrysts of Ti-augite has been used as a petrographic indication of the alkalic nature of Hawaiian alkali basalts (Macdonald and Katsura, 1964). As well as Ti-augite, Clague (1974) has also used the presence of biotite, hornblende, and groundmass olivine to classify volcanic rocks as alkalic basalts, while hypersthene, pigeonite, or subcalcic augite are indicators of tholeiitic basalts.

Two varieties of inclusions are observed in the volcanic rocks of this study. Few alkali basalts (59-1, 9, 10, 15; 63-7) contain inclusions of clinopyroxene-olivine aggregates, generally less than 1 cm in diameter. The amphibole-bearing alkali basalts (59-7, 12, 13) contain rare inclusions (1-2 cm in diameter) of clinopyroxenes and spinels poikilitically enclosed in a cumulate texture of brown amphibole. The amphiboles and clinopyroxenes contain abundant exsolved opaques along cleavage traces and grain boundaries. The amphiboles also contain rare, irregular-shaped, dark brown patches of aenigmatite and clusters of fine biotite flakes. The clinopyroxenes exhibit fine exsolution lamellae and contain very fine-grained needles of brown apatite. Neither orthopyroxene nor phlogopite was observed. A thin vein of fine-grained, twinned plagioclase (<2 mm) cuts through the one amphibole-bearing inclusion studied (59-13 Xenolith), but does not extend into the surrounding basalt. Otherwise, plagioclase does not occur as a phenocryst phase in either inclusion type. Microprobe analyses have been performed on clinopyroxenes, amphiboles, and biotites in one of these inclusions (59-13 Xenolith) and the results are presented in the Mineral Chemistry section. Amphibole-bearing xenoliths in Hawaii are exceedingly rare. To date, only a few xenoliths composed predominantly of amphibole have been found in Honolulu Volcanic Series tephra from Salt Lake Crater and Aliamanu (M. O. Garcia, pers. comm., 1986). Neither Line Islands inclusion type contains high pressure mineral phases, particularly aluminous orthopyroxene or garnet, found in xenoliths in the SiO_2-undersaturated lavas of the Honolulu Volcanic

Series, which have been used to imply a depth of origin of over 20 Kb (Jackson and Wright 1977).

Mineral Chemistry

Mineral analyses were made on groundmass and phenocryst clinopyroxenes from ten Line Islands volcanic rocks. Coish and Taylor (1979) presented data suggesting that pyroxenes in quenched chill margins were generally higher in Al and Ti than pyroxenes in interiors from the same rock. Therefore, microprobe sections were made from sample interiors. Particular attention will be paid to RD-59 basalts, which exhibited the most petrographic variety of all the Line Islands dredges. Amphibole phenocrysts from three samples (46-1, 59-7, 59-13) were also analyzed and classified on the basis of the cation content of the structural formulas (Leake, 1978). In addition, mineral analyses were obtained on clinopyroxenes, amphiboles, and biotites in a lamprophyric inclusion (59-13 Xenolith; see Appendix C). Structural formulae were calculated for the pyroxenes on the basis of six oxygens and for the amphiboles and biotites on the basis of twenty-three oxygens.

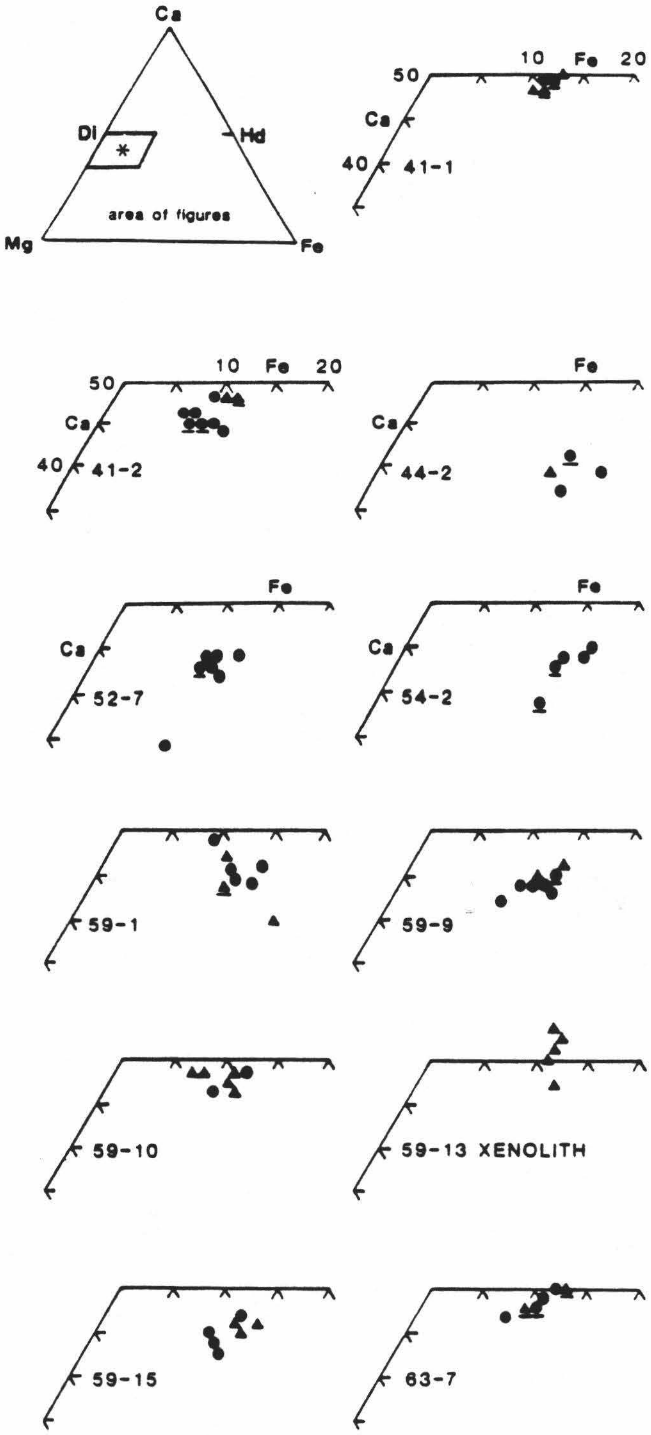
Clinopyroxenes from the analyzed Line Islands samples are titaniferous augites. The content of TiO_2 varies from 0.71-4.23 wt %. Compositional variations of Ca:Fe:Mg in these pyroxenes are shown in partial pyroxene quadrilaterals in FIGURE 5, along with pyroxene trends in Hawaiian lavas. With the exceptions of clinopyroxenes from samples

FIGURE 5. Clinopyroxene compositions in volcanic rocks from the Line Islands and Tuamotu Archipelago plotted on partial pyroxene quadrilaterals:

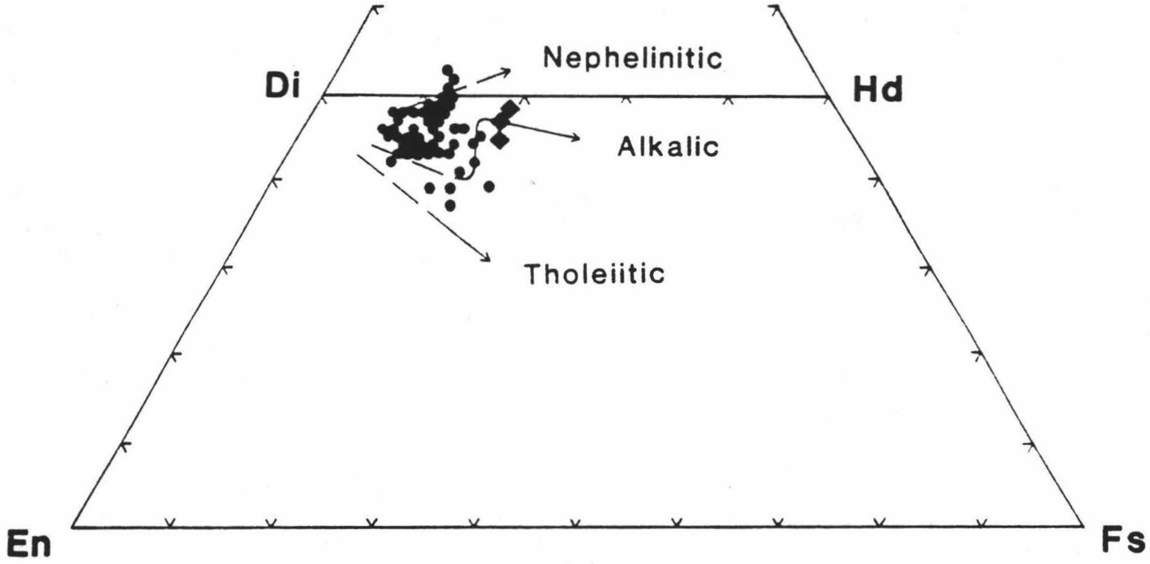
a) Ca:Fe:Mg ternary diagram showing 'area of figures' for plots of Line Islands and Tuamotu Archipelago clinopyroxenes on partial Ca:Fe:Mg ternary diagrams; ▲ = phenocrysts, ● = groundmass, underlined symbol indicates more than one analysis at the same plot point.

b) summary figure of Line Islands clinopyroxene compositions from this study (●) and from DSDP Site 315A (◆, data from Jackson et al., 1976) plotted on a partial pyroxene quadrilateral showing compositional trends of Hawaiian clinopyroxenes (after Fodor et al., 1975).

(5a)


Ca
Di
Hd
*
area of figures
Mg
Fe
50
10
Fe
20
Ca
40
41-1
41-2
44-2
52-7
54-2
59-1
59-9
59-10
59-13 XENOLITH
59-15
63-7

(5b)



44-2, 54-2, and 59-13 Xenolith, all of the pyroxenes are high Ca (43-50) and low Fe (10-15), similar to pyroxenes from Site 315A basalts (Jackson et al., 1976) and from Hawaiian alkali basalt suites (Fodor et al., 1975; Beeson, 1976). Clinopyroxenes from samples 44-2 and 54-2 are lower in Ca (38-46) and higher in Fe (15-21), similar to pyroxenes of Hawaiian basalts transitional between tholeiitic and alkali basalts (Beeson, 1976). Pyroxenes in 59-13 Xenolith have high CaO (20.68-23.84 %) and high atomic Ca (47-53), similar to pyroxenes in the nephelinite suite of Hawaiian lavas (Fodor et al., 1975). Groundmass and phenocryst compositions generally overlap, suggesting that the phenocrysts are cognate. The remaining figures of pyroxene compositions are presented in pairs of plots to separate the RD-59 samples from the others and to simplify the plots.

FIGURE 6 is a plot of Line Islands clinopyroxenes on partial Ca+Na:Fe+Mn:Mg ternary diagrams showing their relations to whole rock alkali content and degree of SiO_2-undersaturation. Pyroxenes from 41-2, 44-2, and 52-7 overlap the nonalkaline-alkaline boundary, implying a transitional affinity of the host basalt. Pyroxenes from 54-2 and all the RD-59 samples (except for one 59-9 analysis and the 59-13 Xenolith analyses) lie in the alkaline host field. 41-1, 63-7, and 59-13 Xenolith pyroxenes plot into the peralkaline host field, resembling pyroxenes from Hawaiian post-erosional lavas. Fodor et al. (1975) noted that pyroxenes in Hawaiian differentiated alkalic suite lavas span the entire nonalkaline, alkaline, and peralkaline fields, reflecting their wide range in whole rock alkali content and degree of

FIGURE 6. Partial atomic Ca + Na : Fe + Mn : Mg ternary diagram showing compositions of Line Islands and Tuamotu Archipelago clinopyroxenes (after LeBas, 1962); open symbol = phenocryst, closed symbol = groundmass.

<u>KEY</u>

Figure a

● = 41 - 1

■ = 41 - 2

◆ = 44 - 2

⬢ = 52 - 7

▼ = 54 - 2

▲ = 63 - 7

Figure b

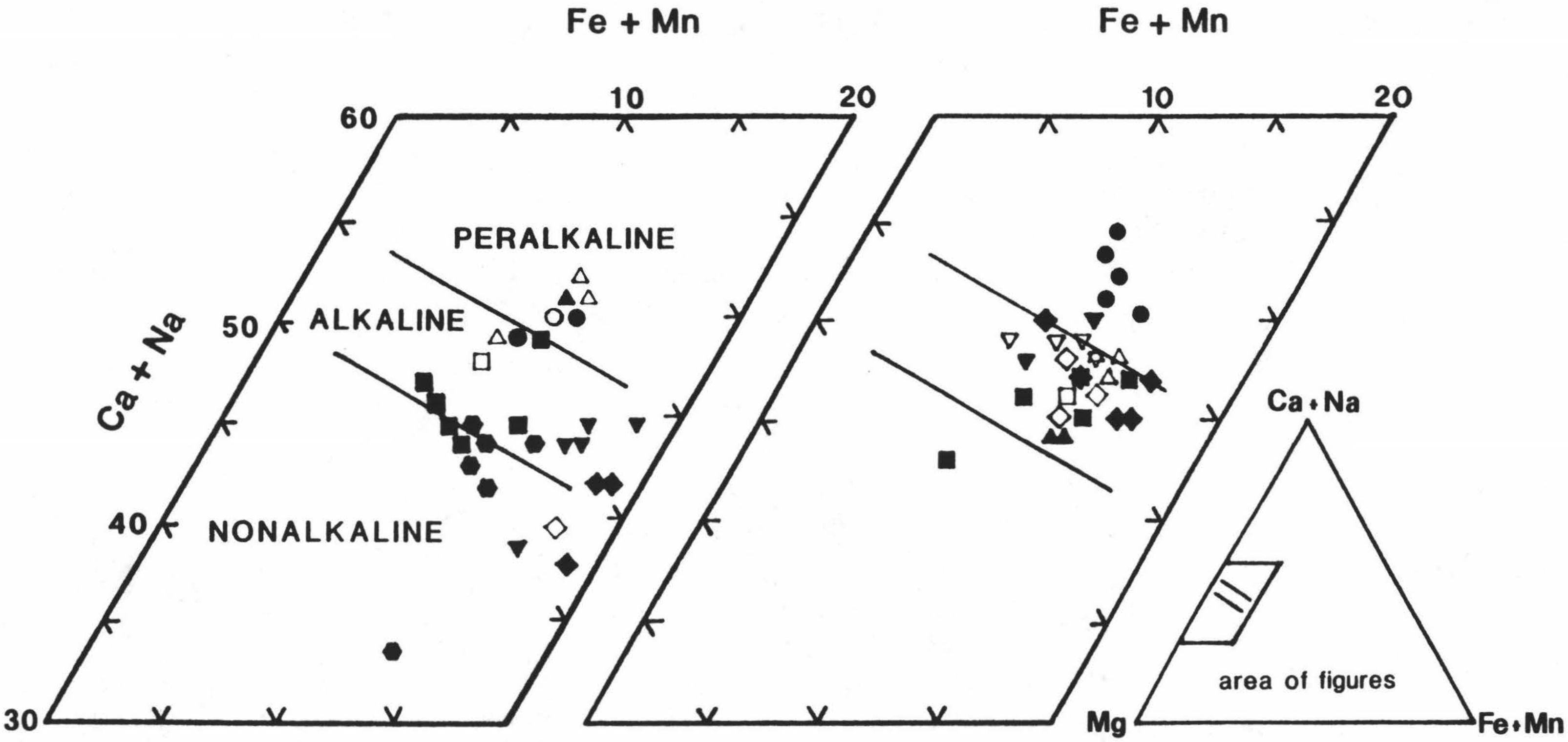
◆ = 59 - 1

■ = 59 - 9

▼ = 59 - 10

● = 59 - 13 Xenolith

▲ = 59 - 15

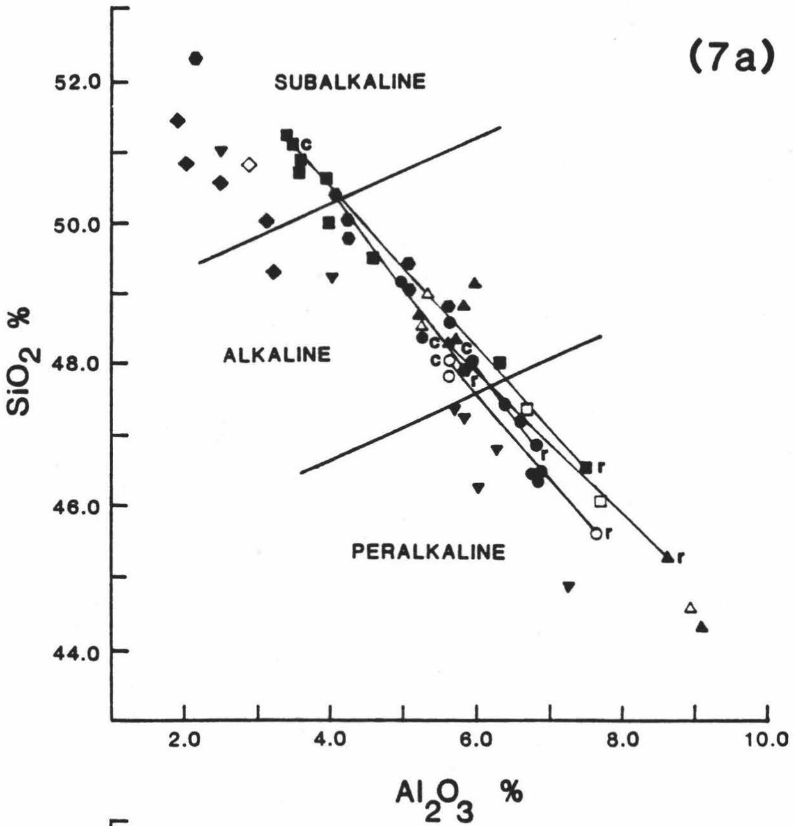

Fe + Mn
10
20
60
PERALKALINE
ALKALINE
50
Ca + Na
40
NONALKALINE
30
Fe + Mn
10
20
Ca + Na
area of figures
Mg
Fe + Mn

(6a) (6b)

SiO_2-undersaturation, but may also reflect the limited validity of this figure as a host magma affinity discriminant.

Kushiro (1960) and LeBas (1962) have shown that the proportions of Al and Ti in clinopyroxenes increase as they crystallize from increasingly SiO_2-undersaturated magmas. FIGURES 7 and 8 show the inverse variation of Al_2O_3 and TiO_2, respectively, with SiO_2 in the Line Islands pyroxenes. The fields in FIGURE 7 distinguish the subalkaline, alkaline, and peralkaline nature of the host magmas from which the pyroxenes crystallized (LeBas, 1962). Core to rim analyses in FIGURE 7 show an increasing Al_2O_3/SiO_2 ratio from core to rim, which LeBas (1962) noted may reflect the change in an alkaline host magma chemistry as fractionation proceeds (generally an increasing Fe/Ca+Mg+Fe ratio and a decreasing total Si) or, possibly, a temperature effect caused during quenching. With less Si (+4 valence) available to enter the tetrahedral (Z) coordination position , more Al (+3 valence) is substituted into that position. The charge imbalance is made up by the substitution of Ti (+4 valence) into octahedral coordination (Kushiro, 1960). Fodor et al. (1975) observed an increasing Al_2O_3 and TiO_2 content of groundmass clinopyroxenes with fractionation in Hawaiian alkali basalt suite lavas. Clinopyroxenes from samples 41-2 and 44-2 are transitional between the subalkaline and alkaline fields; 52-7 and 59-10 lie in the alkaline field; 41-1, 59-1,59-9, 59-15, and 63-7 straddle the alkaline-peralkaline boundary; and 59-13 Xenolith lies in the peralkaline field. Core to rim analyses of 41-2 and 54-2 show extreme variations in Al and Ti compositions plotting across all field boundaries; chemical

FIGURE 7. SiO_2 percent versus Al_2O_3 percent for Line Islands and Tuamotu Archipelago clinopyroxenes; symbols same as in FIGURE 6; lines connect core-to-rim analyses of same crystal (fields after LeBas, 1962).


(7a)
SUBALKALINE
ALKALINE
PERALKALINE
SiO$_2$ %
52.0
50.0
48.0
46.0
44.0
2.0
4.0
6.0
8.0
10.0
Al$_2$O$_3$ %
c
r

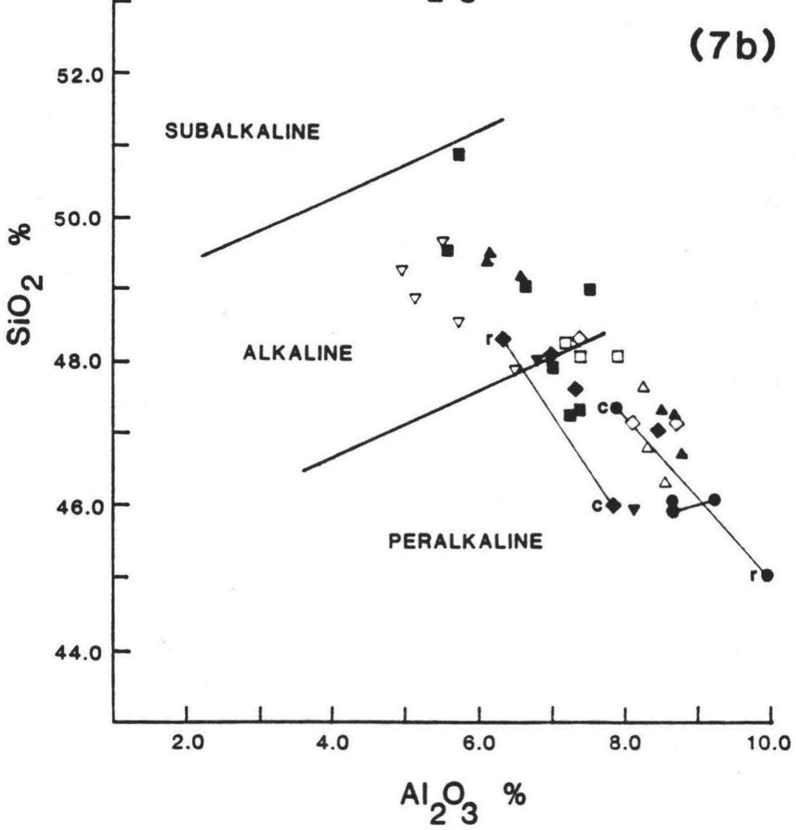
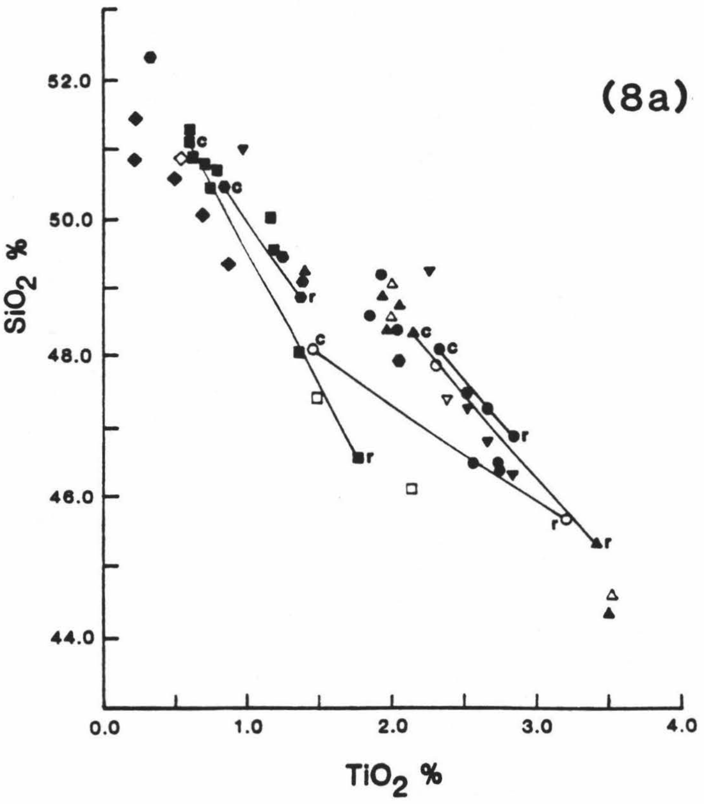
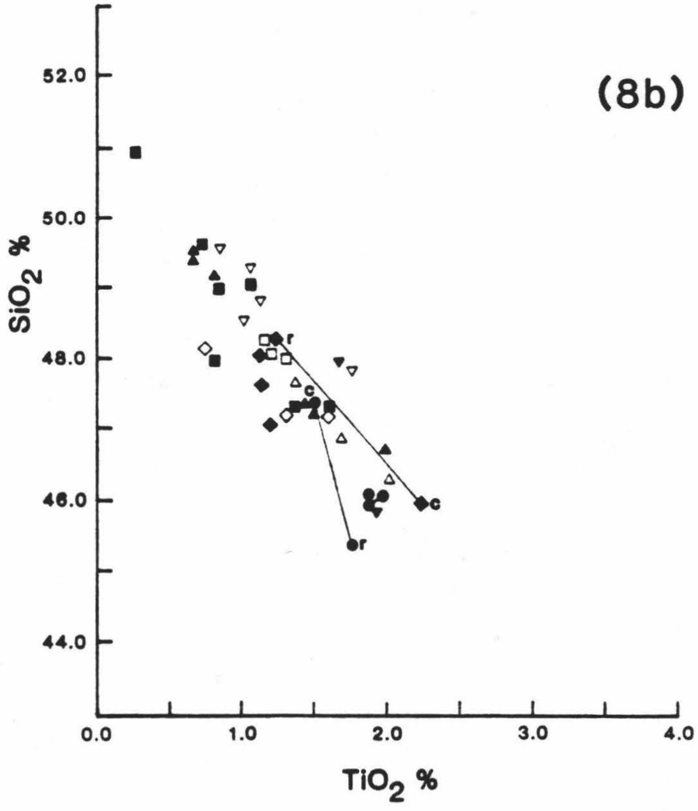

(7b)
SUBALKALINE
ALKALINE
PERALKALINE
SiO$_2$ %
52.0
50.0
48.0
46.0
44.0
2.0
4.0
6.0
8.0
10.0
Al$_2$O$_3$ %
c
r

FIGURE 8. SiO_2 percent versus TiO_2 percent for Line Islands and Tuamotu Archipelago clinopyroxenes; symbols same as in FIGURE 6; lines connect core-to-rim analyses of same crystal.


(8a)
SiO$_2$ %
TiO$_2$ %
52.0
50.0
48.0
46.0
44.0
0.0
1.0
2.0
3.0
4.0
c
r

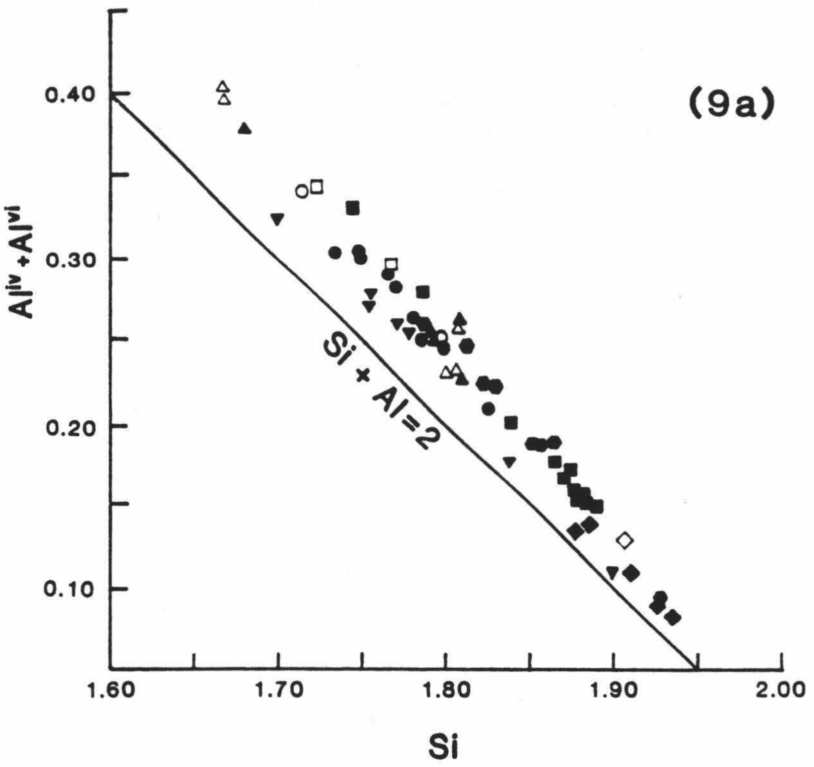

(8b)
SiO$_2$ %
TiO$_2$ %
52.0
50.0
48.0
46.0
44.0
0.0
1.0
2.0
3.0
4.0
c
r

trends not seen in other major elements as shown in FIGURES 5 and 6. The groundmass pyroxenes in both of these samples are fine-grained and 54-2 contains 44% altered interstitial material (see TABLE 2). These factors indicate a rapid growth history for the basalts despite the attempt to avoid chilled rims when making the sample selections. Their variable compositions are consistent with the observed variations in Al and Ti contents of pyroxenes with increasing cooling rates (Coish and Taylor, 1979).

Atomic proportions of Al and Si for the pyroxenes are plotted in FIGURE 9. Kushiro (1960) indicated that the concentration of Si in the magma determines the amount of Si in the tetrahedral (Z) site of the crystallizing pyroxenes; clinopyroxenes from tholeiitic rocks have more Si (greater than 1.83) and less Al (less than 0.22) than clinopyroxenes from either alkalic or, especially, feldspathoid-bearing rocks (Si less than 1.78, Al greater than 0.23). All Line Islands pyroxenes plot above the tetrahedral (Z) site saturation line (Si+Al=2), the excess Al present entering the octahedral (Y) site. 59-13 Xenolith pyroxenes contain the most Al and the least Si, similar to clinopyroxenes from ultramafic and mafic inclusions in Japanese basaltic rocks (Aoki, 1964), which were suggested to be rich in Ca-Tschermak's component ($CaAl_2SiO_6$).

A plot of TiO_2 versus the atomic proportion on the tetrahedral (Z) site filled by Al atoms ((Al (Z) = Al^{iv} times 100/z; stoiciometric z being taken as 2 (LeBas, 1962)) is shown in FIGURE 10. A positive correlation between TiO_2 and Al (Z) for Line Islands pyroxenes is observed. Fodor et al. (1975) also observed a positive correlation

FIGURE 9. Atomic proportions of $Al^{iv} + Al^{vi}$ versus Si for Line Islands and Tuamotu Archipelago clinopyroxenes; symbols same as in FIGURE 6 (after Fodor et al., 1975).


(9a)
$Al^{iv}+Al^{vi}$
0.40
0.30
0.20
0.10
1.60
1.70
1.80
1.90
2.00
Si
Si + Al=2

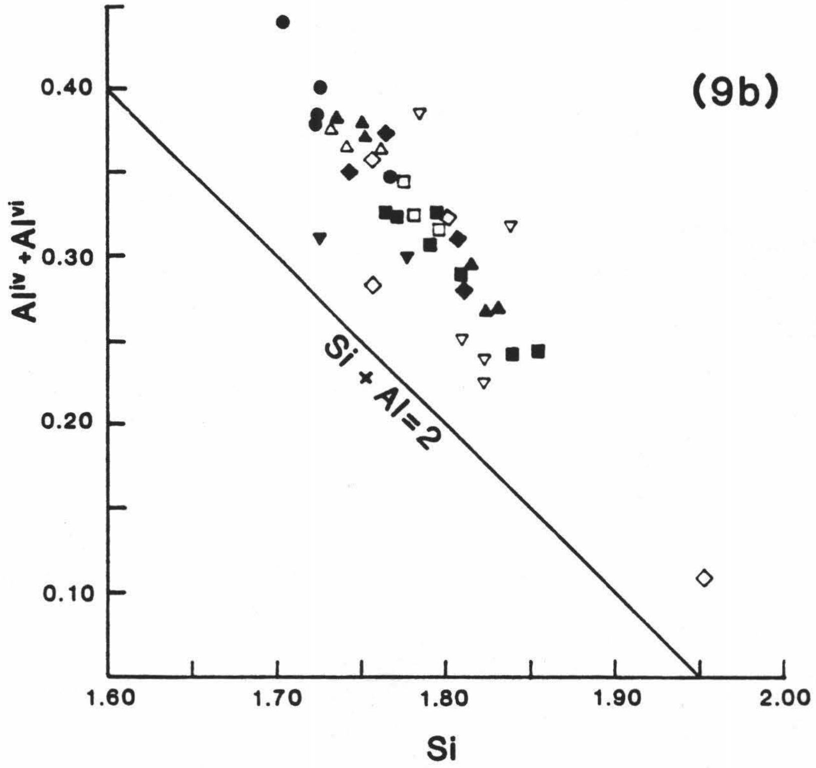
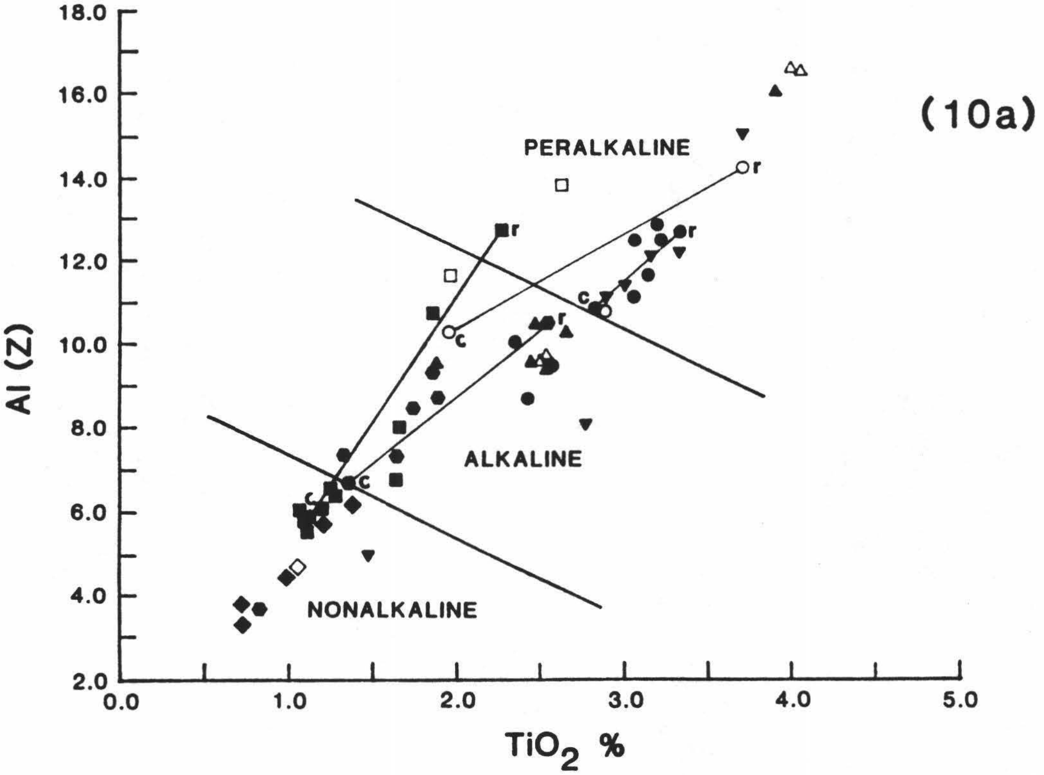
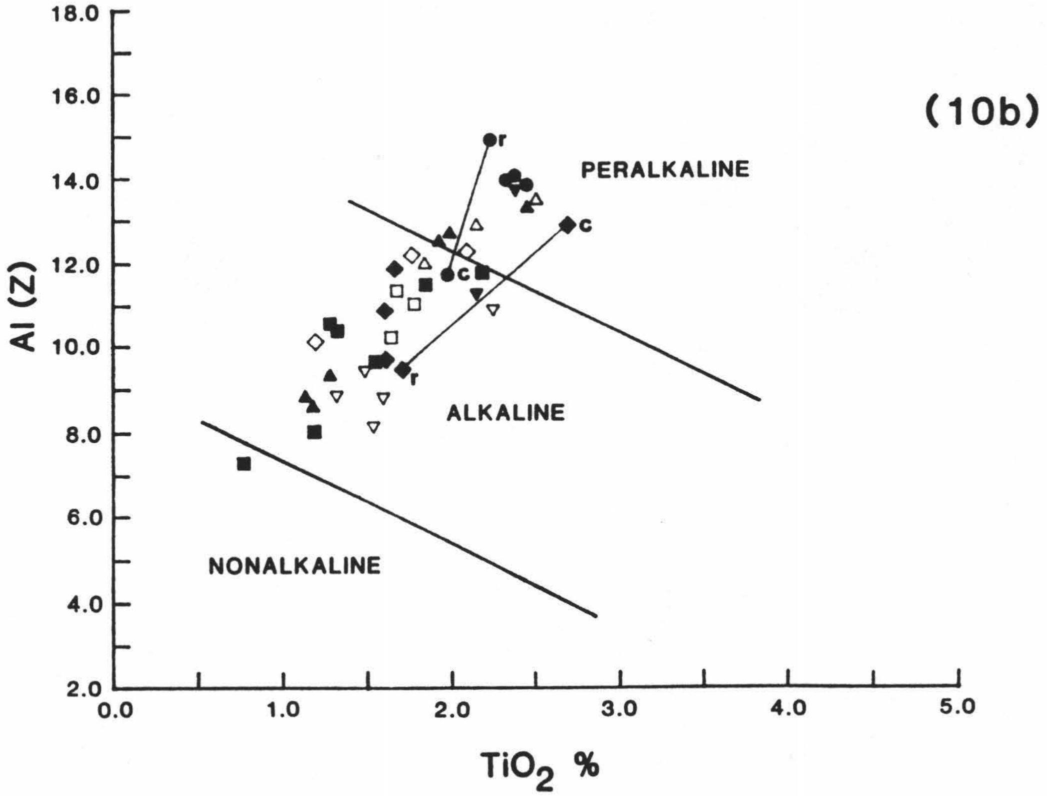

(9b)
$Al^{iv}+Al^{vi}$
0.40
0.30
0.20
0.10
1.60
1.70
1.80
1.90
2.00
Si
Si + Al=2

FIGURE 10. TiO_2 percent versus AL (Z), the atomic proportion of Al in the tetrahedral (Z) site defined by

$$AL\ (Z) = Al^{iv} \times \frac{100}{z}, \text{ where } z = 2,$$

for Line Islands and Tuamotu Archipelago clinopyroxenes; symbols same as in FIGURE 6; lines connect core-to-rim analyses of the same crystal (after LeBas, 1962).


(10a)
PERALKALINE
ALKALINE
NONALKALINE
Al (Z)
TiO$_2$ %
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
1.0
2.0
3.0
4.0
5.0
c
r


(10b)
PERALKALINE
ALKALINE
NONALKALINE
Al (Z)
TiO$_2$ %
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
1.0
2.0
3.0
4.0
5.0
c
r

between TiO_2 and Al (Z) for pyroxenes in Hawaiian alkali basalt suite lavas. LeBas (1962) noted that Al (Z) in pyroxenes rises with fractionation in alkaline host magmas, compatible with the core to rim analyses measured. Clinopyroxenes from samples 41-2 and 44-2 are nonalkaline to transitional; 52-7, 59-1, 59-9, and 59-10 are alkaline; 41-1, 59-15, and 63-7 are transitional between alkaline and peralkaline; and 59-13 Xenolith is peralkaline. Clinopyroxenes from samples 41-2 and 54-2 again show extreme variability, 54-2 perhaps being more peralkaline or transitional to alkaline.

A suite of groundmass clinopyroxene analyses were selected for recalculation of total iron to Fe_2O_3 and FeO on a twofold basis: 1) that their oxides total near 100.0%, indicating that each element analysis was reasonably accurate and 2) that their structural formulae were between 4.000-4.015, indicating reasonable precision in the structural formulae calculation. C.I.P.W. norms were calculated for these pyroxenes (TABLE 3) to see if the norms would reflect an increasing degree of SiO_2-undersaturation (appearance of normative Ne) with alkali basalt fractionation as described by Coombs (1968). Only 63-7 contains normative Ne. 41-2, 44-2, 52-7, and 54-2 pyroxenes contain Ol and Hy in their norms, more typical of tholeiitic clinopyroxenes.

These recalculated groundmass clinopyroxene compositions were also used in a ternary plot of TiO_2:Na_2O:MnO as a further check on the parental magma type (after Nisbet and Pearce, 1977). The results are presented in FIGURE 11, as well as data for Hawaiian groundmass clinopyroxenes from Fodor et al. (1975) and Beeson (1976). The wide

TABLE 3

C. I. P. W. NORMS FOR SELECTED CLINOPYROXENES WITH RECALCULATED Fe_2O_3 FOR VOLCANIC ROCKS FROM THE LINE ISLANDS AND TUAMOTU ARCHIPELAGO

	41-2A	41-2B	41-2C	44-2A	44-2B	52-7A	52-7Bc
SiO2	50.67	51.24	50.91	51.43	50.59	49.42	52.32
TiO2	1.27	1.08	1.11	0.71	0.98	1.75	0.81
Al2O3	3.91	3.40	3.56	1.84	2.44	5.07	2.10
Cr2O3	0.42	0.53	0.48	0.06	0.01	0.78	0.35
Fe2O3	0.94	0.63	1.00	1.41	1.97	0.95	0.33
FeO	5.12	4.55	4.53	10.36	9.40	5.91	7.39
MnO	0.09	0.06	0.11	0.38	0.31	0.11	0.19
MgO	15.58	15.84	15.69	15.11	13.85	15.08	18.95
CaO	21.50	22.04	22.01	18.04	19.72	20.59	16.61
Na2O	0.26	0.25	0.23	0.29	0.37	0.30	0.14
TOTAL	99.76	99.62	99.63	99.63	99.64	99.96	99.19
Ab	2.2	2.1	2.0	2.5	3.1	2.5	1.2
An	9.5	8.2	8.7	3.7	5.0	12.5	5.1
Ne							
Wo	40.7	42.4	42.1	35.9	38.9	37.5	32.5
Di En	31.3	33.0	32.9	23.0	25.4	28.5	23.6
Fs	5.1	4.8	4.6	10.6	10.8	5.1	6.0
Hy En	1.6	1.1	1.0	12.8	6.5	1.4	20.9
Fs	0.3	0.2	0.1	5.9	2.7	0.2	5.3
Ol Fo	4.3	3.8	3.7	1.4	1.9	5.4	2.2
Fa	0.8	0.6	0.6	0.7	0.9	1.1	0.6
Cs							
Mt	1.4	0.9	1.5	2.1	2.9	1.4	0.5
Cm	0.6	0.8	0.7	0.1	0.0	1.1	0.5
Il	2.4	2.1	2.1	1.4	1.9	3.3	1.6

TABLE 3 (continued)

C. I. P. W. NORMS FOR SELECTED CLINOPYROXENES WITH RECALCULATED Fe_2O_3 FOR VOLCANIC ROCKS FROM THE LINE ISLANDS AND TUAMOTU ARCHIPELAGO

	52-7Br	52-7C	54-2A	54-2B	63-7A	63-7B	63-7C
SiO2	48.82	49.10	49.22	50.99	48.83	48.70	49.16
TiO2	1.86	1.88	2.78	1.46	2.45	2.56	1.89
Al2O3	5.60	5.09	4.02	2.48	5.84	5.22	5.96
Cr2O3	0.62	0.45	0.03	0.00	0.25	0.17	0.48
Fe2O3	1.32	1.73	1.21	1.18	0.65	1.81	1.85
FeO	6.01	6.23	10.06	8.52	5.88	5.26	3.97
MnO	0.12	0.12	0.26	0.22	0.14	0.11	0.09
MgO	15.24	15.35	14.46	15.77	13.40	13.73	14.67
CaO	19.91	19.68	18.12	19.02	22.54	22.47	22.15
Na2O	0.27	0.32	0.44	0.23	0.39	0.41	0.41
TOTAL	99.77	99.95	100.60	99.87	100.37	100.44	100.63
Ab	2.3	2.7	3.7	1.9			
An	14.1	12.5	8.9	5.7	14.1	12.3	14.3
Ne					1.8	1.9	1.9
Wo	35.4	35.6	33.6	37.1	38.5	39.9	39.1
Di En	27.1	27.1	22.6	25.1	29.1	31.6	32.2
Fs	4.7	4.8	8.4	8.3	5.5	3.7	2.1
Hy En	2.6	3.8	7.1	10.3			
Fs	0.5	0.7	2.6	3.3			
Ol Fo	5.9	5.1	4.2	2.3	2.9	1.7	2.9
Fa	1.1	1.0	1.7	0.8	0.6	0.2	0.2
Cs					1.6	1.0	0.4
Mt	1.9	2.5	1.7	1.7	0.9	2.6	2.7
Cm	0.9	0.7	0.0	0.0	0.4	0.2	0.7
Il	3.5	3.6	5.2	2.8	4.6	4.8	3.6

52-7Bc = 52-7B core analysis

52-7Br = 52-7B rim analysis

FIGURE 11. TiO_2 : Na_2O : MnO ternary diagram of Line Islands and Tuamotu Archipelago groundmass clinopyroxenes with recalculated Fe_2O_3. Key to fields: A - volcanic arc basalts (VAB), B - ocean floor basalts, C - within plate alkali basalts (WPA), D - all, E - VAB + WPA + within plate tholeiitic basalts, F - VAB + WPA, G - WPA (after Nisbet and Pearce, 1977).

KEY

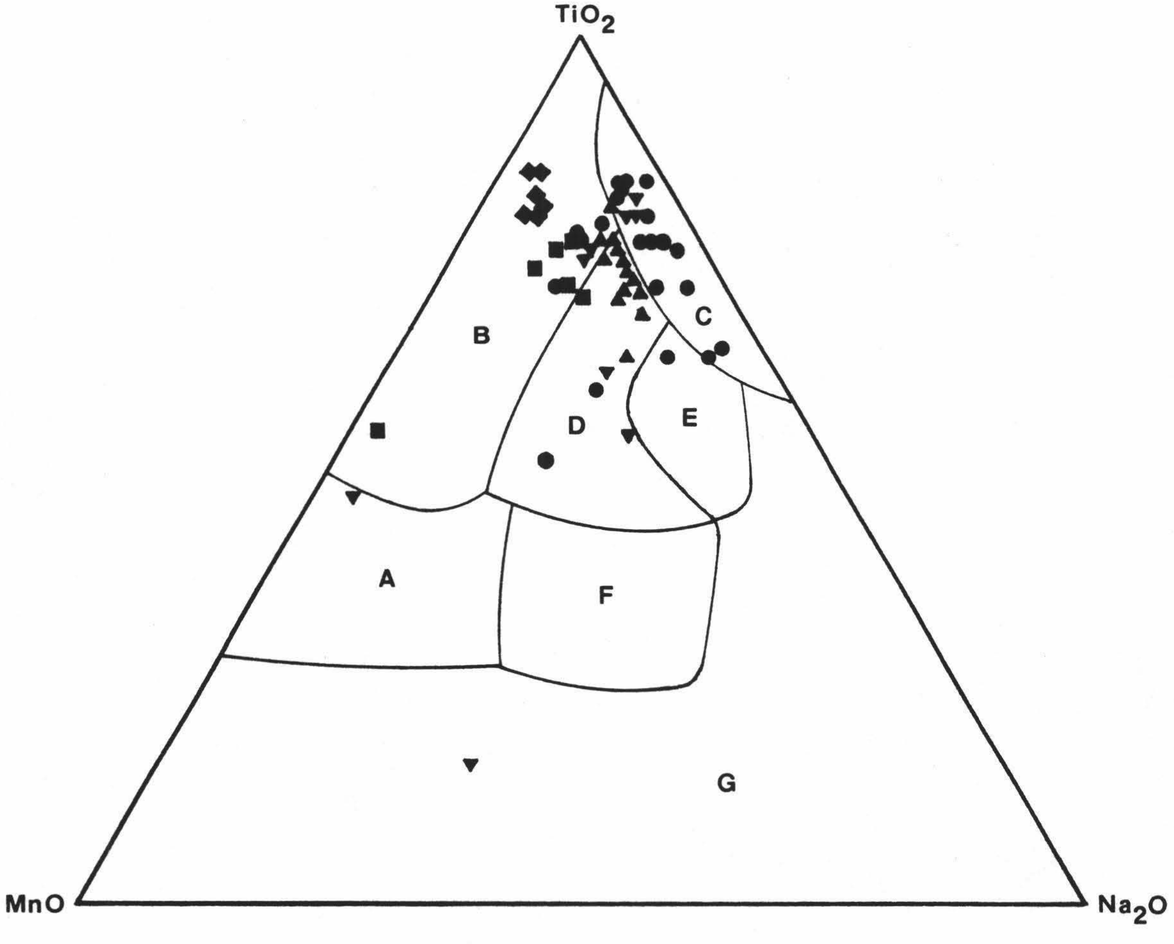
● = Line Islands and Tuamotu Archipelago

▼ = groundmass clinopyroxenes in Hawaiian alkali basalts (Fodor et al., 1975)

▲ = groundmass clinopyroxenes in Hawaiian alkali basalts (Beeson, 1976)

■ = groundmass clinopyroxenes in Hawaiian tholeiites (Fodor et al., 1975)

◆ = groundmass clinopyroxenes in Hawaiian nephelinites (Fodor et al., 1975)


TiO2
MnO
Na2O
A
B
C
D
E
F
G

scatter of the Line Islands and Hawaiian alkali basalt data is apparent. With a few exceptions which plot in the "Ocean Floor Basalt" field, the Line Islands and Hawaiian alkali basalt pyroxenes plot in discrimination fields which include "Within-Plate Tholeiite" or "Within-Plate Alkalic" field. It is apparent that more pyroxene analyses from a variety of "Within-Plate Tholeiite" and nephelinitic suites are needed before TiO_2:Na_2O:MnO discriminating fields for these rock types may be used with confidence.

Most of the Line Islands pyroxenes analyzed exhibit a variable behavior of Al, Ti, and Si, as seen in the wide scatter in the data across host magma boundaries. Despite attempting to avoid chilled rims on the basalt pillows, experimental studies on cooling rates of lunar basalt composition melts by Lofgren et al. (1974) and Donaldson et al. (1975) have shown that fast cooling rates favor the entry of Al, Ti, Ca, and Fe into the crystallizing pyroxenes, artificially giving them a more-alkaline affinity.

On the collective basis of the Ca:Fe:Mg proportions, the behavior of Al, Ti, and Si, and the pyroxene norms for these Line Islands pyroxenes, the affinities of the host magmas may be inferred. Samples 41-2, 44-2, and 52-7 have affinities that are tholeiitic or transitional between tholeiitic and alkaline. Sample 59-10 has affinities with alkaline magmas. Samples 41-1, 54-2, 59-1, 59-9, and 59-15 have affinities transitional between alkaline and peralkaline magmas. Samples 63-7 and 59-13 Xenolith have affinities with more SiO_2-undersaturated, peralkaline magmas.

Analyses of amphibole phenocrysts in samples 46-1, 59-7, and 59-13 appear in APPENDIX C. In the absence of H_2O data, the structural formulae are calculated on the basis of twenty-three (23) oxygens. With no analyses or recalculation of ferric iron in these samples, amphibole phenocrysts in 46-1 and 59-13 may be classified as either ferroan pargasites or magnesian hastingsites (Si less than 6.25, Ti less than 0.50, and Mg/Mg+Fe between 0.30-0.69). Phenocrysts in sample 59-7 are kaersutites (Si less than 6.50, Ti greater than 0.50, and Mg/Mg+Fe greater than 0.50). Both of these varieties are calcic amphiboles based on a chemical classification by Leake (1978). Amphibole-bearing alkali basalts in Hawaii are exceedingly rare. Macdonald and Powers (1946) described a hornblende-bearing hawaiite flow from Haleakala, Maui, Hawaii. Clague (1974) described an amphibole-bearing hawaiite dredged from a seamount 380 km west of Midway Island. Chemical analyses of amphiboles occurring in Hawaiian Island lavas have been reported from only two locations, edenite phenocrysts from a Kohala Volcano trachyte and richterite phenocrysts (with arfvedsonite microphenocrysts) from a West Maui Volcano trachyte (M. O. Garcia, pers. comm., 1986).

Analyses of clinopyroxenes, amphiboles, and biotites in a lamprophyric inclusion in an amphibole-bearing alkali basalt (the 59-13 Xenolith) also appears in APPENDIX C. The clinopyroxenes are titaniferous augites, but are higher in atomic Ca, Ca+Na, Al, and Ti and lower in Si than pyroxenes in the rocks from other RD-59 samples. In all cases, the 59-13 Xenolith pyroxene compositions indicate a SiO_2-undersaturated, peralkaline host magma affinity, similar to the pyroxenes in Hawaiian nephelinitic lavas (Fodor et al., 1975). Thompson (1974) and Wass (1979) noted that an increase in the atomic Al^{iv}/Al^{vi} ratio in clinopyroxenes accompanies decreasing pressure of crystallization. Little variation in the Al^{iv}/Al^{vi} ratios between the clinopyroxenes of the RD-59 lavas and the analyzed inclusion suggest no pressure difference between the origin for the inclusion and for the host lava. It is of note that no clinopyroxenes were observed in the 59-13 rock. Therefore, comparison between the clinopyroxenes of the 59-13 Xenolith and the host lavas is impossible.

The amphiboles in the 59-13 Xenolith are also titaniferous and, without ferric iron analyses, may be classified as either ferroan pargasites or magnesian hastingsites (Leake, 1978). The amphiboles in the inclusion are generally lower in TiO_2 and K_2O and are higher in SiO_2 and Al_2O_3 than amphiboles in the 59-13 lava. The analyzed micas are biotites with Mg/Fe less than 2.0, suggesting they were derived from an evolved source (Deer, Howie, and Zussman, 1966).

Collectively, the petrographic and mineral composition data indicate that the 59-13 Xenolith is not a cognate fragment of the RD-59 hawaiites. The thin vein of plagioclase observed in the amphibole phenocryst indicates a probable multistage history of the xenolith. Xenolith pyroxene compositions indicate a more peralkaline host magma affinity than the more alkaline affinities of the RD-59 hawaiites. The xenolith amphiboles are higher in SiO_2 and Al_2O_3 and lower in TiO_2 and K_2O than the amphiboles in the hawaiites. And the biotite compositions suggest the xenolith is derived from a more evolved source magma.

In a study of titaniferous amphibole-bearing peridotite inclusions in alkali basalts from the Grand Canyon region, Best (1974) suggested that these inclusions crystallized from hydrous melts of nephelinitic to basanitic composition, which matches the peralkaline affinity of the 59-13 Xenolith clinopyroxenes. Green et al. (1974), in reviewing experimental studies on basanite and nepheline mugearite compositions, noted that Ti-amphibole occurs near the liquidus for these compositions from 5-25 Kb pressure, with accompanying phases of olivine, clinopyroxene, and biotite. Kesson and Price (1972), Best (1974), and Green et al. (1974) have all emphasized the importance of a kaersutitic amphibole in deep-crustal and upper mantle fractionation of hydrous undersaturated basaltic magmas.

Major And Trace Element Geochemistry

Whole rock major and selected trace element (Cr, Ni, V, and Zr) analyses were performed on twenty-four volcanic rocks from the Line Islands and four volcanic rocks from the Tuamotu Archipelago. The results are presented in TABLE 4. The analyses were recalculated to anhydrous totals of 100.00% with the $Fe_2O_3/(FeO + Fe_2O_3)$ ratio adjusted to 0.15 (after Macdonald, 1968). C.I.P.W. norms and differentiation indices (D.I.) were calculated from these anhydrous, adjusted values, which will be used in all data plots in this section. Plotting symbols for samples from dredges RD-33, RD-52, RD-59, and RD-61 and for piston core PC-6 are distinguished from the samples from the other dredges to

TABLE 4

WHOLE ROCK MAJOR AND SELECTED TRACE ELEMENT ABUNDANCES AND C.I.P.W. NORMS OF VOLCANICS ROCKS FROM THE LINE ISLANDS AND TUAMOTU ARCHIPELAGO

MAJOR ELEMENT ANALYSES WITH Cr, Ni, V, AND Zr

	33-1	33-4	41-2	43-1	44-2	44-3	45-1	46-1	52-1	52-2	52-4	52-7	54-2	58-1
SiO2	45.60	45.20	45.20	42.75	38.40	41.75	38.65	42.65	47.05	44.55	46.25	44.05	40.05	48.85
Al2O3	15.37	15.19	13.74	17.97	12.72	15.50	15.72	15.12	16.01	15.87	15.16	15.14	13.27	17.04
Fe2O3	8.88	11.41	11.12	13.27	12.15	13.68	11.36	5.94	9.55	9.70	8.08	9.33	11.12	7.29
FeO	3.60	1.44	1.96	0.79	1.32	0.92	0.48	1.64	3.24	3.04	3.92	3.32	5.80	2.76
MgO	4.58	1.82	6.85	0.97	0.90	1.92	1.13	1.18	4.85	4.05	5.61	4.35	4.69	3.64
CaO	11.23	6.26	12.55	8.58	17.20	10.19	14.76	14.82	10.61	11.53	11.36	11.15	9.20	8.45
Na2O	2.82	3.20	2.58	3.34	3.75	3.02	2.83	3.82	2.59	2.60	2.57	3.57	2.46	3.91
K2O	0.86	2.85	0.91	1.75	0.80	1.29	1.71	1.88	0.72	0.92	0.68	0.82	0.64	1.92
TiO2	2.64	3.54	2.80	2.60	1.94	3.22	2.34	1.05	3.09	2.93	2.94	3.08	5.42	3.26
P2O5	0.56	2.12	0.37	2.12	8.99	2.81	5.87	6.68	0.56	1.48	0.70	1.30	0.63	0.80
MnO	0.18	0.16	0.18	0.13	0.17	0.12	0.21	0.08	0.13	0.15	0.14	0.16	0.15	0.15
H2O+	2.38	3.43	0.62	3.39	2.34	2.54	2.51	2.46	0.31	1.50	1.29	1.75	2.86	0.86
H2O-	1.23	3.09	0.74	1.90	1.44	2.16	1.37	1.82	1.12	1.27	1.27	1.73	3.64	0.66
CO2	0.01	0.26	0.16	0.29	1.26	0.37	0.83	1.02	0.00	0.24	0.06	0.17	0.12	0.28
TOTAL	99.94	99.97	99.78	99.85	99.78	99.79	99.77	100.16	99.83	99.83	100.03	99.92	100.02	99.87
Cr	768	340	591	338	36	147	192	10	493	527	523	461	25	13
Ni	296		155				77	40	163	66	154			
V	262	298	359	328	172	331	207	20	295	264	317	324	585	305
Zr	205	300	204	190	305	190	215	327	170	213	220	140	280	375

ANHYDROUS ANALYSES NORMALIZED TO 100% : Fe_2O_3 / (FeO + Fe_2O_3) = 0.15

	33-1	33-4	41-2	43-1	44-2	44-3	45-1	46-1	52-1	52-2	52-4	52-7	54-2	58-1
SiO2	47.34	48.51	46.00	45.34	36.73	44.09	40.66	44.96	47.82	46.01	47.48	45.75	42.86	49.82
Al2O3	15.96	16.30	13.98	19.06	13.43	16.68	16.54	15.94	16.27	16.39	15.56	15.73	14.20	17.38
Fe2O3	1.94	2.06	1.99	2.23	2.10	2.30	1.85	1.19	1.95	1.97	1.85	1.97	2.71	1.53
FeO	11.01	11.69	11.30	12.64	11.93	13.05	10.50	6.72	11.05	11.16	10.46	11.17	15.38	8.69
MgO	4.76	1.95	6.97	1.03	0.95	2.03	1.19	1.24	4.93	4.18	5.76	4.52	5.02	3.71
CaO	11.66	6.72	12.77	9.10	18.16	10.75	15.53	15.62	10.78	11.91	11.66	11.58	9.85	8.62
Na2O	2.93	3.43	2.63	3.54	3.96	3.19	2.98	4.03	2.63	2.69	2.64	3.71	2.63	3.98
K2O	0.89	3.06	0.93	1.86	0.84	1.36	1.80	1.98	0.73	0.95	0.70	0.85	0.69	1.95
TiO2	2.74	3.80	2.85	2.76	2.05	3.40	2.46	1.11	3.14	3.03	3.02	3.20	5.80	3.32
P2O5	0.58	2.27	0.38	2.25	9.48	2.97	6.17	7.04	0.57	1.53	0.72	1.35	0.67	0.82
MnO	0.19	0.17	0.18	0.14	0.18	0.13	0.21	0.09	0.13	0.16	0.14	0.17	0.17	0.15

C.I.P.W. NORMATIVE MINERALOGY (using dry, normalized analyses)

		33-1	33-4	41-2	43-1	44-2	44-3	45-1	46-1	52-1	52-2	52-4	52-7	54-2	58-1
Q															
C			0.6		0.1										
Or		5.3	18.1	5.5	11.0	5.0	8.0	10.6	11.7	4.3	5.6	4.1	5.0	4.1	11.5
Ab		23.8	29.0	14.2	29.5	22.4	27.0	19.9	30.8	22.3	22.8	22.3	22.8	22.3	32.8
An		27.8	18.5	23.6	30.4	16.4	27.2	26.4	19.6	30.4	29.8	28.5	23.8	24.9	23.8
Ne		0.5		4.3	0.2	6.0		2.9	1.8				4.7		0.5
	Wo	11.0		15.6		4.9	2.8	4.3	5.0	8.1	8.0	10.3	10.4	8.2	5.7
Di	En	4.9		8.2		0.6	0.7	0.8	1.3	3.6	3.4	5.3	4.6	3.5	2.8
	Fs	6.0		6.9		4.7	2.3	3.8	4.0	4.2	4.6	4.8	5.7	4.7	2.8
Hy	En		4.5				1.0			6.4	2.1	3.8		0.4	
	Fs		12.8				3.4			7.1	2.8	3.4		0.6	
Ol	Fo	4.9	0.3	6.4	1.8	1.2	2.3	1.5	1.3	1.5	3.5	3.7	4.6	6.0	4.5
	Fa	6.5	0.8	6.0	13.2	9.8	8.6	8.0	4.5	1.9	5.2	3.7	6.3	8.9	5.2
Mt		2.8	3.0	2.9	3.2	3.1	3.3	2.7	1.7	2.8	2.9	2.7	2.9	3.9	2.2
Il		5.2	7.2	5.4	5.2	3.9	6.5	4.7	2.1	6.0	5.8	5.7	6.1	11.0	6.3
Ap		1.4	5.4	0.9	5.3	22.5	7.0	14.6	16.7	1.4	3.6	1.7	3.2	1.6	1.9
D.I.		29.6	47.1	24.1	40.8	33.4	35.0	33.4	44.3	26.6	28.4	26.5	32.5	26.3	44.8

ANALYST : K. Ramlal, University of Manitoba

TABLE 4 (continued)

WHOLE ROCK MAJOR AND SELECTED TRACE ELEMENT ABUNDANCES AND C.I.P.W. NORMS OF VOLCANIC ROCKS FROM THE LINE ISLANDS AND TUAMOTU ARCHIPELAGO

MAJOR ELEMENT ANALYSES WITH Cr, Ni, V, AND Zr

	59-1	59-2	59-7	59-10	59-12	59-13	60-6	61-1	61-3	61-4	62-1	63-7	PC6-1	PC6-2
SiO2	47.30	43.60	50.25	45.45	51.60	42.90	46.45	45.20	40.50	42.05	45.90	41.70	47.60	49.75
Al2O3	16.57	16.62	17.72	16.94	17.71	17.64	16.20	17.02	15.82	17.22	18.19	13.53	18.69	16.62
Fe2O3	11.63	12.70	4.19	9.91	4.68	5.81	8.44	9.48	10.78	12.10	8.14	9.19	5.69	6.40
FeO	1.52	1.12	2.76	2.96	2.44	5.56	2.56	2.60	2.60	2.58	1.46	3.62	2.60	3.96
MgO	1.59	1.48	1.31	2.76	1.49	4.57	4.57	2.20	1.16	1.51	1.19	5.48	1.06	2.37
CaO	5.55	6.46	7.08	6.96	7.40	8.11	10.30	8.66	9.90	7.46	8.45	11.85	6.92	7.19
Na2O	3.16	3.13	4.97	2.82	5.02	2.86	2.95	3.22	2.57	2.38	3.84	1.97	3.98	4.46
K2O	3.19	2.51	3.64	2.74	3.74	1.94	1.03	2.46	2.77	1.69	2.34	1.21	1.56	1.98
TiO2	2.85	2.80	1.52	3.69	1.44	2.78	2.02	3.88	4.32	4.82	3.32	3.48	2.89	2.74
P2O5	1.15	1.81	2.57	1.48	2.14	1.88	0.58	1.98	3.67	1.85	2.68	0.93	1.45	1.08
MnO	0.11	0.19	0.11	0.11	0.11	0.18	0.09	0.09	0.09	0.15	0.16	0.14	0.06	0.13
H2O+	2.67	3.46	2.90	2.25	0.93	3.60	2.43	1.95	3.11	3.33	1.99	3.29	3.23	2.11
H2O-	2.74	3.67	0.76	1.65	0.67	1.93	1.92	1.26	2.14	2.75	1.78	2.48	3.82	0.91
CO2	0.09	0.14	0.34	0.12	0.35	0.17	0.08	0.02	0.45	0.13	0.28	1.05	0.14	0.07
TOTAL	100.12	99.69	100.12	99.84	99.72	99.93	99.62	100.02	99.88	100.02	99.72	99.92	99.68	99.77
Cr	343	335	6	274	15	27	472	244	253	265	82	554	6	10
Ni				104	14			75		88				13
V	308	340	132	332	91	282	236	317	453	405	256	355	278	108
Zr	305	235	460	255	285	445	310	405	378	355	325	320	635	415

ANHYDROUS ANALYSES NORMALIZED TO 100% : Fe_2O_3 / (FeO + Fe_2O_3) = 0.15

SiO2	49.98	47.17	52.29	47.43	52.78	45.53	48.80	46.70	42.99	44.82	47.98	44.78	51.47	51.46
Al2O3	17.51	17.98	18.43	17.68	18.11	18.73	17.02	17.58	16.80	18.36	19.01	14.53	20.20	17.19
Fe2O3	2.08	2.24	1.08	2.01	1.09	1.81	1.73	1.87	2.12	2.34	1.50	2.04	1.34	1.61
FeO	11.80	12.69	6.13	11.40	6.17	10.23	9.82	10.61	12.02	13.29	8.51	11.57	7.61	9.12
MgO	1.68	1.60	1.36	2.88	1.52	4.85	4.80	2.27	1.23	1.61	1.24	5.89	1.15	2.45
CaO	5.87	6.99	7.36	7.26	7.57	8.60	10.82	8.95	10.51	7.95	8.84	12.73	7.48	7.44
Na2O	3.34	3.39	5.17	2.94	5.14	3.03	3.10	3.33	2.73	2.54	4.01	2.12	4.30	4.61
K2O	3.37	2.72	3.79	2.86	3.83	2.60	1.08	2.54	2.94	1.80	2.45	1.30	1.69	2.05
TiO2	3.01	3.03	1.58	3.85	1.47	2.95	2.12	4.01	4.59	5.14	3.47	3.74	3.12	2.83
P2O5	1.22	1.96	2.67	1.55	2.19	1.99	0.61	2.05	3.90	1.97	2.80	1.00	1.57	1.12
MnO	0.12	0.21	0.12	0.12	0.11	0.19	0.10	0.09	0.10	0.16	0.16	0.15	0.06	0.13

C.I.P.W. NORMATIVE MINERALOGY (using dry, normalized analyses)

Q											2.8			3.1	
C		0.6	1.4		0.3		0.6				2.5	0.4		1.5	
Or		19.9	16.1	22.4	16.9	22.6	12.2	6.4	15.0	17.4	10.6	14.5	7.7	10.0	12.1
Ab		28.3	28.7	37.2	24.9	34.9	25.6	26.2	28.2	23.1	21.5	33.9	15.2	36.4	39.0
An		21.2	21.9	15.9	25.9	15.0	29.7	29.3	25.5	24.9	26.6	25.6	26.3	26.9	20.2
Ne				3.6		4.7							1.5		
	Wo			1.3		3.4		8.5	2.3	0.7			12.7		3.9
Di	En			0.4		1.1		4.0	0.8	0.1			6.4		1.4
	Fs			1.0		2.4		4.4	1.6	0.7			6.0		2.6
Hy	En	3.4	2.0		4.3		1.2	1.4	0.7	0.5	4.0	1.3		2.9	1.0
	Fs	12.3	8.6		7.8		1.3	1.5	1.3	2.2	14.3	3.8		7.8	1.8
Ol	Fo	0.6	1.4	2.1	2.0	1.9	7.6	4.6	3.0	1.7		1.2	5.8		2.6
	Fa	2.3	6.4	5.4	4.1	4.5	8.9	5.7	6.6	7.9		4.0	6.1		5.1
Mt		3.0	3.2	1.6	2.9	1.6	2.6	2.5	2.7	3.1	3.4	2.2	3.0	1.9	2.3
Il		5.7	5.8	3.0	7.3	2.8	5.6	4.0	7.6	8.7	9.8	6.6	7.1	5.9	5.4
Ap		2.9	4.6	6.3	3.7	5.2	4.7	1.4	4.9	9.2	4.7	6.6	2.4	3.7	2.7
D.I.		48.2	44.8	63.1	41.8	62.2	37.8	32.6	43.2	40.5	34.9	48.4	24.4	49.5	51.1

ANALYST : K. Ramlal, University of Manitoba better illustrate and assess the variations within each group.

The high abundance of altered interstitial material in the modes of these samples is reflected in the abundance of total H_2O, the large proportion of iron as Fe_2O_3, and the low values of MgO in most of these samples. The absence of alkali feldspar rims or the effects of sericitization on plagioclase crystals, the absence of chlorite or epidote, and the appearance of low temperature zeolites (natrolite and phillipsite) suggests that the alteration occurred at low temperatures, probably less than 50°C (Humphris and Thompson, 1978). The chemical effects of basalt-sea water interaction at low temperatures have been studied and reviewed by several authors (Moore, 1966; Philpotts et al., 1969; Hart, 1970; Bass et al., 1973; Thompson, 1973; Hart et al., 1974; Ludden and Thompson, 1979). The hydration of basaltic glass to palagonite and of olivine to iddingsite, the formation of smectite-group clay minerals, the effects of the formation of calcite or zeolites, and the influx of carbonate, marine phosphate, and manganese-oxide into vesicles and fractures may greatly alter the whole rock chemistry. Although the effects may be quite variable, the more typical changes in whole rock chemistry are a general increase in K_2O, Na_2O, Fe_2O_3/total iron, H_2O, and CO_2, a decrease in SiO_2, MgO, and CaO, variable effects on Al_2O_3, TiO_2, total iron, P_2O_5, Ni and Cr, but little effect on Zr and the rare-earth elements (except, possibly, La and Ce). On this basis, caution should be used in the detailed interpretation of the compositions of altered volcanic rocks.

The unusually high values of P_2O_5 for samples 44-2, 45-1, 46-1, and

61-3 (3.67-8.99 wt.%) are reflected in the high normative apatite (Ap) values, most likely an effect of marine phosphoritization. It is significant to note that normative nepheline (Ne), commonly a criterion for alkali basalt classification, is absent from samples 54-2, 59-1, and 59-10, basalts of alkalic affinities based on clinopyroxene compositions; that samples 41-2 and 44-2, with transitional basalt clinopyroxene compositions, contain moderate Ne (4.3-6.0, respectively); and that samples 52-7 and 63-7 both contain Ne and have clinopyroxene of alkalic affinity. Further, the appearance of normative corundum (C), occurring in several samples, has been suggested by Coombs (1963) to indicate altered major element chemistry. The above inconsistencies between clinopyroxene and whole rock compositional affinities and the presence of normative C further reflects the altered state of the analyzed volcanic rocks.

The alkalic affinities of all the analyzed volcanic rocks from the Line Islands is suggested in FIGURE 12. The Tuamotu samples straddle the alkalic-tholeiitic boundary and show little variation. For comparison, part of the Hawaiian alkali basalt to trachyte differentiation trend is also plotted (data from Macdonald, 1968). Samples from RD-33 and RD-59 appear to be similar to this trend and the PC-6 samples plot near the more-differentiated Hawaiian mugearites. RD-61 samples may also reflect this trend but, as with most analyses, show moderate variability, most likely a result of increasing alkalies during alteration.

Differentiation in these volcanic rocks is also suggested in FIGURE

FIGURE 12. SiO_2 percent versus $Na_2O + K_2O$ percent for volcanic rocks from the Line Islands and Tuamotu Archipelago; curved line shows partial Hawaiian alkali basalt differentiation trend; symbols are A - Alkali Basalt, H - Hawaiite, M - Mugearite. Modified from Macdonald and Katsura, 1964.

KEY

■ = RD - 33

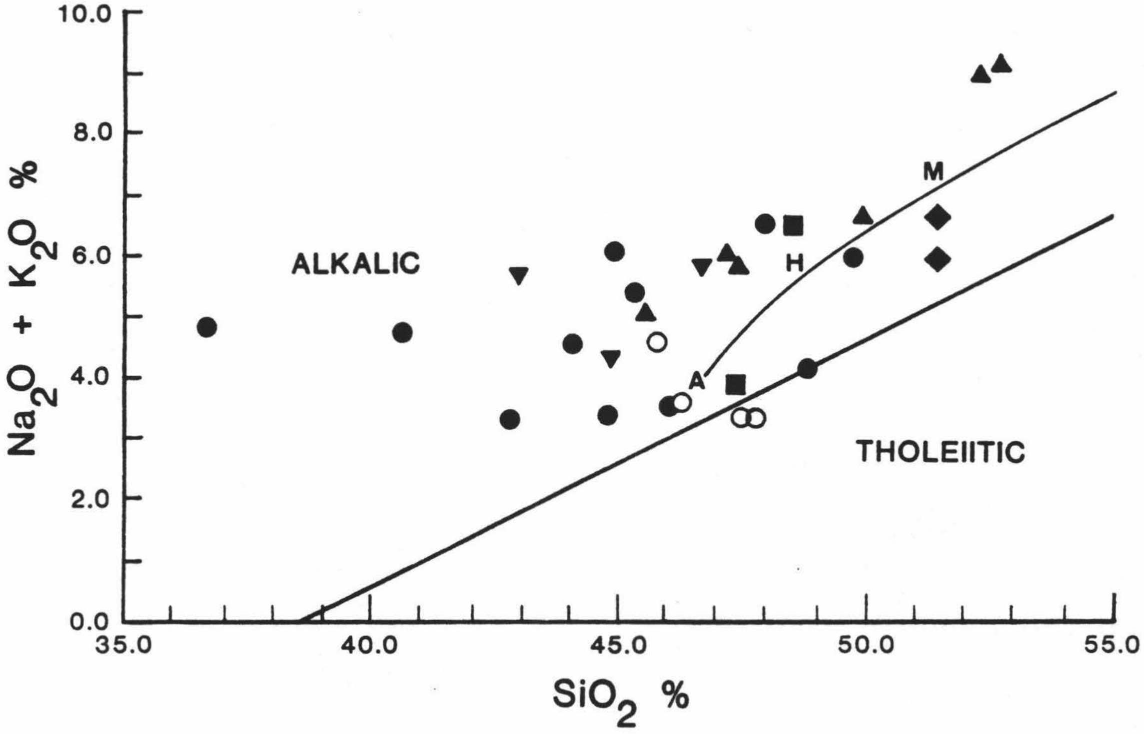
○ = RD - 52

▲ = RD - 59

▼ = RD - 61

◆ = PCOD - 6

● = remaining samples


10.0
8.0
6.0
4.0
2.0
0.0
Na$_2$O + K$_2$O %
35.0
40.0
45.0
50.0
55.0
SiO$_2$ %
ALKALIC
THOLEIITIC
M
H
A

13, a plot of differentiation index versus normative plagioclase composition (after Coombs and Wilkinson, 1969). Samples from RD-33, RD-59, and RD-61 plot across the alkali olivine basalt field into hawaiite compositions. The PC-6 samples lie in the hawaiite field. The remaining samples, especially 44-2, are scattered, but appear roughly to reflect the differentiation trend. The RD-52 samples all lie within the Alkali Olivine Basalt field.

Macdonald (1968) suggested that the trends in the Hawaiian alkali basalt suite shown in FIGURES 12 and 13 was controlled by the separation of pyroxene, olivine, and plagioclase. The coupled increase in total alkalies with silica (especially RD-59) and the increase in normative plagioclase compositions with differentiation index shown are common trends in differentiated alkali basalt suites from numerous localities (Hawaii-Macdonald, 1968; St. Helena-Baker, 1969; New Zealand-Coombs and Wilkinson, 1969; Gough Island-Zielinski and Frey, 1970; Comores Archipelago-Flower, 1973; Easter Island-Baker et al., 1974; Reunion Island-Zielinski and Frey, 1975 and Ludden, 1978).

Two relatively immobile constituents, TiO_2 and Zr, were plotted for Line Islands alkali basalts only (FIGURE 14), with discriminant fields for ocean ridge basalts and Hawaiian tholeiites and alkali basalts (after Hubbard, 1969). The amphibole-bearing hawaiites (46-1, 58-1, 59-7, 59-12, and 59-13) and the PC-6 hawaiites were not plotted on this diagram. No Line Islands basalt in this study resembles ocean ridge basalts. RD-33 samples plot in both the alkalic and tholeiitic fields. The RD-59 basalts all have Zr contents similar to alkalic

FIGURE 13. Diagram of Differentiation Index versus Normative Plagioclase Compositions for volcanic rocks from the Line Islands and Tuamotu Archipelago illustrating differentiation within the alkali basalt lavas; solid line indicates trend of Hawaiian alkali basalt suite differentiation for comparison (data from Macdonald, 1968); symbols same as in FIGURE 12. Modified from Coombs and Wilkinson, 1969.

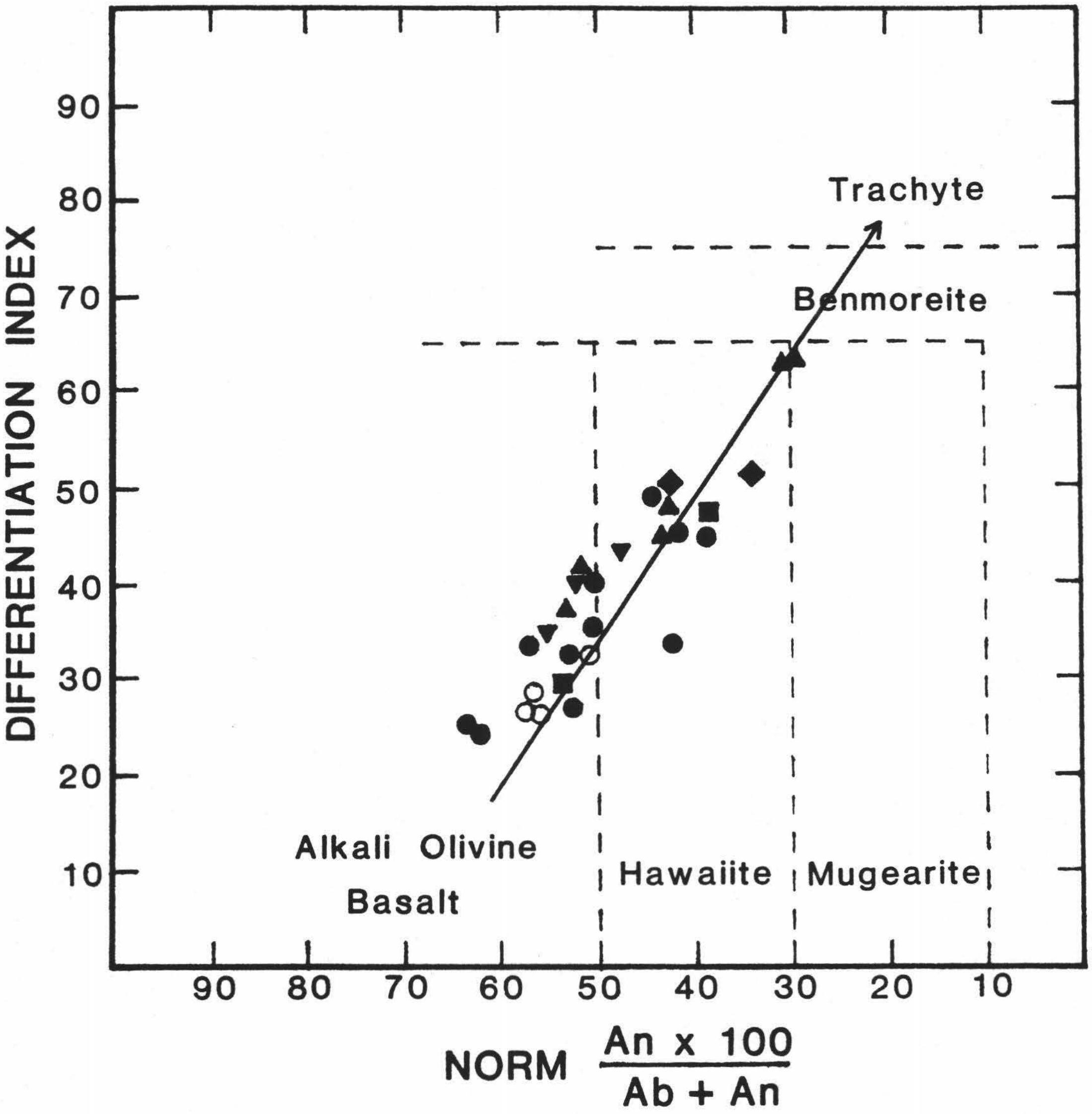
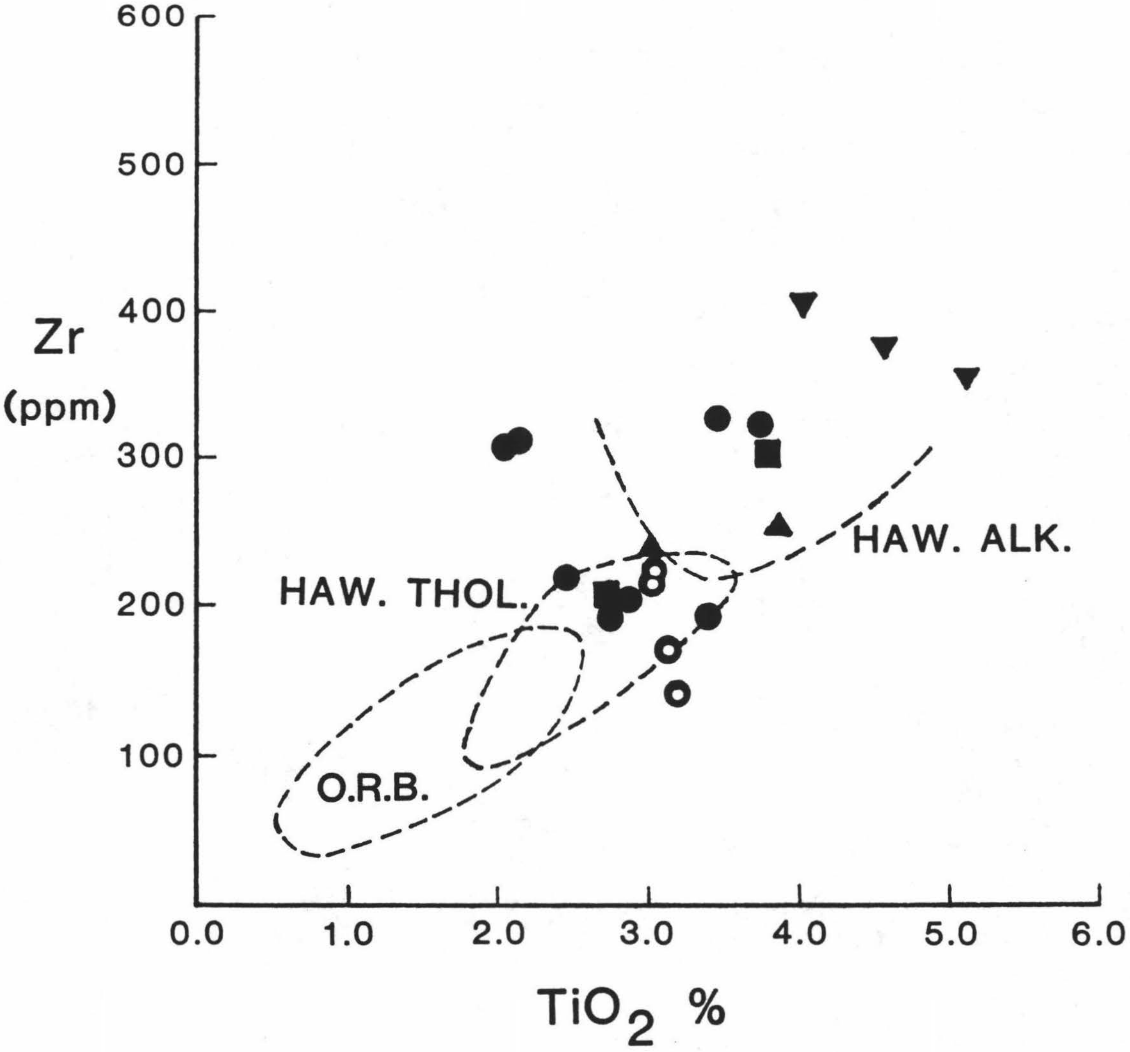

DIFFERENTIATION INDEX
90
80
70
60
50
40
30
20
10
Trachyte
Benmoreite
Alkali Olivine
Basalt
Hawaiite
Mugearite
90
80
70
60
50
40
30
20
10
NORM $\frac{An \times 100}{Ab + An}$

FIGURE 14. TiO_2 weight percent versus Zr (ppm) for selected volcanic rocks from the Line Islands and Tuamotu Archipelago; symbols same as in FIGURE 12; fields are: O.R.B. - Ocean Ridge Basalt, HAW. THOL. -Hawaiian Tholeiite, HAW. ALK. - Hawaiian Alkali Basalt. Modified from Hubbard, 1969.

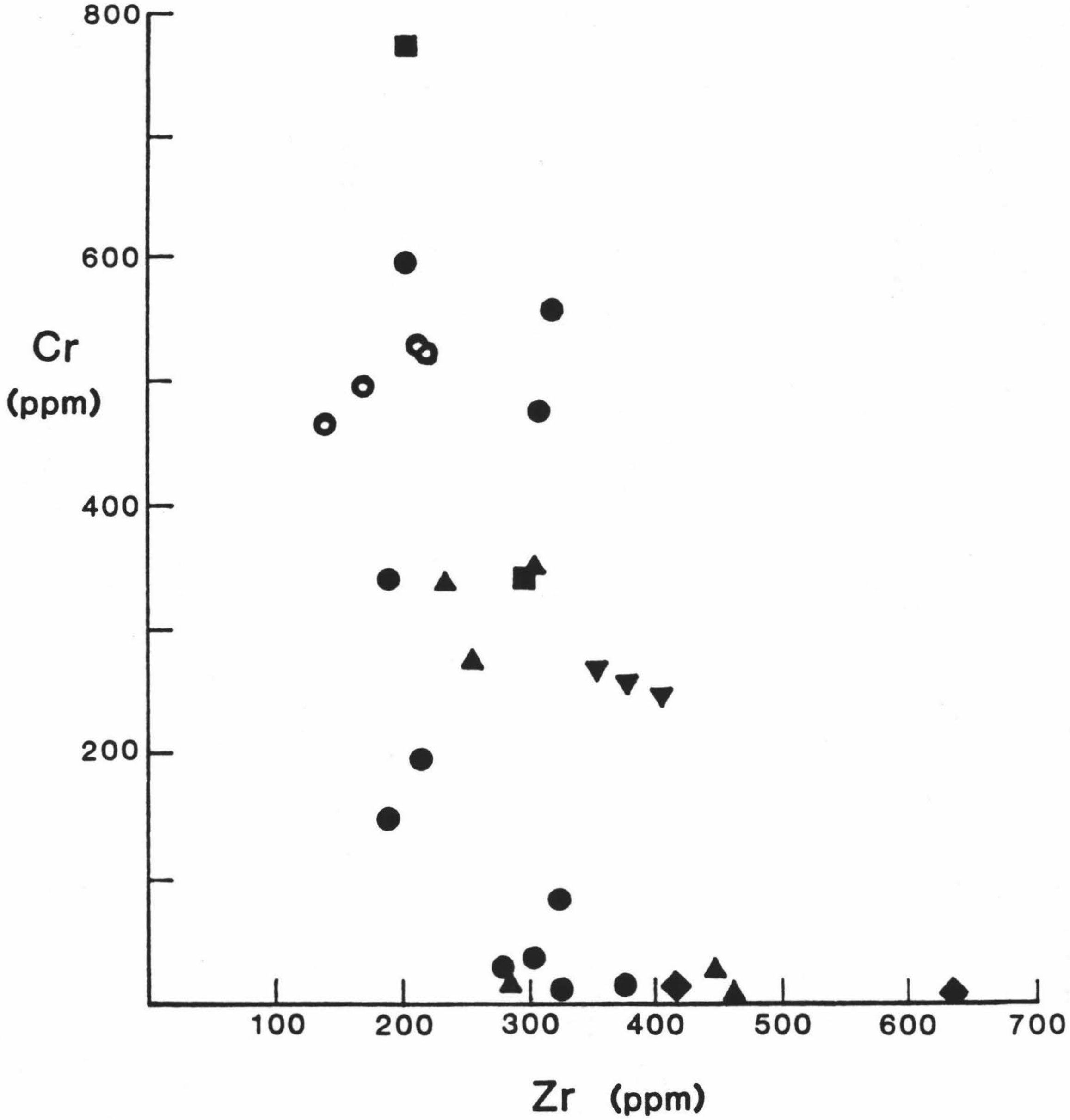

600
500
400
300
200
100
Zr
(ppm)
HAW. THOL.
HAW. ALK.
O.R.B.
0.0
1.0
2.0
3.0
4.0
5.0
6.0
TiO2 %

basalts, but scattered TiO_2 values. The RD-61 basalts are somewhat grouped in the alkalic field. The Tuamotu basalts all lie within the tholeiitic basalt field. Hubbard (1969), however, noted considerable overlap between adjacent groups in the Hawaiian data.

The trace elements Cr and Zr are plotted in FIGURE 15. The RD-52 and RD-61 basalts continue to show little variation. The RD-59 lavas show extreme variation with a sharp decrease in Cr and a slight increase in Zr between the alkali basalts and the amphibole-bearing hawaiites. The other amphibole-bearing hawaiites (46-1, 58-1), the PC-6 hawaiites, and samples 44-2 and 54-2 also contain low amounts of Cr and variable amounts of Zr. Clinopyroxene is conspicuously absent as a phenocryst phase in these lavas, while plagioclase occurs as an abundant groundmass constituent in most of these lavas. The observed RD-59 trend may best be explained by the fractionation of Cr-spinel and, probably, clinopyroxene. That Ni decreases from an ankaramite, such as sample 59-10 (104 ppm), to an amphibole-bearing hawaiite, such as sample 59-12 (14 ppm), suggests fractionation of olivine in these lavas as well. Ni is high in the remaining basalts, but is low in the PC-6-2 hawaiite (13 ppm), again probably reflecting olivine fractionation in the hawaiites. Hughes and Brown (1972) and Ludden (1978) suggested that low pressure fractionation of olivine and clinopyroxene, constituents of inclusions in the RD-59 alkali basalts, led to the evolution of hawaiites from alkali basalts on the Madeiran Islands and Reunion Island, respectively.

V content is not systematic between rock types within any dredge

FIGURE 15. Zr (ppm) versus Cr (ppm) for volcanic rocks from the Line Islands and Tuamotu Archipelago; symbols same as in FIGURE 12.


800
600
400
200
Cr
(ppm)
100
200
300
400
500
600
700
Zr (ppm)

group. The variable appearance of groundmass opaques, mostly titanomagnetite, in these samples and their alteration probably accounts for the observed variation.

The data available for the trace elements Ba, Li, Rb, and Sr appear in TABLE 5. Ba and Rb are very susceptible to alteration, while Sr appears to be less mobile (Philpotts et al., 1969; Hart et al., 1974). The alteration behavior of Li is poorly known, but may be expected to be similar to large-ion lithophile elements (K, Na, Rb, Ba). The Sr abundances for the analyzed Line Islands basalts and hawaiites range from 414-1350 ppm, much higher than for ocean ridge basalts, and are similar to the Sr abundances in the Hawaiian alkali basalts (Hubbard, 1969).

Volcanic rocks from RD-59 showed the most petrographic variation with alkali basalts (59-1, 59-2, and 59-10) and amphibole-bearing hawaiites (59-7, 59-12, and 59-13). Major element comparisons show that, in general, the hawaiites are higher in SiO_2, Al_2O_3, Na_2O, and K_2O and are lower in total iron and TiO_2 than the alkali basalts. Also, the hawaiites are higher in Ba, Rb, Sr, and Zr and lower in Cr and V. These systematic variations are compatible with fractional crystallization of an alkali basalt parent of olivine, clinopyroxene, and, possibly, Cr-spinel and Ti-magnetite (Gast, 1968; Philpotts and Schnetzler, 1970; Allegre et al., 1977), all common phenocryst phases in the RD-59 and other ocean island alkali basalt suite lavas. The presence of clinopyroxene-olivine inclusions in the alkali basalts and amphibole-clinopyroxene-spinel inclusions in the hawaiites further suggests an

TABLE 5

RARE-EARTH AND OTHER TRACE ELEMENT ABUNDANCES OF VOLCANIC ROCKS FROM THE LINE ISLANDS AND CHONDRITE-NORMALIZED RARE-EARTH ABUNDANCES. IN PPM BY WEIGHT.

	44-3	59-1	59-2	59-7	59-13	60-6	61-3	62-1	PC6-1	BCR-1	BLANK	CHONDRITE VALUES
Li	21.1	17.3	23.5	17.7	60.5	28.5	12.6	17.7	32.2	12.6	0.004	
K	10500	27500	18100	31100	17000	7640	22200	19800	13200	13100	1.369	
Rb	29.7	57.9	39.5	97.8	41.7	13.3	35.6	37.1	23.7	45.4	0.002	
Sr	428	583	611	633	1350	414	727	635	866	318	0.049	
Ba	153	406	354	1090	981	188	267	761	311	628	0.035	
Ce	89.9			121	175	35.4	61.0	70.9	80.4	50.2	0.006	0.787
Nd	34.5	45.3	87.7	46.1	72.0	21.3	43.5	53.1	71.6	27.3	0.004	0.580
Sm	7.83	9.00	15.8	7.52	11.2	4.89	8.93	11.6	14.1	6.40	0.001	0.185
Eu	2.55	2.76	4.52	2.08	3.19	1.68	2.84	3.58	4.32	1.86	<0.001	0.071
Gd	8.95	10.1	18.5	6.50	9.17			12.4	11.8		<0.001	0.256
Dy	8.75	8.52	17.0	5.25	7.41	4.59	5.63	10.7	10.8	6.18	<0.001	0.303
Er	5.32	4.45	10.3	2.88	3.81	2.19	2.73	5.42	4.97	3.50	<0.001	0.182
Yb	4.46	3.75	8.41	2.82	3.05	1.77	2.31	4.47	4.66	3.15	<0.001	0.188
Lu	0.69	0.49	1.22	0.41	0.52	0.26	0.36	0.81	0.54	0.48	<0.001	0.034

CHONDRITE-NORMALIZED ABUNDANCES

Ce	114			154	223	45.0	77.5	90.1	102
Nd	59.4	78.0	151	79.4	124	36.7	75.1	91.6	124
Sm	42.3	48.6	85.3	40.6	60.3	26.4	48.3	62.9	76.0
Eu	35.9	38.9	63.6	29.3	44.9	23.7	40.0	50.4	60.8
Gd	35.0	39.3	72.2	25.4	35.8			48.4	46.1
Dy	28.9	28.1	56.1	17.3	24.5	15.1	18.6	35.2	35.8
Er	29.2	24.4	56.6	15.8	20.9	12.0	15.0	29.8	27.3
Yb	23.7	19.9	44.7	15.0	16.2	9.39	12.3	23.8	24.8
Lu	20.3	14.5	35.9	12.0	15.2	7.72	10.6	23.8	15.8

Analyst: G. Davis, University of Hawaii, except: BCR-1 and Blank - R. Harma;
59-1 - D. P. Mattey

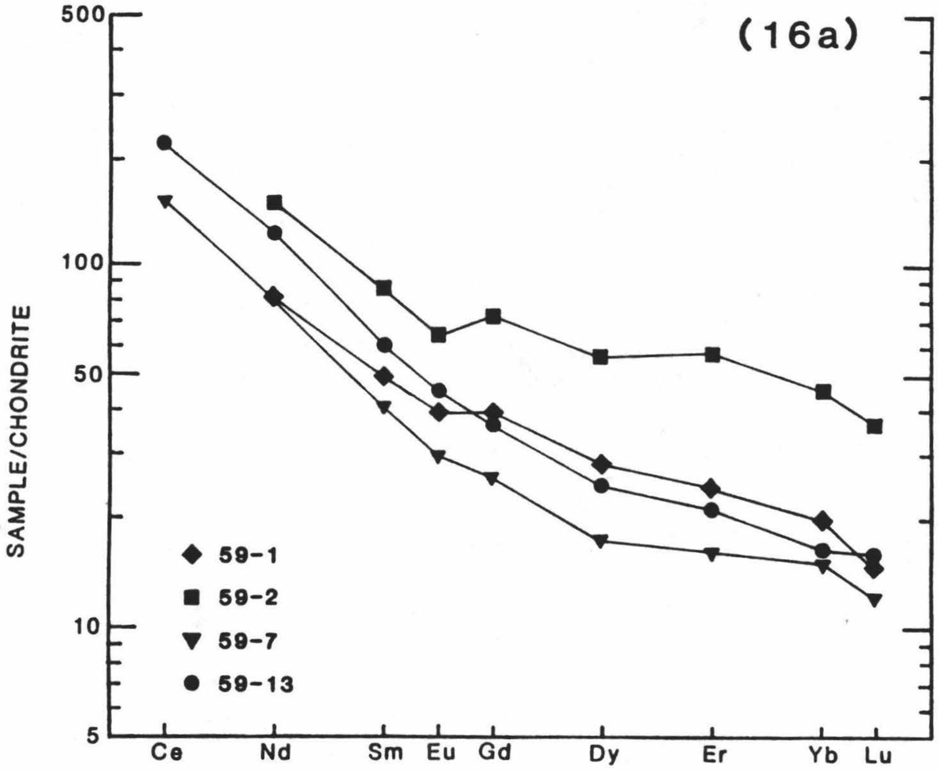
early crystallization history of these phases from the host lavas.

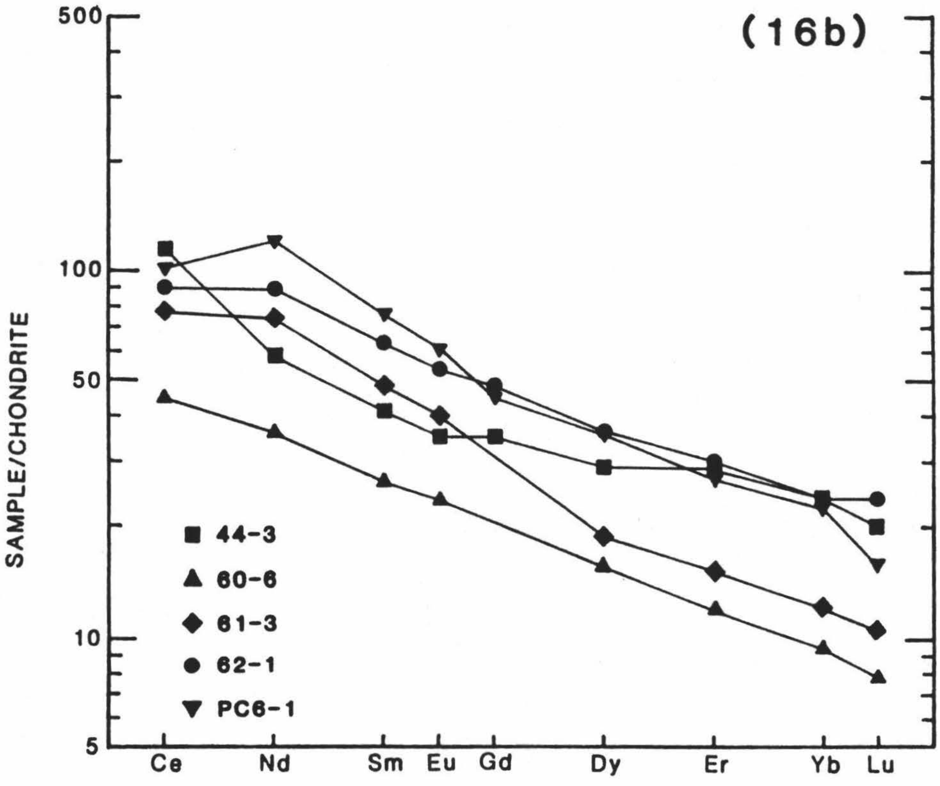
Rare-Earth Element Geochemistry

Rare-earth element (REE) analyses were performed on nine Line Islands volcanic rocks. The results of these analyses, of rock standard BCR-1 and blank analyses, chondrite-normalized REE values, and the chondrite values used in the calculations appear in TABLE 5. Ce values were not obtained for samples 59-1 and 59-2. Gd values were not obtained for samples 61-3 and PC6-1, most likely due to BaF interference during sample ionization in the mass spectrometer.

All of the analyzed Line Islands rocks exhibit a light rare-earth element-enriched (LREE) pattern (FIGURE 16) typical of most alkali basalts (Sun and Hanson, 1975). The RD-59 analyses are again separated from the other analyses to assist in the evaluation of their variations. The RD-59 samples show stronger enrichment in the LREE than the other samples and they are all slightly concave-up. Sample 59-2 also shows a very strong enrichment in the heavy rare-earth elements (HREE) over the other RD-59 rocks. Samples 59-1 and 59-2 show slight negative Eu anomalies, suggesting plagioclase fractionation. Sample 60-6 exhibits a flatter pattern and has the least LREE-enriched pattern, possibly indicative of a more transitional composition between ocean island tholeiite and alkali basalt. The sharp break in slope of the pattern for Ce in sample 44-3 may be indicative of Ce^{+4} addition during low temperature alteration, especially since the sample was oxidized

FIGURE 16. Chondrite-normalized rare-earth element patterns for volcanic rocks from the Line Islands; (16a) = RD-59 samples, (16b) = remaining samples.


(16a)
SAMPLE/CHONDRITE
500
100
50
10
5
Ce
Nd
Sm
Eu
Gd
Dy
Er
Yb
Lu
◆ 59-1
■ 59-2
▼ 59-7
● 59-13


(16b)
SAMPLE/CHONDRITE
500
100
50
10
5
Ce
Nd
Sm
Eu
Gd
Dy
Er
Yb
Lu
■ 44-3
▲ 60-6
◆ 61-3
● 62-1
▼ PC6-1

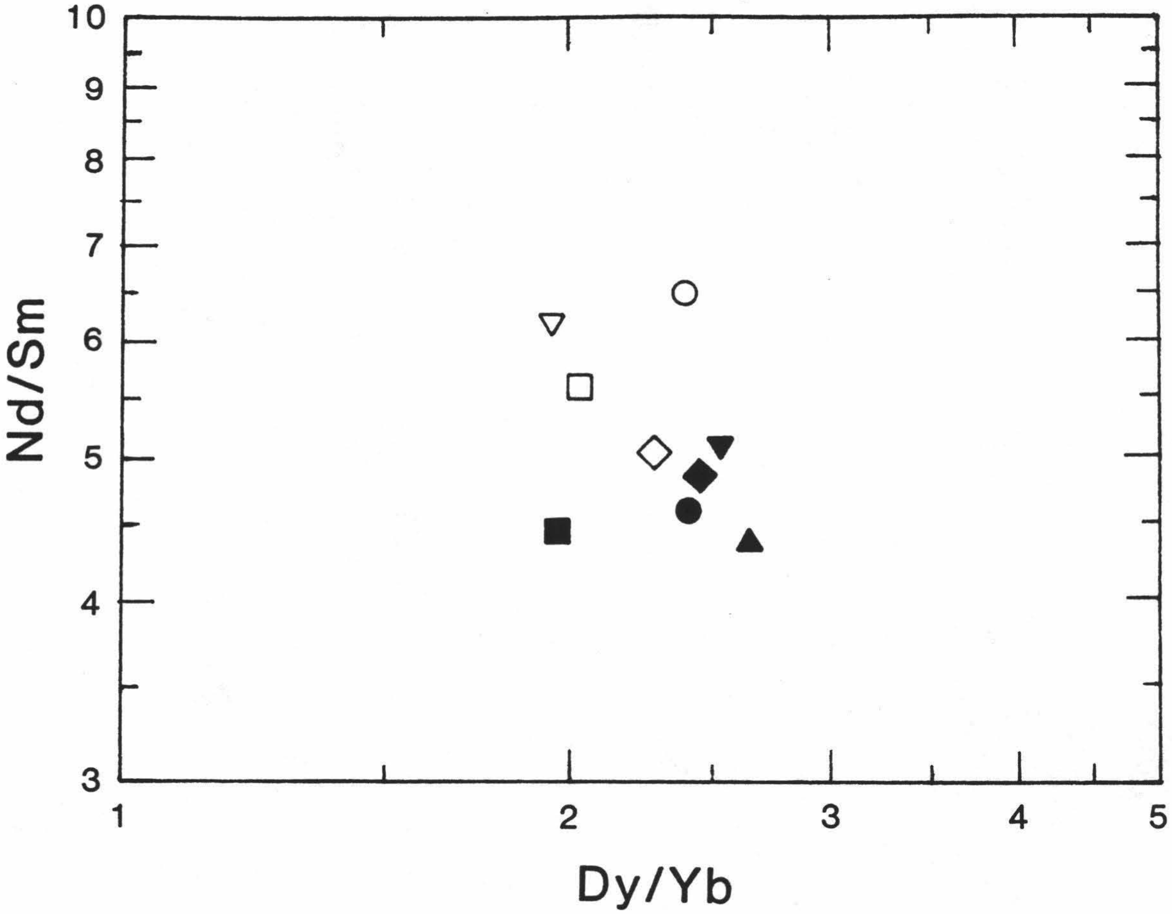
reddish-brown (Ludden and Thompson, 1979).

The REE differences between the RD-59 rocks and the other analyzed Line Islands rocks are further illustrated in FIGURE 17. The RD-59 rocks exhibit noticeably higher LREE slopes, but similar HREE slopes, to the other samples. However, sample 44-3 also exhibits a low Dy/Yb ratio.

A closer examination of the RD-59 REE abundances shows that both the alkali basalts (59-1, 59-2) and the hawaiites (59-7, 59-13) are LREE-enriched. However, the abundances of the HREE's are lower for the more-fractionated hawaiites than for the alkali basalts. This opposes the increase in total REE's from alkali basalts to hawaiites with low pressure fractionation described in the alkalic lava suites of Hawaii (Schilling and Winchester, 1969) and Reunion Island (Zielinski, 1975). Although apatite was identified as trace groundmass microcrystalline needles in only a few RD-59 hawaiites, normative Ap was calculated for all whole rock compositions reported in TABLE 4 due to the presence of P_2O_5. Apatite fractionation in Hawaiian lavas results in a decrease in total REE abundances during middle to late-stage fractionation from hawaiites to benmoreites. The lower HREE abundances observed from RD-59 alkali basalts (59-1, 59-2) to hawaiites (59-7, 59-13) may be explained by apatite fractionation earlier in the alkali lava suite evolution in the RD-59 lavas than occurs in Hawaiian alkali lavas. Again, caution is advised when interpreting chemical analyses of moderately altered rocks, particularly P_2O_5 due to marine phosphoritization.

However, if the alkali basalts and hawaiites were derived from

FIGURE 17. Rare-earth element ratios $\frac{Nd}{Sm}$ versus $\frac{Dy}{Yb}$ for volcanic rocks from the Line Islands; symbols same as in FIGURE 16 except that RD-59 symbols are open. Note the log-log scale.


10
9
8
7
6
5
4
3
Nd/Sm
1
2
3
4
5
Dy/Yb

related parental liquids without the fractionation of apatite, fractionation would have to include a mineral phase(s) with HREE partition coefficients greater than unity ($D^{solid}/_{liquid}$ greater than 1). Clinopyroxene and, occassionally, amphibole are common minerals in basalts, while garnet is a common xenolith mineral, for which HREE partition coefficients are sufficient for the fractionation effects observed (Schnetzler and Philpotts, 1968, 1970; Kay and Gast, 1973). HREE partition coefficients for garnet greatly exceed unity and the extraction of garnet as a residual phase in the partial melting of a garnet peridotite has been suggested for the derivation of LREE-enriched alkalic liquids (Sun and Hanson, 1975). The HREE partition coefficients for clinopyroxene and amphibole, although usually less than unity, may approach or exceed unity. The large decrease in Cr between samples 59-1 and 59-7 (343 ppm to 6 ppm) suggests that fractionation of Cr-spinel and/or clinopyroxene was probably an important process in these lavas. As with clinopyroxene, amphibole fractionation from a liquid similar to sample 59-1 might deplete the liquid in the HREE's while affecting the LREE's less because of their lower partition coefficients in these minerals. Clinopyroxene fractionation was suggested earlier in these lavas on the basis of Cr data and the absence of clinopyroxene from the hawaiites. Kesson and Price (1972) suggested that a pargasitic amphibole may be an important accessory phase in the uppermost mantle which, when partially melted to yield alkalic liquids, exhibits REE fractionation behavior similar to clinopyroxene. However, Varne and Graham (1971) observed in modelling the partial melting behavior of a hornblende lherzolite assemblage in the upper mantle that, even if hornblende were to remain on the liquidus, the REE would be fractionated very little.

If the RD-59 alkali basalts and amphibole-bearing hawaiites are derived from related liquids, their chemical differences may be explained by low pressure fractional crystallization of clinopyroxene and/or amphibole and, possibly, apatite in a LREE-enriched alkali basalt liquid. The fractionation of these minerals in the source region for these lavas is compatible with the trace and REE abundances. If fractionation of an alkali basalt parent has produced the hawaiites, it is also probable that the lavas evolved under conditions of increasing P_{H_2O}. Gast (1968) and Sun and Hanson (1975) suggested that alkali basalts, in general, result from low degrees of partial melting of a garnet-bearing mantle more enriched in the incompatible elements than the source mantle for mid-ocean ridge tholeiites. Griffin and Murthy (1969) suggested that alkali basalts may also be derived from low degrees of partial melting of a phlogopite-bearing hornblende peridotite, which could account for the observed abundances of large-ion lithophile (LIL) elements (ie. K, Na, Rb, Ba) and REE.

The presence of amphibole-bearing inclusions in the amphibole-bearing hawaiites is a possible indication of an earlier crystallization history of amphibole in these lavas. The concave-up REE patterns of the RD-59 rocks, more marked in the hawaiites, is consistent with amphibole fractionation. Also, the whole rock K/Rb ratio, although highly susceptible to alteration, decreases from the alkali basalts to the hawaiites, a trend which generally accompanies increasing amphibole fractionation (Hart and Aldrich, 1967; Kesson and Price, 1972).

The behavior of REE's with fractionation in the alkali basalt suite of Hawaii shows a uniform increase in total REE's from alkali basalt to hawaiite with no overlap of the REE patterns (Schilling and Winchester, 1969). From FIGURE 16a, it can be seen that the patterns for the RD-59 lavas do overlap. This suggests that, if the hawaiites were derived from the alkali basalts by fractional crystallization, then the operative minerals with their various partition coefficients differed from those in the fractionation of Hawaiian lavas. The geochemical differences observed may be the result of different degrees of partial melting of the same source material or the result of partial melts from different source mineralogies (Kay and Gast, 1973). The source for the alkali basalts may be more clinopyroxene-rich than the source for the hawaiites (Leeman et al., 1977), resulting in the higher abundances of HREE in the RD-59 alkali basalts with partial melting.

Natland (1975, 1976a) called upon the presence of amphibole and mica in the source region, at mantle depths of less than 85 km, as the source for the extremely SiO_2-undersaturated potassic nephelinites of the Line Islands cross-trend region, the trachyte of dredge 142, and the 'mugearites' of DSDP Site 165. In studying amphibole-bearing xenoliths in alkali basalts from Arizona, Best (1974) suggested that the mantle source region for these lavas was enriched in Ti, LIL elements, and LREE due to the ascent of hydrous melts from deeper in the mantle. Boettcher and O'Neil (1980) studied evidence for the derivation of primary alkalic magmas by anatexis of metasomatized, enriched mantle and concluded that upward-migrating fluids, associated with either mantle plumes or diapiric rises, have modified the source for alkali basalts from numerous localities and may account for at least some mantle heterogeneity. Although no direct evidence exists, the RD-59 lavas may also be the result of varying degrees of partial melting of mantle source region which underwent a metasomatic event which enriched the source region in the LIL elements and the LREE.

Geochronology

Conventional K-Ar age determinations for thirteen Line Islands volcanic rocks and one Tuamotu Archipelago basalt were performed at the Hawaii Insitute of Geophysics. The whole rock ages and analytical data used for the calculations are presented in TABLE 6. Each of these samples have been petrographically described and chemically analyzed. The dual ages reported are for separates of the same rock chips treated with either a nitric acid (N) or sulfuric acid (S) leach prior to analysis. Discrepancies between the ages for the same rock are due to slight, but variable, effects the different acid leaches have on the rock (J. J. Naughton, pers. comm., 1981). $^{40}Ar/^{39}Ar$ total fusion age determinations performed at Oregon State University for ten Line Islands and two Tuamotu Archipelago volcanic rocks of this study (prefaced RD and PCOD) and for four Scripps' Line Islands dredge samples (D suffix), listed from 19°N to 15°S, are presented in TABLE 7.

TABLE 6

SUMMARY OF WHOLE ROCK K-AR AGE DATA FOR VOLCANIC ROCKS FROM THE LINE ISLANDS AND TUAMOTU ARCHIPELAGO

SAMPLE	SAMPLE WT. (g)	%K	R. S. D.* (x10-2)	RADIO. AR/g (std cc/g)	R%**	CALCULATED*** AGE (my)
33-4N	1.24	2.50	2.92	5.26x10-6	57.2	53.2 ± 3.2
33-4S	0.835	2.10	1.23	3.84x10-6	28.7	47.0 ± 2.3
43-1N	1.21	1.38	1.45	2.54x10-6	57.0	47.3 ± 2.2
43-1S	0.656	1.43	1.25	2.76x10-6	60.2	49.6 ± 2.3
44-2N	1.08	0.592	3.31	8.99x10-6	38.7	39.1 ± 3.5
44-3N	0.859	0.916	1.16	8.57x10-6	25.1	24.1 ± 1.2
44-3S	1.00	0.646	1.73	1.13x10-6	18.9	44.9 ± 4.5
44-3X	5.05	1.06	6.59	5.75x10-6	29.3	13.9 ± 9.6
52-7N	1.17	0.631	8.99	5.16x10-6	16.5	21.0 ± 1.3
52-7S	1.09	0.469	2.77	3.73x10-6	13.6	20.5 ± 1.8
54-2N	1.28	0.377	6.12	5.84x10-6	56.6	39.9 ± 2.0
54-2S	0.949	0.353	2.18	6.65x10-6	32.2	48.4 ± 3.1
58-1N	0.982	1.58	2.76	4.80x10-6	82.2	76.7 ± 4.0
58-1S	1.07	1.64	2.58	4.84x10-6	84.7	74.4 ± 3.8
59-2N	1.09	2.02	3.87	5.44x10-6	62.5	68.1 ± 4.1
59-2S	1.17	2.19	5.47	6.19x10-6	62.4	71.3 ± 5.0
59-7N	1.09	2.98	7.65	9.59x10-6	80.7	80.9 ± 3.7
59-7S	1.06	2.78	2.67	9.89x10-6	71.9	89.3 ± 4.9
59-13X	2.27	1.30	2.17	4.41x10-6	83.5	86.8 ± 2.3

TABLE 6 (continued)

SUMMARY OF WHOLE ROCK K-AR AGE DATA FOR VOLCANIC ROCKS FROM THE LINE ISLANDS AND TUAMOTU ARCHIPELAGO

SAMPLE	SAMPLE WT. (g)	%K	R. S. D.* (x10-2)	RADIO. AR/g (std cc/g)	R%**	CALCULATED*** AGE (my)
60-6N	0.910	0.846	0.798	1.53x10-6	54.9	46.6 ± 2.7
60-6S	0.782	0.789	1.66	1.37x10-6	54.2	44.8 ± 2.3
63-7N	1.15	0.501	1.08	8.57x10-7	32.9	44.0 ± 2.3
63-7S	1.15	0.420	1.69	6.63x10-7	30.6	40.6 ± 2.0
PC6-1X	1.91	1.28	2.82	3.60x10-6	71.8	72.4 ± 3.6
PC6-2X	1.11	1.55	2.28	2.69x10-6	73.2	44.6 ± 2.2

Sample Preparation Leach: N = 6 Normal Nitric Acid

Sample # __ S = 6 Normal Sulfuric Acid

X = 2% Nitric Acid

* Mean and range of two measurements

** $R\% = \frac{^{40}\text{Ar (Radio)}}{^{40}\text{Ar (Total)}} \times 100$

*** Errors are estimates of standard deviation of precision

Analysts: G. Bochicchio and D. Glick, Hawaii Institute of Geophysics

TABLE 7

SUMMARY OF ^{40}AR/^{39}AR TOTAL FUSION AGE DATA FOR VOLCANIC ROCKS FROM THE LINE ISLANDS AND TUAMOTU ARCHIPELAGO *

SAMPLE	LOCATION	^{40}AR-^{36}AR	^{40}AR-^{39}AR	^{37}AR-^{40}AR**	PERCENT RADIOGENIC ^{40}AR	AGE ± 1σ (my)
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
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
RD59-12	12°31'N, 167°03'W	2463.	71.24	0.0106	88.0	85.0 ± 1.3
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
PCOD6-2	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

* - Modified from Schlanger et al., 1984.

** - ^{37}AR corrected for decay since irradiation.

Analyst: R. A. Duncan, Oregon State University

In light of the moderate degree of alteration of even the freshest samples from each dredge, the K-Ar ages determined should only be considered 'tentative' ages. The effects of basalt-sea water interaction discussed by Ozima et al. (1977) generally lowers the K-Ar age through the gradual loss of Ar and the influx of K into smectites during matrix glass alteration and renders the K-Ar ages unreliable. These effects are maximized in more vesicular samples, which permit more sea water circulation, or in samples that have been subjected to elevated temperatures during hydrothermal alteration. The four samples for which age determinations were performed by both methods (RD63-7, PCOD-6-2, RD43-1, and RD44-3) show the K-Ar ages to be 11-44 my younger than the $^{40}Ar/^{39}Ar$ ages. Schlanger et al. (1984) pointed out that the radiometric ages determined for multiple samples from the same seamount or from or very near seamounts and ridges for which paleontological and seamount magnetic data exists indicates that the $^{40}Ar/^{39}Ar$ ages should be considered more reliable. Total fusion ages for samples RD61-1 and RD61-5 are very close at 81.4 my and 82.6 my, respectively. Total fusion ages for samples RD52-1 and RD52-2 are somewhat close at 47.4 my and 41.8 my, respectively, while the K-Ar ages for rock splits for RD-52-7 average 20.7 my.

The 70-75 my Cretaceous biostratigraphic ages for dredges RD-45 and RD-44 reported by Haggerty et al. (1982) compare favorably with the $^{40}Ar/^{39}Ar$ volcanic rock ages of 70.5 my and 71.9 my, respectively, from the same dredges. K-Ar ages for rock splits from sample RD-44-3 range from 24.1 my to 44.9 my. Sager and Keating (1984) reported a near

Maestrichtian virtual geomagnetic pole (VGP) for seamount L8 (RD-44 dredge site) which had a $^{40}Ar/^{39}Ar$ age of 71.9 my. Seamount L2 (RD-59 dredge site) also had a Cretaceous VGP with a $^{40}Ar/^{39}Ar$ age of 85.0 my (Sager et al., 1982). Seamount L4 (RD-33 dredge site) had an Eocene-Oligocene VGP and a $^{40}Ar/^{39}Ar$ age of 39.3 my (Sager and Keating, 1984). Additionally, $^{40}Ar/^{39}Ar$ ages for samples RD63-7, 142D-11, and 143D-102, within a 150 km radius of each other, range from 86.0 my to 93.4 my while K-Ar ages for rock splits of sample RD63-7 average 42.3 my.

FIGURE 18 summarizes the available $^{40}Ar/^{39}Ar$ radiometric and biostratigraphic ages from along the Line Islands chain and northwestern Tuamotu Archipelago for samples obtained by the Hawaii Institute of Geophysics, Scripps Institution of Oceanography, and during legs 17 and 33 of the Deep Sea Drilling Project, as reported by Schlanger et al. (1984). Plots of $^{40}Ar/^{39}Ar$ ages (19a) and K-Ar and biostratigraphic ages (19b) versus distance along the chain from the Line-Tuamotu bend are presented in FIGURE 19, also as reported by Schlanger et al. (1984). The ages will be evaluated here from northwest to southeast along the chain. Prior to this Hawaii Institute of Geophysics investigation, no age dates existed in or along the Line Islands south of DSDP Site 315A.

Six $^{40}Ar/^{39}Ar$ total fusion ages of seamounts and ridges in the northern region of the Line Islands, samples 143D-102, 142D-11, RD63-7, RD61-1, RD61-5, and RD59-12, range from 81.4 my to 93.4 my and indicate fairly widespread middle to late Cretaceous volcanism in this region.

FIGURE 18. Map summarizing the distribution of $^{40}Ar/^{39}Ar$ radiometric ages, as reported in TABLE 7, and biostratigraphic ages from along the Line Islands chain and northwestern Tuamotu Archipelago. Dashed lines separate the northern, cross-trend, islands, and southern regions of the Line Islands, as in FIGURE 3. Modified from Schlanger et al., 1984.

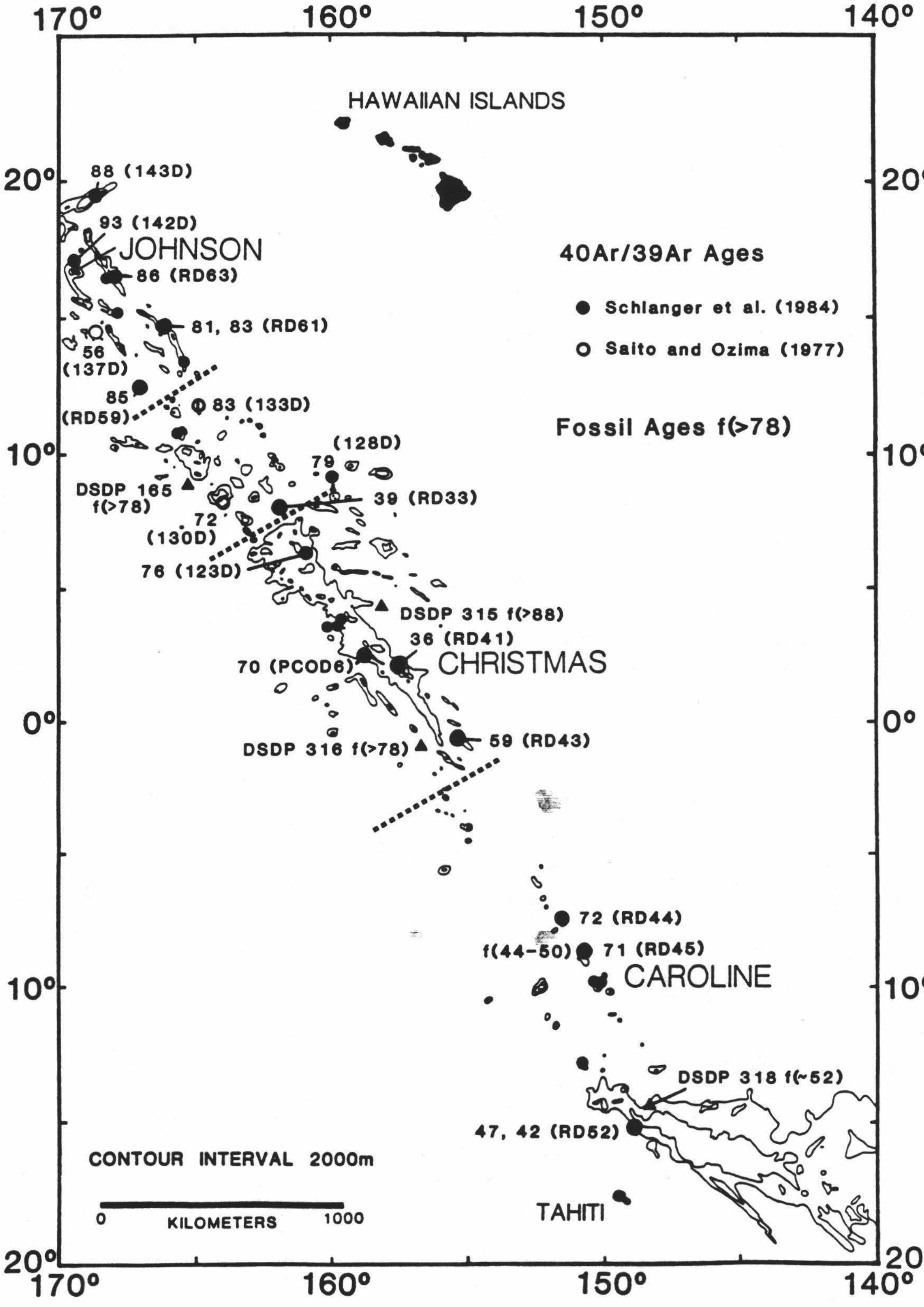
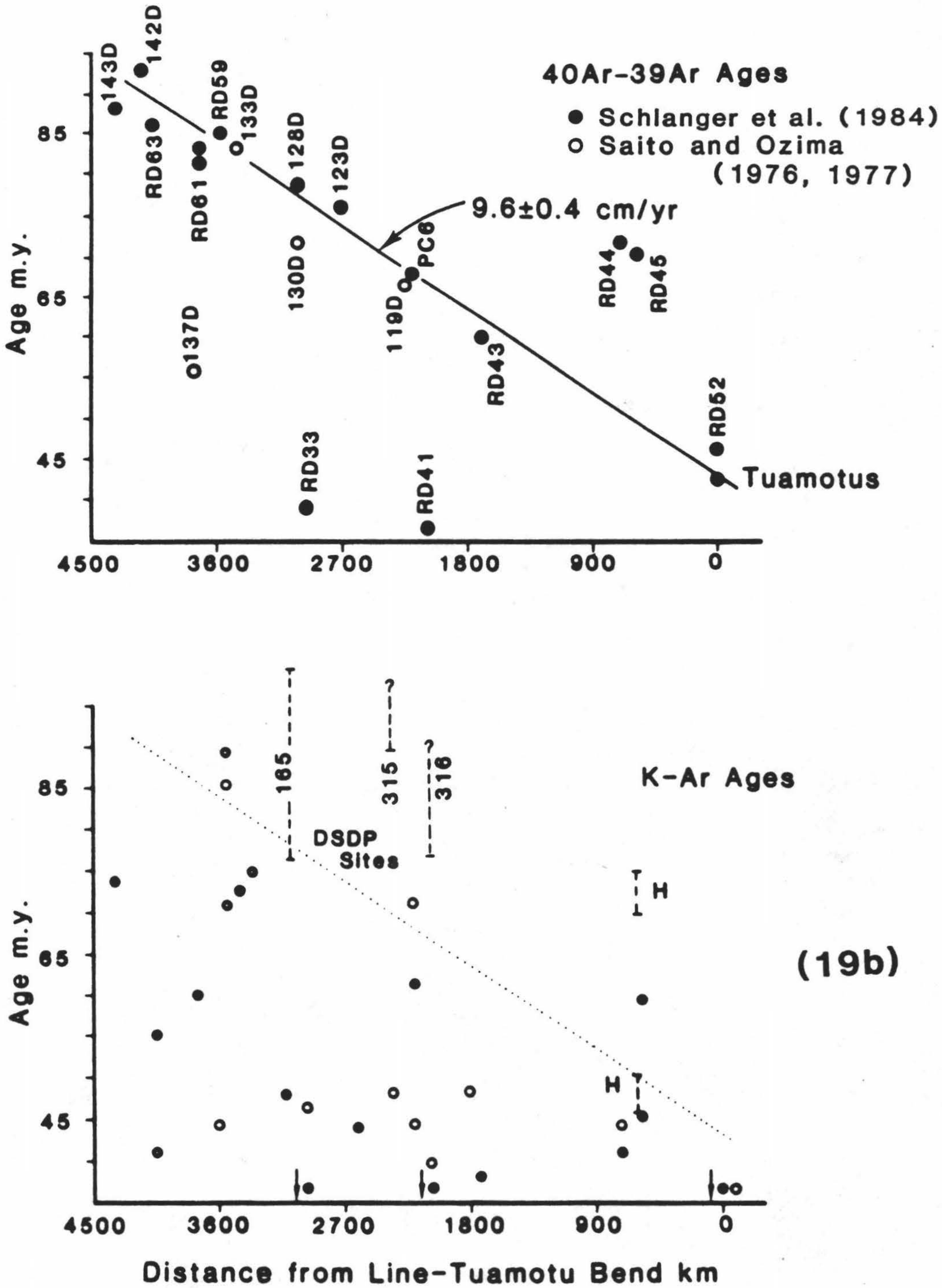

170°
160°
150°
140°
20°
10°
0°
10°
20°
HAWAIIAN ISLANDS
88 (143D)
93 (142D)
JOHNSON
86 (RD63)
81, 83 (RD61)
56
(137D)
85
(RD59)
83 (133D)
(128D)
79
DSDP 165
f(>78)
39 (RD33)
72
(130D)
76 (123D)
DSDP 315 f(>88)
36 (RD41)
70 (PCOD6)
CHRISTMAS
59 (RD43)
DSDP 316 f(>78)
72 (RD44)
f(44-50)
71 (RD45)
CAROLINE
DSDP 318 f(~52)
47, 42 (RD52)
TAHITI
40Ar/39Ar Ages
● Schlanger et al. (1984)
○ Saito and Ozima (1977)
Fossil Ages f(>78)
CONTOUR INTERVAL 2000m
0
KILOMETERS
1000

FIGURE 19. Radiometric and paleontologic ages along the Line Islands chain and the Tuamotu Archipelago. Modified from Schlanger et al., 1984.

a) ^{40}Ar/^{39}Ar ages as solid circles from Schlanger et al. (1984) and as open circles from Saito and Ozima (1976, 1977). The solid line shows a 9.6 + 0.4 cm/yr rate of migration of volcanism which Schlanger et al. (1984) reported 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)).


40Ar-39Ar Ages
● Schlanger et al. (1984)
○ Saito and Ozima (1976, 1977)
9.6±0.4 cm/yr
143D
142D
RD63
RD61
RD59
133D
128D
123D
130D
137D
119D
PC6
RD43
RD44
RD45
RD52
RD33
RD41
Tuamotus
Age m.y.
85
65
45
4500
3600
2700
1800
900
0
K-Ar Ages
165
315
316
?
DSDP Sites
H
H
Age m.y.
85
65
45
4500
3600
2700
1800
900
0
Distance from Line-Tuamotu Bend km

(19b)

However, Saito and Ozima (1977) reported both an isochron age of 127.5 my for sample 142D (note FIGURE 2) and a total fusion age of 114.8 my (note the 115 my open circle above 142D on FIGURE 19a), each significantly older than the 93.4 my total fusion age reported by Schlanger et al. (1984). No explanation was given for this discrepancy. Support for the 93.4 my age lies in the agreement to ages from samples 143D-102 and RD63-7. Additionally, a 55.6 my total fusion ages reported at Scripps' dredge 137D also indicates a northern region late Paleocene volcanic event (Saito and Ozima, 1977).

Three Cretaceous total fusion ages for cross-trend region samples 133D, 130D, and 128D-11 range from 71.5 my to 84.4 my (Saito and Ozima, 1977; Schlanger et al., 1984). Fossiliferous sediments interbedded with basalts at DSDP Site 165 indicate Cretaceous volcanism from 72 my to 83 my and possibly longer (Schlanger et al., 1984). A late Eocene age of 39.3 my reported for sample RD33-1 indicates an early Tertiary period of volcanism in the cross-trend region as well as the northern region.

Cretaceous total fusion ages of 76.4 my and 69.8 my are reported for islands region samples 123D-15 and PCOD6-2, respectively (Schlanger et al., 1984). A K-Ar age for plagioclase separates from a basalt cored at DSDP Site 315A of 93.3 my coupled with a nannofossil age of 88 my in overlying sediments indicates edifice-building volcanism at Site 315A ceased by 93 my ago, but is at least older than 88 my. Further, the oldest sediments reached at DSDP Site 316, which was associated with basaltic breccias, yielded nannofossil and foraminifera ages of 77 my to 80 my (early Campanian). Evidence for the extension of Tertiary volcanism into the islands region as well as the northern and cross-trend regions comes from a 59.0 my total fusion age for sample RD43-1.

The extension of Cretaceous volcanism into the southern region of the Line Islands can be seen in the 71.9 my and 70.5 my ages for samples RD44-3 and RD45-26D, respectively (Schlanger et al., 1984). However, Haggerty et al. (1982) reported a middle Eocene age of 44 my to 50 my for sediments interbedded with alkali basalts which gives the RD-45 seamount multiple ages of volcanism.

Two Eocene $^{40}Ar/^{39}Ar$ total fusion ages from the northwestern Tuamotu Archipelago of 47.4 my and 41.8 my reported for samples RD52-1 and RD52-2 coupled with early Eocene shallow water fossils cored at DSDP Site 318 indicates volcanism occurred from at least 42 my to 51 my in the area of the Line Islands-Tuamotu Archipelago bend (Schlanger et al., 1984). These ages are fairly compatible with the 37.5 my to 53.5 my range in fossil ages reported from five other northwestern Tuamotu Archipelago dredges (Jarrard and Clague, 1977). Also, these age ranges indicate that the volcanic nature of the Line-Tuamotu bend may be more complex than the 42 my age reported for the Hawaii-Emperor bend (Dalrymple and Clague, 1976).

SUMMARY

The petrology, geochemistry, and ages of volcanic rocks described in this study approximately doubles the previously available data base for the Line Islands Chain and expands the sampling coverage to include the entire length of the chain. Prior to this study, no volcanic rocks had been collected or described between DSDP Sites 316 and 318, a nearly 2100 km distance along the southern region of the chain. Volcanic rocks from eighteen rock dredges and one piston core collected aboard the R. V. Kana Keoki during three 1979 legs of the Hawaii Institute of Geophysics Line Islands Project were examined. Whole rock and clinopyroxene mineral compositions of the volcanic rocks examined in this study support the results of previous petrologic studies and suggest that the chain is composed for the most part of differentiated ocean island alkali basalt suite lavas. A variety of alkali basalts and mildly differentiated hawaiites have been recovered from dredges of seamounts and elongate ridges along the entire Line Islands Chain. Additionally, basalts transitional between tholeiites and alkali basalts are described from RD-44 and, possibly, RD-41 of this study, from Scripps dredge 133 (Natland, 1975, 1976a), and from DSDP Site 315A (Jackson et al., 1976). Natland (1975, 1976a) also described a phonolite from Scripps dredge 137 and potassic nephelinites from dredges 122, 129, and 138 along the chain and from dredge 134 on a ridge in the cross-trend region. A single dredge on the northwestern Tuamotu Archipelago of this study (RD-52) recovered a variety of alkali olivine basalt pillow lavas. No basalts resembling mid-ocean ridge basalts (MORB) or lavas of moderately to strongly ocean island tholeiitic affinity have been recovered from these dredges or from any previous dredges or DSDP sites in the Line Islands or Tuamotu Archipelago. Although ocean island tholeiites may comprise up to 99% of Hawaiian shield lavas (Macdonald and Katsura, 1964), it is not at all unusual for shield lavas from other oceanic islands or linear ridge volcanoes to be comprised primarily of alkali basalt suite lavas (St. Helena - Baker, 1969; Walvis Ridge - Hekinian, 1972; Madeira - Hughes and Brown, 1972; Samoa - Natland, 1975; Easter - Bonatti et al., 1977; Reunion - Ludden, 1978).

The volcanic rocks recovered in this study are, in general, slightly to severely altered pillow fragments, commonly manganese-oxide encrusted. Some of the fragments were embedded in volcanoclastic breccias. Two samples were recovered in an oriented piston core (PCOD-6). Iddingsite-replaced olivine is the major phenocryst phase in a majority of the rocks examined (up to 18% by mode) with lesser amounts of plagioclase and titaniferous augite. Modal counts for phenocrysts rarely exceeds 20%. Plagioclase (subhedral laths) and opaques (magnetite clots and titanomagnetite needles) are the dominant groundmass phases, with lesser amounts of clinopyroxene and, rarely, amphibole. All rocks examined contained altered interstitial, formerly glassy, matrix material (9-44% by mode). Groundmass textures are commonly hypocrystalline to hypohyaline in the alkali basalts (52-7, 59-1, 59-9, 59-10, 59-15, 63-7) and subtrachytic to intersertal in the amphibole-bearing hawaiites (59-7, 59-13, 46-1) and aphyric hawaiites (58-1, PCOD-6-1).

All samples show some petrographic or whole rock geochemical effect of alteration resulting from either rapid devitrification during quenching of the fresh lavas or during millions of years of exposure to sea water. The predominance of formerly-glassy or very fine-grained interstitial groundmass, the occurrence of thin, pale yellow celadonite vesicle linings, probably after glass, and the rare presence of trellice-patterned titanomagnetite needles indicates that these rocks were rapidly cooled. The original glass has been hydrated and variably altered to smectite-group clay minerals. These effects are manifested in the high total H_2O and alkalies values in most analyzed rocks. Most rocks have also been slightly to moderately oxidized to a dull reddish-brown color, reflected in the high Fe_2O_3/FeO ratios. The penetration of carbonate and marine phosphorite into rock fractures and vesicles probably accounts for the high values of CaO, CO_2, and P_2O_5, especially in sample 44-2. Olivine phenocrysts and groundmass grains are, in all cases, completely iddingsite-replaced, except where they are partially preserved in altered pillow rims (RD-52, RD-61). This replacement is likely to be the cause of low MgO abundances observed in many of these basalts.

Whole rock major element analyses are of limited use in altered samples such as these. Clinopyroxene mineral compositions have been used in a number of studies to infer magmatic affinities of altered host lavas. Microprobe analyses of clinopyroxenes from nine Line Islands rocks and one Tuamotu Archipelago basalt confirm the alkalic nature of the host lavas, with the exception of the transitional character of samples 44-2 and, possibly, 41-2. The alkalic to differentiated alkalic compositions of the clinopyroxenes analyzed here are indicated by several discriminant diagrams and plots (FIGURES 5, 6, and 7) and are similar to compositions of Hawaiian clinopyroxenes described by Fodor et al. (1975). The wide degree of scatter of the Al_2O_3 and TiO_2 abundances in clinopyroxenes of some samples, especially 63-7, 41-2, and 59-10, may best be explained by the effects of quenching on crystal chemistry (Coish and Taylor, 1979). Other possible, secondary, effects include the proximity of nearby plagioclase or titanomagnetite crystallization and the availability of Al and Ti atoms, respectively, for incorporation into a co-existing clinopyroxene (Gibb, 1973; Lofgren et al., 1974; Donaldson et al., 1975).

Amphibole phenocrysts were analyzed in three hawaiites from two dredges, RD-46 and RD-59. The amphiboles range in composition from kaersutite to ferroan pargasite or magnesian hastingsite. These hydrous phases are interpreted to be the result of low to moderate pressure crystallization, less than 10-20 Kb, under conditions of high P_{H_2O}.

Some alkali basalts (59-1, 59-9, 59-10, 59-15, 63-7) contain peridotitic inclusions of clinopyroxene-olivine aggregates, similar to Hawaiian alkali basalts. Some amphibole-bearing hawaiites (59-7, 59-12, 59-13) contain rare inclusions of clinopyroxene and spinels poikilitically enclosed in brown amphibole, inclusions exceedingly rare in Hawaiian lavas. Microprobe analyses of clinopyroxene in an inclusion of an amphibole-bearing hawaiite (59-13) resemble clinopyroxenes of more SiO_2-undersaturated, peralkaline lavas, suggestive of an undersaturated primary alkalic magma (as long as the clinopyroxenes are a cumulate phase). The titaniferous amphiboles in the inclusion poikilitically enclose the clinopyroxenes, similar to textures observed in kaersutite-bearing inclusions in alkali basalts from Arizona proposed by Best (1974) to represent stable hydrous mantle phases in the alkali basalt source region. The clinopyroxenes and amphiboles of the inclusion were of different compositions than clinopyroxene and amphibole phenocrysts in other RD-59 lavas, suggesting the possiblility of at least a different source region for the inclusion. Natland (1975, 1976a) proposed that, at least for the cross-trend region, the thermal convecting event under the Line Islands was much more dispersed than the thermal event under the Hawaiian Islands. According to Natland, this allowed for the formation of voluminous hydrous-phase enriched mantle which, when partially melted, yielded liquids similar to the strongly SiO_2-undersaturated potassic nephelinites.

It was this argument for a hydrous-phase enriched mantle that Natland (1975, 1976a) used as a source for the potassic nephelinites described from Scripps dredges 122, 129, 134, and 138. Natland described the biotites and amphiboles in the inclusions as being petrographically similar to the biotites and amphiboles in the host rocks and further suggested that the host rocks and inclusions were "comagmatic". Information from two directions in this study, however, may be used to question the occurrence of potassic nephelinites along the Line Islands chain.

First, Natland's classification of the potassic nephelinites appears to be based primarily on whole rock chemical analyses. Oxide totals for the four reported analyses of potassic nephelinites (samples 122-1, 129-2, 134-1, and 134-N) along the chain range from 87.08-97.27% (92.32% average), below even Natland's 94-97% range indicating a "moderate degree of alteration". The alteration of interstitial glass, replacement of olivine with clay minerals, and infilling of vesicles with phosphorite and calcareous debris has probably influenced the whole rock compositions towards artificially alkalic and phosphorous totals. Second, the amphiboles in the rocks observed in this study differ both optically and chemically from those minerals in the analyzed inclusion (59-13 Xenolith). The amphiboles in the rock are euhedral to slightly rounded crystals with no inclusions. The amphiboles in the inclusion are severely exsolved with inclusions of resorbed titanaugites. Crystalline plagioclase generally infills the fractures. The xenolith amphiboles are also lower in TiO_2 and K_2O and higher in Na_2O than the amphiboles in the rock. Therefore, a determination that the Line Islands contain the first occurrence of potassic nephelinites on oceanic crust based on whole rock analyses of moderately altered rocks should be viewed with caution until a more complete evaluation of immobile trace and rare-earth elements and mineral compositions on the samples in question is performed.

Rare-earth element patterns for the Line Islands rocks analyzed are all light rare-earth element (LREE) enriched, typical of most ocean island alkali basalt suite lavas (Sun and Hanson, 1975). Four samples analyzed from RD-59 show that both the alkali basalts (59-1, 59-2) and the hawaiites (59-7, 59-13) are LREE-enriched. However, the hawaiites are lower in the heavy rare-earth elements (HREE) than the alkali basalts, contrary to the increase in total REE abundances noted previously in Hawaiian alkali basalt suite lavas (Schilling and Winchester, 1969).

It was noted in the RESULTS Chapter that a majority of alkali basalts probably result from low degrees of partial melting of a garnet-bearing mantle more enriched in the incompatible elements than the source for MORBS's. Low pressure fractionation of clinopyroxene and, possibly, Cr-spinel could be supported here by the absence of clinopyroxene phenocrysts and by the low abundance of Cr in the hawaiites. If the RD-59 alkali basalts and hawaiites are related, apatite fractionation at an earlier stage of alkali basalt suite differentiation than in Hawaiian lavas could account for the lower HREE abundances observed in the hawaiites than the alkali basalts. Without apatite, amphibole and clinopyroxene fractionation under conditions of increasing P_{H_2O} in the source region could deplete the parental liquids in the HREE's more than the LREE's. Also, the concave-up REE patterns in the hawaiites is also consistent with amphibole fractionation from alkali basalt parental liquids. Amphibole encloses clinopyroxenes and spinels in the 59-13 Xenolith in the hawaiites. The hawaiites also contain high abundances of the Large Ion Lithophile (LIL) elements and show a decrease in whole rock K/Rb ratio from the alkali basalts to the hawaiites.

$^{40}Ar/^{39}Ar$ total fusion ages for thirteen Line Islands and one Tuamotu Archipelago dredge or piston core sites were reported in TABLE 7. These ages, coupled with previous total fusion ages and biostratigraphic ages, including DSDP Sites 165, 315, and 316, were presented in FIGURE 18. Evidence was provided for the unreliability of K-Ar age determinations on moderately altered volcanic rocks, a point best illustrated in FIGURE 19b by the scatter of K-Ar ages in direct comparison to total fusion ages along the chain.

A plot of the radiometric data versus distance along the chain from the Line-Tuamotu bend to the Mid-Pacific Mountains (FIGURE 19a) illustrated that an approximate rate of migration of volcanism of 9.6 cm/yr provided a reasonable fit to the bulk of the ages for a single hot-spot model (Schlanger et al., 1984). The rate of migration of hot-spot volcanism along the Hawaiian Islands is 9.2 cm/yr, using a 42.0 my age for the Hawaii-Emperor bend (Dalrymple and Clague, 1976). However, the occurrence of Tertiary volcanics in the northern (137D), cross-trend (RD-33), and islands (RD-41) regions, as well as the southern region (RD-45), provided clear evidence that no single episode of volcanic activity affected the Line Islands chain. The apparent synchronicity of Cretaceous volcanism throughout the enitre chain first proposed by Haggerty et al. (1982) was supported by radiometric ages of 93.4 my (142D-11) in the northern region to 70.5 my (RD45-26D) in the southern region (Schlanger et al., 1984). Further, direct evidence for recurrent volcanism, after an approximate 25 my hiatus, at the same edifice was provided by late Cretaceous radiometric and middle Eocene biostratigraphic ages at dredge site RD-45.

Several points can be made to summarize the age data reported along the Line Islands chain to date. The bulk of the available age data describes a age-progressive volcanic trend of 9.6 cm/yr for a single hot-spot now active near the intersection of the East Pacific Rise with the Sala y Gomez ridge (Easter Island), as originally proposed by Morgan (1972a, 1972b) and later modified by Schlanger et al. (1984). Tertiary volcanic ages for northern, cross-trend, and islands region seamounts and ridges, however, suggests a later overprinting of a second hot-spot along the current Line Islands-Marquesas Islands Swell (Crough and Jarrard, 1981). Haggerty et al. (1981) proposed an alternative to a second hot-spot for these Paleocene and Eocene ages in the Line Islands by attributing this volcanism to a broader, Pacific-wide Eocene volcanic event which also affected the Marshall Islands and the Nauru Basin areas. The Cretaceous ages at dredge sites RD-44 and RD-45, also not easily reconcilable with a single hot-spot, may also by attributed to apparent widespread Cretaceous Pacific mid-plate volcanism as observed in the Mid-Pacific Mountains, Emperor Seamounts, Marshall Islands, Geisha Guyots, Musicians Seamounts, the Marianas area of the western Pacific, and the Line Islands (Haggerty et al., 1981; note especially Figure 8). Finally, multiple volcanic events on the same seamount (RD-45) precludes a single hot-spot origin for this edifice.

Conclusions

Several models were presented in the INTRODUCTION Chapter for the origin of the Line Islands chain. Although the addition of petrologic, geochemical, and age data from this study more than doubles the previous work of Bass et al. (1973), Jackson et al. (1976), Natland (1975, 1976a), and Saito and Ozima (1976, 1977) and extends the analytical coverage to include the entire length of the chain, conclusions drawn from the complete set of data should still be considered preliminary. However, sufficient data exists to address several of these models of origin on the basis of comparison to other linear volcanic chains, especially the Hawaii-Emperor chain.

Petrologic and geochemical data from volcanic rocks analyzed in this and previous studies indicate that the volcanic edifices sampled along the chain are composed primarily of ocean island alkali basalt suite lavas with ocean island tholeiitic to transitonal lavas less prevalent. These lavas were shown to be similar to Hawaiian alkali basalt suite lavas and tholeiites. No basalts analyzed in this study were similar to mid-ocean ridge basalts (MORB's) or to the peralkaline volcanics common to continental extensional tectonic regimes.

Collectively, the petrologic and geochemical data are consistent with a hot-spot model of origin for the Line Islands similar to that of the Hawaiian Islands. The proposed models of Winterer (1976b) for contemporaneous spreading ridge volcanism about 110 my ago coupled with ridge jumps and the spreading ridge origin based solely on gravity modelling by Watts et al. (1980) may be discounted on the basis of variety and geographic extent of ocean island alkali basalt suite and tholeiitic lavas, seamount paleomagnetic data, and middle to late Cretaceous through early Tertiary edifice-building radiometric and biostratigraphic ages. Also, the Line Islands do not display the extreme petrologic diversity of rock types, ranging from tholeiites to alkalic differentiates to rhyolites, observed where hot-spots lie on or near active spreading ridge crests (Iceland, Easter, Galapagos-Carmichael et al., 1974; Ninety East Ridge-Hekinian, 1974). No evidence from this study appears to refute or support the propagating fracture models of Betz and Hess (1942) and Jackson and Wright (1970) other than that the resulting tectonic regime implied by the models is tensional, similar to mid-ocean ridge regimes, and no MORB's were described in this study.

No modern analog to a 'leaky' transform fault has been described to date. The coeval formation of the Line Islands 85 my ago along a remnant Central Pacific Rise transform fault as proposed by Orwig and Kroenke (1980) may be refuted by the Cretaceous age of 93.4 my for Scripps dredge 142 and by numerous early Tertiary ages presented in this and previous studies. The Farrar and Dixon (1981) model of volcanism between 67-40 my ago along a transform fault as a result of up to 1700 km of fault propagation through Cretaceous crust does not attempt to explain the presence of Cretaceous age alkali basalt suite volcanic edifices along the entirety of the chain. Nor have volcanic rocks described in this or previous studies resembled intrusive gabbroic and peridotitic rocks and fractionated MORB's common to oceanic transform faults described by Thompson and Melson (1972) and Hekinian and Thompson (1976).

Although the petrologic and geochemical data presented in this and previous studies suggests a mid-plate origin for the Line Islands chain similar to the Hawaii-Emperor chain, the collective appraisal of the determined ages of volcanism along the chain suggest a more complex origin than that of a single hot-spot. Volcanic activity along the Line Islands had occurred sporadically for nearly 50 my. The radiometric and biostratigraphic ages available confirm the complex nature of volcanic activity along the entirety of the Line Islands chain from the middle to late Cretaceous to the early Tertiary. No single hot-spot model could account for this range in ages. Epp (1978) suggested the possibility of multiple hot-spot events under the Pacific crust from the Cretaceous to early Tertiary time through a residual structural weakness in the Pacific plate parallel to a former ridge crest. Further possible support for a remnant structural weakness near a ridge crest where oceanic islands may be formed was presented by Batiza (1977), who described differentiated alkali basalts, including hawaiites and mugearites, from Guadelupe Island, a Pacific Ocean island built up on a fossil ridge crest within 7 my of formation of the crust.

The Line Islands are not the only Pacific plate feature to undergo a long-lasting Cretaceous volcanic history or a later Tertiary overprinting. From biostratigraphic data reviewed by Schlanger et al. (1981) and supported by Haggerty et al. (1982) and Schlanger et al.

(1984), widespread intra-plate volcanism occurred during the Cretaceous between 110-70 my and into the Tertiary as young as 39 my in several Pacific localities. More clearly, the formation history of several Pacific plate features, especially the Line Islands, were greatly affected by complex tectonic processes during the Cretaceous and Tertiary time periods which cannot be attributed to volcanism from a single hot-spot or to volcanism at or near mid-ocean ridge crests, along leaky transform faults, or along propagating ridges. The key to unravelling the history of formation of the Line Islands chain lies in further detailed dredging, description, and age dating of volcanic rocks and reefal debris from seamounts and ridges along the chain, coupled with continued understanding of the tectonic processes which have affected the entire Pacific plate.

APPENDIX A

SUMMARY OF THE ANALYTICAL TECHNIQUES USED IN THE LABORATORY OF K. RAMLAL, DEPARTMENT OF EARTH SCIENCES, UNIVERSITY OF MANITOBA*

ELEMENT	METHOD
Si, Al, total Fe Ca, K, Mn, Zr	X-Ray Fluorescence Spectrophotometry. Weighed sample plus $Li_2B_4O_7$ and La_2O_3 heated in a graphite crucible at about 1100°C for one half hour. Resulting bead with H_3BO_4 ground to $^{-}200$ mesh, then compressed to 50,000 psi. Analyzed on a multichannel ARL Spectrometer.
Na, Mg	Atomic Absorption Spectrophotometry. Rock dissolved with HF, H_2SO_4, and HNO_3 in platinum crucibles. Analyzed on a Perkin-Elmer 303 A. A. S..
P_2O_5	Colorimetry. Solution as for Na above. The absorption at 430 mu of molybdivanadophosphoric acid complex. Analyzed on a Unicam 500 Spectrophotometer.
FeO	Rock decomposed with HF and 1:3 H_2SO_4, solution titrated with $K_2Cr_2O_7$ using sodium diphenylamine sulfonate as the indicator.
Total H_2O	Determined by heating sample in a stream of dry oxygen in an induction furnace at >1100°C. H_2O collected on anhydrone and weighed.
H_2O^-	Determined by heating sample to a constant weight at 110°C.
H_2O^+	Total H_2O - H_2O^-.
CO_2	Sample decomposed by HCl and heat. CO_2 evolved passed through drying train and collected on ascarite.
CO_2 (low S samples)	Determined simultaneously with Total H_2O. CO_2 evolved collected on ascarite. Small amounts of SO_2 removed on MnO (activated).

APPENDIX A (continued)

CONSTITUENTS, CONCENTRATIONS, PRECISION, AND ACCURACY OF MAJOR ELEMENT DETERMINATIONS, DEPARTMENT OF EARTH SCIENCES, UNIVERSITY OF MANITOBA*

Constituent	Concentration Percent	Instrument Precision	Accuracy of Replicates
SiO_2	59.60	0.12	0.20
Al_2O_3	9.34	0.05	0.13
Fe_2O_3 (total)	10.08	0.017	0.03
MgO	4.04	0.04	0.10
CaO	10.22	0.02	0.07
Na_2O	4.20	0.01	0.05
K_2O	2.69	0.01	0.01
TiO_2	0.48	0.02	0.02
P_2O_5	0.20	0.01	0.01
MnO	0.41	0.01	0.01
H_2O (total)	1.60	0.03	0.06
CO_2	1.15	0.05	0.12
FeO	10.92	—	0.04
Zr	0.027	0.003	0.005
Cr	360 ppm	2.0	5.0
Ni	77 ppm	1.0	3.0
V	380 ppm	10.0	15.0

* = written communication by K. Ramlal, 1981.

APPENDIX B

DREDGE SITE MORPHOLOGY AND PETROGRAPHIC DESCRIPTIONS OF VOLCANIC ROCKS RECOVERED BY THE R/V KANA KEOKI FROM THE LINE ISLANDS IN 1979

ROCK DREDGE-33

Northeast flank of a small ridge 255 km north of Palmyra Island. Pillow fragments and rounded to angular basalt cobbles (5-25 cm long), variably Mn-coated (1-5 cm), slightly to moderately altered. Five thin-sections, two chemical analyses (33-1, 4), and one age date (33-4).

Lithology: vesicular (10-15%) olivine-plagioclase phyric alkali olivine basalts. Texture: dominantly hyalopilitic porphyry to intergranular, may be locally sub-ophitic. Phenocrysts: Olivine - 10-15%, iddingsite-replaced, euhedral, skeletal crystals and fragments (<2 mm); Plagioclase - 1-5%, both as prismatic crystals and as rounded tabular grains (<1 mm), commonly twinned, An_{40}-An_{45}*. Groundmass: abundant plagioclase microlites and fragments, angular chips and microphenocrysts of replaced olivine and minor clinopyroxene, and abundant opaques as very fine-grained needles of titanomagnetite (commonly trellice-patterned), and variable amounts of pale to orangish-brown oxidized matrix (up to 30%), altered to smectite-group clay minerals. Vesicles are round, generally <2 mm in diameter,

* = All plagioclase compositions given in APPENDIX B were determined by the Michel-Levy optical technique.

and are commonly thinly bright yellow clay-lined (celadonite), few are Mn-stained. Several samples were partially rimmed (<5 mm thick) with bright orangish-brown altered glass (sideromelane).

ROCK DREDGE-35

Western flank of a seamount 360 km northwest of Christmas Island. Few basalt pebbles (<1.5 cm diameter) embedded in lead dredge weight. One thin-section.

Lithology: massive plagioclase-clinopyroxene phyric hawaiite. Texture: sub-trachytic. Phenocrysts: Plagioclase - 5-10%, euhedral to subhedral crystals (<1.5 mm), most twinned, some slightly zoned; Clinopyroxene - 1%, very few rounded, partially resorbed crystals (<1 mm). Groundmass: abundant plagioclase microlites, very few small clinopyroxene fragments, rare iddingsite-replaced olivine fragments, and abundant very fine-grained clots of titanomagnetite set in abundant gray to pale brown, slightly altered matrix.

ROCK DREDGE- 41

Northern flank of Christmas Island. Volcanoclastic breccias containing basalt clasts (<10 cm in diameter). Clasts are rounded, slightly to moderately altered, and are thinly Mn-coated (<1 cm thick). Three basalt clasts were thin-sectioned, one chemical analysis (41-2), and two microprobe analyses (41-1, 41-2).

Lithologies: 1) vesicular (15-30%) olivine-clinopyroxene phyric alkali olivine basalt (41-2). Texture: porphyritic. Phenocrysts: Olivine - 10-25%, euhedral to subhedral, iddingsite-replaced (<4 mm); Clinopyroxene - 5-10%, titanaugite, subhedral, tabular, fragments (<2 mm). Groundmass: abundant plagioclase microlites, fine-grained glomeroporphyritic aggregates and elongate chips of clinopyroxene, few iddingsite-replaced olivine fragments, and abundant very fine-grained clots of titanomagnetite set in a fine-grained medium gray to pale brown altered matrix. Vesicles are irregularly shaped and up to 7 mm in diameter, commonly carbonate filled.

2) vesicular (15%) clinopyroxene-plagioclase-olivine phyric alkali basalt (41-1). Texture: hypohyaline porphyry, may be locally sub-ophitic. Phenocrysts: Clinopyroxene - 15%, titanaugite, euhedral to subhedral, commonly concentric zoned crystals (1-7 mm), may include opaques and replaced olivine fragments, few are partially resorbed; Plagioclase - prismatic and rounded tabular crystals (1-2 mm long), commonly twinned, some zoned; Olivine - 5%, euhedral to suhedral, partially replaced crystals and minor anhedral grains (<2 mm). Groundmass: few very fine-grained plagioclase laths, very few clinopyroxene and replaced olivine fragments, and titanomagnetite clots set in a very fine-grained, dark gray to black, partially altered matrix. Vesicles are irregularly shaped, <7 mm in diameter, and are

generally infilled with carbonate and minor zeolites.

ROCK DREDGE-42

Southwestern flank of a ridge 150 km southwest of Christmas Island. Volcanic breccias with few clasts (<5 cm long) of moderately to severely altered, Mn-coated (4-6 cm thick) basalts. One thin-section.

Lithology: vesicular (20%) olivine phyric alkali olivine basalt. Texture: hyalopilitic porphyry. Phenocrysts: Olivine - 10%, subhedral to angular, iddingsite-replaced crystals (<2 mm). Groundmass: replaced olivine fragments and microphenocrysts, plagioclase microlites, abundant titanomagnetite needles and clots, and very few clinopyroxene fragments set in a medium grayish-brown altered matrix. Vesicles are irregularly shaped, <2 mm in diameter, and are commonly thinly brown clay-lined and zeolite infilled.

ROCK DREDGE-43

Northern flank of a ridge 330 km southeast of Christmas Island. Very few, Mn-coated (4-5 cm thick), moderately altered basalts. One thin-section, chemical analysis, and age date (43-1).

Lithology: vesicular (18%) olivine-plagioclase phyric alkali olivine basalt. Texture: variolitic to intergranular. Phenocrysts: Olivine - 12%, euhedral to subhedral, iddingsite-replaced crystals (<1.5 mm); Plagioclase - 1%, few tabular, anhedral, twinned crystals (<2 mm). Groundmass: abundant plagioclase microlites (commonly as coarse-grained spherulites, An_{60}-An_{65}, 0.5 mm) and tabular anhedral grains (commonly with undulose extinction), replaced olivine fragments, and titanomagnetite needles and clots set in a pale to medium brown, altered matrix with minor Mn-stains. Vesicles are round to irregular shaped, <1 mm in diameter, and are unfilled, very few are thinly brown clay-lined.

ROCK DREDGE-44

Southern flank of a seamount 280 km northwest of Caroline Island. Volcanoclastic breccia and angular fragments of massive, moderately to severely altered basalts, commonly oxidized reddish-brown and variably covered with Mn-crusts (1-4 cm thick). Four thin-sections, two chemical analyses (44-2, 3), one rare-earth analysis (44-3), one microprobe analysis (44-2), and two age dates (44-2, 3).

Lithologies: 1) massive plagioclase-olivine phyric transitional tholeiite to alkali basalt (44-2). Texture: sub-trachytic. Phenocrysts: Plagioclase - 4-5%, few euhedral to subhedral, tabular crystals (<2 mm), commonly zoned and twinned, some partially resorbed; Olivine - <1%, very few, euhedral, iddingsite-replaced crystals (<1 mm). Groundmass: abundant plagioclase laths and microlites, fine-grained replaced olivine fragments, abundant, very fine-grained titanomagnetite clots, and very few clinopyroxene fragments set in a medium gray to greenish-gray, altered matrix.

2) massive plagioclase phyric hawaiite (44-3). Texture: aphyric. Very few angular to rounded, tabular crystals of plagioclase (<1%, An_{40}-An_{45}, 0.1 mm). Groundmass: abundant very fine-grained plagioclase microlites and replaced olivine fragments, and few irregular titanomagnetite clots and Mn-stains set in a pale to medium brown, altered matrix.

ROCK DREDGE-45

Northeastern flank of a seamount 115 km northwest of Caroline Island. Few volcanic rock fragments, moderately altered and oxidized, thinly Mn-coated (<1 cm). Three thin-sections, one chemical analysis (45-1).

Lithology: vesicular(15-20%) olivine-plagioclase phyric alkali olivine basalt. Texture: hyalopilitic porphyry to hypohyaline. Phenocrysts: Olivine - 5-10%, subhedral to rounded, iddingsite-replaced crystals (<1.5 mm); Plagioclase - 1-5%, subhedral, partially resorbed, severely-altered crystals (<3 mm), generally contain altered glass and replaced olivine inclusions. Groundmass: abundant plagioclase microlites, replaced olivine fragments, and few titanomagnetite clots and Mn-stains set in a pale brown to reddish-brown, altered matrix. Vesicles are round to irregularly shaped, <2 mm in diameter, and are generally celadonite and less commonly zeolite-lined.

ROCK DREDGE-46

Northeastern flank of Caroline Island. Very few basalt cobbles and volcanoclastic breccia fragments, moderately altered and oxidized, and variably Mn-coated (0-2 mm thick). Two thin-sections and one chemical and microprobe analysis (46-1).

Lithology: vesicular (30%) amphibole-plagioclase phyric alkali basalt. Texture: hypohyalline to subtrachytic. Phenocrysts: Amphibole - 2%, few subhedral to rounded brown crystals (<0.5 mm); Plagioclase - <1%, very few anhedral fragments of prismatic crystals (<0.5 mm). A single, anisotropic, orthorhombic phenocryst (0.5 mm) is probably a sulphide phase (marcasite?), likely to be secondary in origin. Groundmass: abundant fine-grained plagioclase microlites and minor iddingsite-replaced olivine fragments and titanomagnetite clots set in a strongly oxidized, medium brown, altered matrix. Vesicles are round to slightly elongate roughly parallel to groundmass plagioclase laths, <2 mm in diameter, and are commonly zeolite or carbonate infilled.

ROCK DREDGE-47

Northeastern flank of Caroline Island in deeper water at the same location as RD-46. One volcanic rock recovered, a moderately altered and slightly oxidized, Mn-coating free basalt. One thin-section.

Lithology: vesicular (30%) olivine-clinopyroxene-plagioclase phyric alkali olivine basalt. Texture: porphyritic. Phenocrysts: Olivine - 5-10%, subhedral, iddingsite-replaced crystals (<2 mm); Clinopyroxene - <5%, titanaugite, rounded cyrstals (<1 mm), few contain altered glass; Plagioclase - <1%, very few altered and partially resorbed crystals (<0.5 mm), most contain minor altered glass. Groundmass: abundant replaced olivine fragments and plagioclase microlites set in a brown to dark gray, altered matrix. Vesicles are round to irregularly shaped, <1 mm in diameter, and are generally thinly celadonite-lined (<0.5 mm thick) and zeolite infilled (natrolite).

ROCK DREDGE-51

Northern flank of a seamount 330 km south of Caroline Island. Volcanoclastic breccias recovered containing pillow and angular basalt fragments. One pillow basalt fragment removed (10 cm long), slightly altered and oxidized, and Mn-coating free. Two thin-sections of the same fragment.

Lithology: vesicular (15%) olivine phyric alkali olivine basalt. Texture: porphyritic. Phenocrysts: Olivine - 15-20%, euhedral to subhedral, iddingsite-replaced crystals (<3 mm). Groundmass: abundant plagioclase microlites and replaced olivine fragments, and minor very fine-grained titanomagnetite needles and clots set in a reddish-brown, altered matrix. Pillow rim (0.5-1.0mm thick) contains slightly-replaced olivine phenocrysts and small plagioclase microlites set in an orangish-brown, slightly altered matrix of sideromelane. Vesicles are round to irregularly shaped, <1 mm in diameter, and are generally thinly Mn-lined (<0.5 mm thick).

ROCK DREDGE-52

Southwestern flank of a ridge at the northwestern end of the Tuamotu Archipelago 305 km north of Tahiti. Angular, broken fragments of pillow basalts, slightly altered and oxidized, with a thin, patchy Mn-coating (<1 cm thick). Nine thin-sections, four chemical analyses (52-1, 2, 4, 7), and one microprobe analysis and age date (52-7).

Lithologies: 1) vesicular (20-25%) olivine-plagioclase-clinopyroxene phyric alkali olivine basalt (52-1, 2, 4, 7). Texture: porphyritic, may be locally sub-ophitic. Phenocrysts: Olivine - 10-15%, subhedral, iddingsite-replaced crystals and angular fragments (<2 mm); Plagioclase - 4-10%, tabular to equant, subhedral, slightly to moderately altered crystals (<2 mm, An_{45}-An_{55}), may contain altered glass and fine-grained opaque clots, may also occur as uncommon rounded to subhedral equant megacrysts, 5-8 mm long, commonly twinned; Clinopyroxene - 1-3%, titanaugite, few, rounded crystals (<2 mm), many contain replaced olivine, altered glass, and fine-grained opaque clots. Groundmass: abundant plagioclase microlites and fragments, common clinopyroxene chips, replaced olivine fragments, and abundant very fine-grained titanomagnetite needles (commonly trellice-patterned) and minor clots set in a medium gray to pale brown, slightly altered matrix. Vesicles are round to irregular, <3 mm in diameter, and only a few are thinly brown clay or Mn-stain lined.

2) vesicular (20-25%) olivine phyric alkali olivine basalt. Texture: hypohyalline porphyry, may be locally spherulitic. Phenocrysts: Olivine - 15-20%, euhedral to subhedral, replaced crystals (<3 mm). Altered glass rims (sideromelane, 0.5-2 cm thick) of pillows contain only slightly-replaced olivine phenocrysts. Groundmass: abundant replaced olivine fragments, plagioclase microlites and fragments, minor fine-grained clinopyroxene chips, and very fine-grained titanomagnetite clots and needles set in a more-oxidized, brownish-gray matrix. Vesicles are irregular to round in shape, <3 mm in diameter, and are free from clay or Mn-infilling or lining.

ROCK DREDGE-54

Northwestern flank of a seamount 320 km norhtwest of Christmas Island. Mixture of massive and very vesicular basalts, moderately to severely altered and oxidized, many with thin, patchy Mn-coats (<1 cm thick). Three thin-sections and one chemical and microprobe analysis and age date (54-2).

Lithologies: 1) massive aphyric alkali basalt (54-2).

Groundmass: abundant plagioclase microlites (An_{40}-An_{45}) and tabular fragments, abundant very fine-grained titanomagnetite clots, iddingsite-replaced olivine fragments and elongate chips, and clinopyroxene fragments set in a very fine-grained reddish-brown matrix. The very few vesicles present (<1%) are round, <0.5 mm in diameter, and are very thinly celadonite or zeolite-lined.

2) vesicular (40%) aphyric alkali basalt. Contain very few plagioclase phenocrysts (<1%) as small, tabular to rounded, crystals (<1 mm), commonly twinned. Groundmass: plagioclase microlites, replaced olivine microphenocrysts and fragments, and abundant titanomagnetite clots and Mn-stains set in a grayish-brown, altered matrix. Vesicles are round, <3 mm in diameter, and are free if infilling material.

ROCK DREDGE-58

Western flank of a seamount 815 km southeast of Johnson Island. Volcanoclastic breccias containing angular fragments of slightly altered volcanic rock clasts (<2 cm long) with a thin, patchy Mn-coating (<1 cm thick). Two thin-sections and one chemical analysis and age date (58-1).

Lithology: massive aphyric hawaiite. Texture: hypocrystalline to felted. Groundmass: abundant plagioclase microlites and rounded, tabular fragments, abundant titanomagnetite as both very fine-grained clots and larger clots (<0.3 mm), anhedral pale brown amphibole grains, and minor iddingsite-replaced olivine fragments set in a very fine-grained medium to dark gray, altered matrix. Also contains very minor alkali feldspar as very fine-grained, irregular patches in the matrix.

ROCK DREDGE-59

Southern flank of a seamount 560 km southeast of Johnson Island. Mixture of sub-angular fragments (5-25 cm long) of massive and vesicular, Mn-coating free volcanic rocks, slightly to moderately altered. Seventeen thin-sections, six chemical analyses (59-1, 2, 7, 10, 12, 13), four rare-earth analyses (59-1, 2, 7, 13), six microprobe analyses (59-1, 7, 9, 10, 13, 15), and three age dates (59-2, 7, 13).

Lithologies: 1) vesicular (10-40%) olivine-clinopyroxene-plagioclase phyric alkali olivine basalt (59-1, 2,). Texture: porphyritic. Phenocrysts: Olivine - 5-15%, euhedral to anhedral, iddingsite-replaced crystals (<2 mm); Clinopyroxene - 1-5%, titanaugite, rounded, slightly altered, partially resorbed crystals (<2 mm); Plagioclase - 1-3%, rounded, partially resorbed and corroded crystals (<1 mm), many contain altered glass and very fine-grained opaque clots. Groundmass: plagioclase microlites and tabular fragments, replaced olivine chips and microphenocrysts, titanomagnetite clots and needles (commonly trellice-patterned), and minor clinopyroxene fragments set in a very fine-grained brownish-gray matrix. Vesicles are round and 1-4 mm in diameter, many are thinly celadonite-lined (<0.5 mm thick).

2) vesicular (15-25%) clinopyroxene-olivine-plagioclase phyric alkali basalt (59-9, 15) and ankaramite (59-10). Texture: hyalopilitic to hypocrystalline. Phenocrysts: Clinopyroxene - 10-15%, titanaugite, subhedral to rounded crystals (2-9 mm), some partially resorbed and corroded, some have altered glass inclusions; Olivine - 5%, euhedral to angular, replaced crystals (<2 mm); Plagioclase - <1%, very few rounded crystals (<3 mm), most are concentric zoned and twinned, some have altered glass inclusions. Groundmass: rounded tabular fragments and microlites of plagioclase, replaced olivine chips and microphenocrysts, titanomagnetite clots and needles (commonly trellice-patterned), variable amounts of very fine-grained amphibole needles, and minor clinopyroxene fragments set in a very fine-grained, pale brown to brown, altered matrix. Vesicles are round and 1-3 mm in diameter, most are thinly celadonite-lined (<0.5 mm thick).

59-2, 59-9, and 59-10 contain clinopyroxene-olivine aggregates as round inclusions up to 1.5 cm long, which also contain minor titanomagnetite as trellice-patterned needles and irregular clots and small plagioclase crystals as interstitial material. The clinopyroxenes are pale pink in thin-section and are euhedral to slightly rounded crystals (1-3 mm). The olivines are rounded, replaced crystals (<1 mm).

3) massive and vesicular (5-20%) amphibole-bearing hawaiites (59-7,

12, 13). Texture: subtrachytic to hypohyalline. Phenocrysts: Amphibole - 1-16%, ferroan pargasite or magnesian hastingsite to kaersutite, euhedral to slightly rounded, dark brown to black crystals (<1 mm), some concentric zoned, some partially resorbed. Uncommon subhedral, tabular, slightly altered clinopyroxene and twinned plagioclase crystals present (<1 mm). Groundmass: fine-grained plagioclase microlites and amphibole needles (commonly aligned) and minor replaced olivine chips and titanomagnetite clots set in a very fine-grained, medium gray, slightly altered matrix. Vesicles are commonly elongate and flattened, 1-5 cm in diameter by 2 mm thick, but are less commonly rounded (<2 mm in diameter), most are calcite-lined.

59-13 contains a small inclusion (<3 cm in diameter) of predominantly exsolved titaniferous amphibole containing partially to severely resorbed titanaugite crystals and irregular shaped patches of dark brown aenigmatite with minor opaques occurring as irregularly shaped clots and along exsolution lamellae and grain boundaries, plagioclase as fine, irregular crystals infilling fractures, and small, anhedral biotite flakes near the larger amphibole crystal rims and in small fractures near the xenolith rim.

ROCK DREDGE-60

Eastern flank of a ridge 595 km southeast of Johnson Island. Mixture of angular to sub-rounded, moderately altered and oxidized, vesicular and massive basalt and pillow fragments (5-20 cm long) with patchy, Mn-coatings up to 2 cm thick. Six thin-sections with one chemical and rare-earth analysis and age date (60-6).

Lithologies: 1) vesicular to massive (5-15%) plagioclase-olivine phyric alkali basalts (60-6). Texture: hyalopilitic. Phenocrysts: Plagioclase - 1-15%, subhedral to rounded crystals (<3 mm), commonly twinned, many are partially resorbed, few are zoned, some contain altered glass and titanomagnetite needle inclusions; Olivine - 1-3%, subhedral to angular, iddingsite-replaced fragments (<2 mm). Groundmass: abundant plagioclase microlites and tabular fragments, replaced olivine chips and microphenocrysts, titanomagnetite clots and needles commonly trellice-patterned), and uncommon clinopyroxene fragments set in a brownish-gray, slightly altered and oxidized matrix. Vesicles are round and <1 mm in diameter, some with pale yellow celadonite and Mn-stain lining.

2) vesicular (10-15%) olivine-clinopyroxene phyric alkali basalt. Texture: hypocrystalline. Phenocrysts: Olivine - 1-3%, subhedral to anhedral, replaced crystals (<1 mm); Clinopyroxene - <1%, titanaugite, very few subhedral crystals (<1 mm), some contain fine-grained, replaced olivine chips and opaque clots. Groundmass: abundant clinopyroxene microlites in radial, spherulitic patterns and as random fragments, abundant replaced olivine fragments and microphenocrysts, and fine-grained titanomagnetite needles (commonly trellice-patterned) and

rhombic clots set in a very fine-grained medium grayish-brown, altered matrix. Vesicles are round to irregularly shaped and are 1-3 mm in diameter, many are thinly brown clay-lined, some are zeolite infilled (natrolite).

ROCK DREDGE-61

Eastern flank of a ridge 400 km southeast of Johnson Island. Angular to sub-rounded fragments of vesicular, slightly to moderately altered, pillow basalts (2-20 cm long) with thin, patchy Mn-coatings (<1 cm thick). Six thin-sections, three chemical analyses (61-1, 3, 4), and one rare-earth analysis (61-3).

Lithologies: 1) vesicular (20-25%) aphyric alkali basalts (61-3, 4). Texture: aphyric, locally intersertal to sub-ophitic. Groundmass: abundant fine-grained plagioclase microlites and tabular fragments (some with very fine-grained opaque clot inclusions), abundant iddingsite-replaced olivine microphenocrysts and fragments, and fine-grained titanomagnetite needles (commonly trellice-patterned) and clots set in a very fine-grained, medium brown, altered matrix. Vesicles are round to irregularly shaped and 1-3 mm in diameter, some are infilled with carbonate, few are lined with Mn-stains and pale brown clay (<0.5 mm thick).

2) vesicular (15-25%) aphyric alkali basalts (61-1). Texture: aphyric to pilotaxitic. Groundmass: abundant plagioclase as

semi-aligned microlites and few tabular fragments, replaced olivine microphenocrysts and fragments, clinopyroxene as rounded fragments and microphenocrysts (few are twinned), and titanomagnetite clots and irregular grains and minor, very fine-grained needles set in a very fine-grained, medium brown, altered matrix. Vesicles are round and irregular in shape and are <3 mm in diameter, few are thinly celadonite-lined.

ROCK DREDGE-62

Eastern flank of a ridge 245 km southeast of Johnson Island. Angular fragments (5-20 cm long) of moderately altered, vesicular basalts with a thick Mn-crust (2-6 cm thick). Three thin-sections and one chemical and rare-earth analysis (62-1).

Lithology: vesicular (20-30%) plagioclase phyric alkali basalt (62-1). Texture: intersertal. Phenocrysts: Plagioclase - 5-15%, euhedral to subhedral, tabular and equant crystals and angular fragments (1-7 mm), most are concentric zoned and twinned, few are partially resorbed, many contain altered glass and fine-grained opaques as inclusions either parallel to the zoning pattern or along twin planes. Very uncommon (<1%), rounded, clinopyroxene fragments (<1 mm) also present. Groundmass: abundant plagioclase as slightly altered, tabular fragments and microlites, irregular shaped and rhombic clots and minor fine-grained, commonly trellice-patterned titanomagnetite needles, and very minor clinopyroxene and iddingsite-replaced, skeletal olivine fragments set in a very fine-grained, medium grayish-brown, altered matrix which commonly contains minor celadonite clay interstitial to plagioclase microlites. Vesicles are round an irregular in shape, 1-4 mm in diameter, and are commonly brown clay-lined and less commonly Mn-stain lined and carbonate infilled.

ROCK DREDGE-63

Eastern flank of a ridge 155 km east of Johnson Island. Angular fragments (5-20 cm long) of moderately altered and oxidized vesicular basalt and less-altered massive basalt, all variably Mn-coated (1-6 cm thick). Nine thin-sections, one chemical and microprobe analysis and age date (63-7).

Lithologies: 1) massive (7%) olivine-clinopyroxene phyric alkali basalt (63-7). Texture: hypocrystalline porphyry. Phenocrysts: Olivine - 5%, euhedral to subhedral, iddingsite-replaced crystals (<1 mm), many contain irregular opaque clots; Clinopyroxene - 2%, titanaugite, few subhedral crystals (<1 mm), some have altered glass inclusions. Groundmass: abundant clinopyroxene fragments and subhedral microphenocrysts, abundant replaced olivine fragments and microphenocrysts, plagioclase microlites and fragments, and very fine-grained titanomagnetite clots set in a very fine-grained, dark gray, slightly altered and oxidized matrix. Vesicles are round and very small (<0.3 mm in diameter) and are commonly infilled with celadonite.

63-7 contains inclusions of clinopyroxene-olivine aggregates (<5 mm long). The clinopyroxenes are subhedral to irregular shaped crystals (<2 mm) containing minor altered glass. The olivine occurs as both small, replaced, subhedral crystals (<0.5 mm) and as fine-grained, intergranular, replaced fragments. Similar to inclusions in 59-9 and 59-10.

2) vesicular (10-20%) olivine phyric alkali basalts. Texture: porphyritic. Phenocrysts: Olivine - 1-5%, subhedral to anhedral, replaced crystals and fragments (<2 mm), commonly contain fine-grained, irregular shaped opaque clots. Also contain clinopyroxene-olivine inclusions similar to 63-7. Groundmass: fine-grained plagioclase microlites, replaced olivine fragments and microphenocrysts, and irregular clots and minor fine-grained needles of titanomagnetite set in a very fine-grained, medium brown to dark gray, moderately altered matrix. Vesicles are variably sized (<5 mm in diameter), round to irregularly shaped, and are commonly thinly brown clay and Mn-stain lined, but are also carbonate or zeolite (natrolite) infilled.

ROCK DREDGE-64

Western flank of the same ridge as for RD-63, 155 km east of Johnson Island. Severely altered and thickly Mn-coated (1-4 cm),

angular basalt fragments. No samples were analyzed from this dredge.

PISTON CORE-6

Piston core in a turbidite fan 160 km northwest of Christmas Island. Slightly altered hawaiite clasts (2-3 cm long) recovered from 362-382 cm depth interval below sediment-sea water interface. Two thin-sections, two chemical analyses and age dates (PC6-1, 2), and one rare-earth analysis (PC6-1).

Lithology: massive aphyric hawaiites. Texture: subtrachytic to intergranular. Contain uncommon, prismatic phenocrysts of plagioclase (<1 mm), commonly zoned. Groundmass: predominantly aligned plagioclase microlites with interstitial, fine-grained, iddingsite-replaced olivine fragments and titanomagnetite clots and minor needles set in a very fine-grained, dark gray, slightly altered and and oxidized intergranular matrix. Very uncommon vesicles (<1%) are small, <1 mm in diameter, elongate parallel to groundmass plagioclase, and are very thinly zeolite-lined.

APPENDIX C

CLINOPYROXENE COMPOSITIONS OF VOLCANIC ROCKS FROM THE LINE ISLANDS AND TUAMOTU ARCHIPELAGO.

	41-1A	41-1B	41-1Cc	41-1Cr	41-1D	41-1E	41-1F	41-1G	41-1H
	gm	gm	gm	gm	gm	gm	gm	gm	gm
SiO_2	47.44	48.55	48.02	46.82	49.17	47.22	46.35	46.46	48.34
TiO_2	3.06	2.36	2.85	3.37	2.43	3.17	3.26	3.09	2.56
Al_2O_3	6.40	5.66	5.97	6.85	5.00	6.61	6.88	6.87	5.28
Cr_2O_3	0.01	0.01	0.03	0.02	0.04	0.03	0.03	0.02	0.02
FeO*	7.27	6.98	7.25	7.65	7.23	7.41	7.71	7.41	7.10
MnO	0.11	0.14	0.16	0.16	0.13	0.10	0.07	0.11	0.18
MgO	12.90	13.83	13.11	12.43	13.52	12.57	12.55	12.61	13.30
CaO	22.46	22.52	22.82	22.49	22.22	22.34	22.36	22.39	22.39
Na_2O	0.63	0.53	0.58	0.66	0.63	0.57	0.56	0.61	0.65
TOTAL	100.28	100.58	100.79	100.45	100.37	100.02	99.77	99.57	99.82
Si	1.769	1.799	1.782	1.749	1.826	1.766	1.743	1.749	1.808
Al iv	0.231	0.201	0.218	0.251	0.174	0.234	0.257	0.251	0.192
Al vi	0.050	0.046	0.043	0.051	0.045	0.057	0.048	0.054	0.041
Ti	0.086	0.066	0.080	0.095	0.068	0.089	0.092	0.087	0.072
Cr	0.000	0.000	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Fe	0.227	0.216	0.225	0.239	0.224	0.232	0.243	0.233	0.222
Mn	0.003	0.004	0.005	0.005	0.004	0.003	0.002	0.004	0.006
Mg	0.717	0.764	0.725	0.692	0.748	0.701	0.704	0.707	0.741
Ca	0.898	0.894	0.907	0.900	0.884	0.895	0.901	0.903	0.897
Na	0.046	0.038	0.042	0.048	0.045	0.041	0.041	0.045	0.047
TOTAL	4.027	4.028	4.028	4.031	4.019	4.019	4.032	4.034	4.027

LINE ISLANDS CLINOPYROXENES

	41-1I	41-1Jc	41-1Jr	41-1K	41-2A	41-2B	41-2C	41-2D	41-2E
	gm	ph	ph	ph	gm	gm	gm	gm	gm
SiO_2	46.41	48.05	45.58	47.81	50.67	51.24	50.91	49.55	50.78
TiO_2	3.25	1.96	3.74	2.83	1.27	1.08	1.11	1.66	1.18
Al_2O_3	6.79	5.65	7.69	5.67	3.91	3.40	3.56	4.60	3.57
Cr_2O_3	0.03	0.51	0.03	0.01	0.42	0.53	0.48	0.17	0.45
FeO*	7.38	6.42	7.52	7.33	5.97	5.12	5.44	6.86	5.71
MnO	0.12	0.08	0.12	0.13	0.09	0.06	0.11	0.12	0.12
MgO	12.45	14.04	12.14	13.15	15.58	15.84	15.69	15.26	15.82
CaO	22.38	22.67	22.45	22.56	21.50	22.04	22.01	21.32	21.75
Na_2O	0.64	0.40	0.65	0.60	0.26	0.25	0.23	0.22	0.23
TOTAL	99.45	99.78	99.92	100.09	99.67	99.56	99.54	99.76	99.61
Si	1.749	1.794	1.714	1.787	1.874	1.891	1.883	1.840	1.879
Al iv	0.251	0.206	0.286	0.213	0.126	0.109	0.117	0.160	0.121
Al vi	0.051	0.043	0.055	0.037	0.044	0.039	0.038	0.041	0.035
Ti	0.092	0.055	0.106	0.080	0.035	0.030	0.031	0.046	0.033
Cr	0.001	0.015	0.001	0.000	0.012	0.015	0.014	0.005	0.013
Fe	0.233	0.200	0.236	0.229	0.185	0.158	0.168	0.213	0.177
Mn	0.004	0.003	0.004	0.004	0.003	0.002	0.003	0.004	0.004
Mg	0.699	0.781	0.680	0.733	0.859	0.871	0.865	0.845	0.872
Ca	0.904	0.907	0.904	0.904	0.852	0.872	0.872	0.848	0.862
Na	0.047	0.029	0.047	0.043	0.019	0.018	0.016	0.016	0.017
TOTAL	4.031	4.033	4.033	4.030	4.009	4.005	4.007	4.018	4.013

FeO* = total iron as FeO

KEY: gm = GROUNDMASS GRAIN ph = PHENOCRYST c = CORE r = RIM

APPENDIX C (continued)

CLINOPYROXENE COMPOSITIONS OF VOLCANIC ROCKS FROM THE LINE ISLANDS AND TUAMOTU ARCHIPELAGO.

	41-2F	41-2G	41-2Hc	41-2Hr	41-2I	41-2J	41-2K	41-2L	44-2A
	gm	gm	gm	gm	gm	gm	ph	ph	gm
SiO2	50.00	47.99	51.17	46.57	50.44	50.95	46.03	47.35	51.43
TiO2	1.64	1.87	1.08	2.29	1.24	1.07	2.65	1.98	0.71
Al2O3	3.99	6.35	3.43	7.50	3.80	3.51	7.78	6.73	1.84
Cr2O3	0.00	0.72	0.57	0.72	0.38	0.55	0.57	0.97	0.06
FeO*	7.90	6.12	5.26	6.80	5.86	5.38	7.26	6.30	11.63
MnO	0.15	0.09	0.10	0.07	0.09	0.08	0.09	0.05	0.38
MgO	14.66	14.12	15.97	13.16	15.68	15.91	13.15	13.83	15.11
CaO	20.88	22.24	22.02	22.21	21.59	22.01	22.13	22.17	18.04
Na2O	0.32	0.29	0.24	0.30	0.24	0.26	0.38	0.29	0.29
TOTAL	99.54	99.79	99.84	99.62	99.32	99.72	100.04	99.67	99.49
Si	1.866	1.786	1.886	1.745	1.872	1.881	1.723	1.768	1.936
Al iv	0.134	0.214	0.114	0.255	0.128	0.119	0.277	0.232	0.064
Al vi	0.041	0.064	0.035	0.076	0.038	0.034	0.066	0.064	0.018
Ti	0.046	0.052	0.030	0.064	0.035	0.030	0.075	0.056	0.020
Cr	0.000	0.021	0.017	0.021	0.011	0.016	0.017	0.029	0.002
Fe	0.247	0.190	0.162	0.213	0.182	0.166	0.227	0.197	0.366
Mn	0.005	0.003	0.003	0.002	0.003	0.003	0.003	0.002	0.012
Mg	0.815	0.783	0.877	0.735	0.867	0.876	0.734	0.770	0.847
Ca	0.835	0.887	0.869	0.892	0.859	0.871	0.888	0.887	0.727
Na	0.023	0.021	0.017	0.022	0.017	0.019	0.028	0.021	0.021
TOTAL	4.012	4.021	4.010	4.025	4.012	4.015	4.038	4.026	4.013

LINE ISLANDS CLINOPYROXENES

	44-2B	44-2C	44-2D	44-2E	44-2F	52-7A	52-7Bc	52-7Br	52-7C
	gm	gm	gm	gm	ph	gm	gm	gm	gm
SiO2	50.59	50.04	49.35	50.83	50.85	49.42	52.32	48.82	49.10
TiO2	0.98	1.19	1.37	0.71	1.03	1.75	0.81	1.86	1.88
Al2O3	2.44	3.07	3.19	1.99	2.87	5.07	2.10	5.60	5.09
Cr2O3	0.01	0.04	0.01	0.02	0.00	0.78	0.35	0.62	0.45
FeO*	11.17	11.15	12.93	10.94	10.24	6.76	7.69	7.19	7.78
MnO	0.31	0.32	0.38	0.33	0.28	0.11	0.19	0.12	0.12
MgO	13.85	13.98	13.32	14.15	15.02	15.08	18.95	15.24	15.35
CaO	19.72	19.55	18.47	19.69	18.62	20.59	16.61	19.91	19.68
Na2O	0.37	0.40	0.42	0.37	0.41	0.30	0.14	0.27	0.32
TOTAL	99.44	99.74	99.44	99.03	99.32	99.86	99.16	99.63	99.77
Si	1.912	1.887	1.879	1.927	1.908	1.831	1.929	1.814	1.825
Al iv	0.088	0.113	0.121	0.073	0.092	0.169	0.071	0.186	0.175
Al vi	0.021	0.023	0.022	0.016	0.035	0.052	0.020	0.059	0.048
Ti	0.028	0.034	0.039	0.020	0.029	0.049	0.022	0.052	0.052
Cr	0.000	0.001	0.000	0.001	0.000	0.023	0.010	0.018	0.013
Fe	0.353	0.352	0.412	0.347	0.321	0.209	0.237	0.223	0.242
Mn	0.010	0.010	0.012	0.011	0.009	0.003	0.006	0.004	0.004
Mg	0.780	0.786	0.756	0.799	0.840	0.833	1.041	0.844	0.850
Ca	0.799	0.790	0.753	0.800	0.749	0.817	0.656	0.793	0.784
Na	0.027	0.029	0.031	0.027	0.030	0.022	0.010	0.019	0.023
TOTAL	4.018	4.025	4.025	4.021	4.013	4.008	4.002	4.012	4.016

APPENDIX C (continued)

CLINOPYROXENE COMPOSITIONS OF VOLCANIC ROCKS FROM THE LINE ISLANDS AND TUAMOTU ARCHIPELAGO.

	52-7D gm	52-7E gm	52-7Fc gm	52-7Fr gm	54-2A gm	54-2B gm	54-2C gm	54-2D gm	54-2E gm
SiO2	49.81	50.08	50.42	47.88	49.22	50.99	44.86	46.26	47.37
TiO2	1.63	1.32	1.34	2.56	2.78	1.46	4.23	3.35	2.91
Al2O3	4.27	4.27	4.08	5.81	4.02	2.48	7.28	6.03	5.72
Cr2O3	0.34	0.74	0.69	0.28	0.03	0.00	0.00	0.00	0.03
FeO*	7.35	6.52	6.81	8.36	11.15	9.58	10.56	10.43	9.61
MnO	0.08	0.10	0.13	0.15	0.26	0.22	0.13	0.13	0.17
MgO	15.14	15.54	15.61	14.24	14.46	15.77	12.26	12.65	13.60
CaO	20.65	20.93	20.49	20.28	18.12	19.02	20.46	20.35	20.21
Na2O	0.31	0.26	0.23	0.31	0.44	0.23	0.43	0.40	0.45
TOTAL	99.58	99.76	99.80	99.87	100.48	99.75	100.21	99.60	100.07
Si	1.854	1.855	1.866	1.789	1.838	1.902	1.698	1.756	1.778
Al iv	0.146	0.145	0.134	0.211	0.162	0.098	0.302	0.244	0.222
Al vi	0.041	0.041	0.044	0.045	0.015	0.011	0.023	0.026	0.031
Ti	0.046	0.037	0.037	0.072	0.078	0.041	0.120	0.096	0.082
Cr	0.010	0.022	0.020	0.008	0.001	0.000	0.000	0.000	0.001
Fe	0.229	0.202	0.211	0.261	0.348	0.299	0.334	0.331	0.302
Mn	0.002	0.003	0.004	0.005	0.008	0.007	0.004	0.004	0.005
Mg	0.840	0.858	0.861	0.793	0.805	0.877	0.692	0.715	0.761
Ca	0.823	0.831	0.812	0.812	0.725	0.760	0.830	0.828	0.813
Na	0.022	0.019	0.016	0.022	0.032	0.017	0.031	0.029	0.033
TOTAL	4.013	4.013	4.005	4.018	4.012	4.012	4.034	4.029	4.028

LINE ISLANDS CLINOPYROXENES

	54-2F gm	54-2G gm	59-1Ac gm	59-1Ar gm	59-1B gm	59-1C gm	59-1D gm	59-1E ph	59-1F ph
SiO2	47.24	46.80	45.94	48.29	48.02	47.02	47.59	47.16	51.76
TiO2	3.04	3.19	2.72	1.71	1.62	1.68	1.61	1.79	0.34
Al2O3	5.85	6.29	7.87	6.35	7.02	8.49	7.38	8.74	2.43
Cr2O3	0.01	0.05	0.04	0.01	0.18	0.22	0.69	0.05	0.04
FeO*	9.55	9.71	9.23	9.31	8.00	7.42	5.93	7.16	11.44
MnO	0.14	0.16	0.17	0.23	0.26	0.11	0.10	0.16	0.79
MgO	13.62	13.23	11.98	13.22	13.05	13.09	13.24	13.11	13.13
CaO	20.31	20.46	20.54	19.81	19.92	20.38	21.79	20.99	18.37
Na2O	0.38	0.40	0.56	0.65	0.68	0.59	0.54	0.45	0.91
TOTAL	100.14	100.29	99.05	99.58	98.75	99.00	98.87	99.61	99.21
Si	1.772	1.757	1.742	1.812	1.807	1.763	1.783	1.756	1.956
Al iv	0.228	0.243	0.258	0.188	0.193	0.237	0.217	0.244	0.044
Al vi	0.028	0.035	0.094	0.093	0.118	0.138	0.109	0.140	0.064
Ti	0.086	0.090	0.078	0.048	0.046	0.047	0.045	0.050	0.010
Cr	0.000	0.001	0.001	0.000	0.005	0.007	0.020	0.001	0.001
Fe	0.300	0.305	0.293	0.292	0.252	0.233	0.186	0.223	0.362
Mn	0.004	0.005	0.005	0.007	0.008	0.003	0.003	0.005	0.025
Mg	0.761	0.740	0.677	0.739	0.732	0.731	0.739	0.728	0.740
Ca	0.816	0.823	0.835	0.796	0.803	0.819	0.875	0.838	0.744
Na	0.028	0.029	0.041	0.047	0.050	0.043	0.039	0.032	0.067
TOTAL	4.023	4.028	4.024	4.022	4.014	4.021	4.016	4.017	4.013

APPENDIX C (continued)

CLINOPYROXENE COMPOSITIONS OF VOLCANIC ROCKS FROM THE LINE ISLANDS AND TUAMOTU ARCHIPELAGO.

	59-1G	59-1H	59-9A	59-9B	59-9C	59-9D	59-9E	59-9F	59-9G
	ph	ph	gm	gm	gm	gm	gm	gm	gm
SiO2	47.12	48.16	49.04	48.99	47.27	49.57	50.91	47.99	47.29
TiO2	2.10	1.22	1.54	1.32	1.87	1.20	0.76	1.30	2.21
Al2O3	8.15	7.33	6.65	7.52	7.31	5.57	5.73	7.01	7.38
Cr2O3	0.28	0.11	0.38	0.37	0.21	0.12	0.39	0.17	0.03
FeO*	6.87	7.60	7.58	6.82	8.64	9.06	6.60	8.43	9.05
MnO	0.13	0.12	0.09	0.14	0.23	0.19	0.15	0.19	0.18
MgO	13.34	14.16	14.07	14.50	13.02	13.78	16.01	13.92	12.96
CaO	21.10	19.88	20.39	20.49	20.51	20.03	19.54	20.14	20.49
Na2O	0.52	0.56	0.77	0.65	0.88	0.91	0.63	0.76	0.83
TOTAL	99.61	99.14	100.51	100.80	99.94	100.43	100.72	99.91	100.42
Si	1.756	1.799	1.810	1.795	1.771	1.841	1.856	1.791	1.765
Al iv	0.244	0.201	0.190	0.205	0.229	0.159	0.144	0.209	0.235
Al vi	0.114	0.122	0.100	0.120	0.094	0.085	0.102	0.099	0.090
Ti	0.059	0.034	0.043	0.036	0.053	0.033	0.021	0.036	0.062
Cr	0.008	0.003	0.011	0.011	0.006	0.003	0.011	0.005	0.001
Fe	0.214	0.237	0.234	0.209	0.271	0.281	0.201	0.263	0.282
Mn	0.004	0.004	0.003	0.004	0.007	0.006	0.005	0.006	0.006
Mg	0.741	0.788	0.774	0.792	0.727	0.763	0.870	0.774	0.721
Ca	0.843	0.796	0.806	0.805	0.823	0.797	0.763	0.805	0.819
Na	0.038	0.041	0.055	0.046	0.064	0.065	0.044	0.055	0.060
TOTAL	4.021	4.025	4.026	4.023	4.045	4.033	4.017	4.043	4.041

LINE ISLANDS CLINOPYROXENES

	59-9H	59-9I	59-9J	59-10A	59-10B	59-10C	59-10D	59-10E	59-10F
	ph	ph	ph	gm	gm	ph	ph	ph	ph
SiO2	48.02	48.23	48.05	47.96	45.90	48.82	49.58	47.81	48.53
TiO2	1.80	1.67	1.70	2.17	2.42	1.62	1.34	2.27	1.51
Al2O3	7.43	7.23	7.96	6.88	8.17	5.11	5.54	6.51	5.72
Cr2O3	0.19	0.05	0.18	0.60	0.41	0.02	0.76	0.01	0.22
FeO*	7.76	8.91	7.66	6.24	7.37	7.55	5.15	7.28	5.53
MnO	0.13	0.21	0.19	0.09	0.11	0.20	0.06	0.10	0.07
MgO	13.66	12.65	13.66	14.26	12.84	13.84	14.89	13.44	14.64
CaO	20.46	20.45	20.52	21.30	21.79	22.09	22.51	21.98	22.38
Na2O	0.76	0.92	0.71	0.64	0.67	0.61	0.52	0.58	0.52
TOTAL	100.21	100.32	100.63	100.14	99.68	99.86	100.35	99.98	99.12
Si	1.781	1.796	1.774	1.776	1.724	1.825	1.824	1.783	1.812
Al iv	0.219	0.204	0.226	0.224	0.276	0.175	0.176	0.217	0.188
Al vi	0.106	0.113	0.120	0.076	0.086	0.050	0.064	0.069	0.064
Ti	0.050	0.047	0.047	0.060	0.068	0.045	0.037	0.064	0.042
Cr	0.006	0.001	0.005	0.018	0.012	0.001	0.022	0.000	0.006
Fe	0.241	0.277	0.236	0.193	0.231	0.236	0.158	0.227	0.173
Mn	0.004	0.007	0.006	0.003	0.003	0.006	0.002	0.003	0.002
Mg	0.755	0.702	0.751	0.787	0.719	0.771	0.817	0.747	0.815
Ca	0.813	0.816	0.811	0.845	0.877	0.885	0.888	0.878	0.895
Na	0.055	0.066	0.051	0.046	0.049	0.044	0.037	0.042	0.038
TOTAL	4.030	4.029	4.027	4.028	4.045	4.038	4.025	4.030	4.035

APPENDIX C (continued)

CLINOPYROXENE COMPOSITIONS OF VOLCANIC ROCKS FROM THE LINE ISLANDS AND TUAMOTU ARCHIPELAGO.

	59-10G	59-15A	59-15B	59-15C	59-15D	59-15E	59-15F	59-15G	59-15H
	ph	gm	gm	gm	gm	gm	gm	ph	ph
SiO2	49.29	47.32	46.70	49.51	47.21	49.19	49.40	47.63	46.82
TiO2	1.55	1.93	2.48	1.16	2.00	1.29	1.15	1.86	2.18
Al2O3	4.97	8.55	8.81	6.16	8.72	6.57	6.15	8.29	8.37
Cr2O3	0.01	0.11	0.04	0.18	0.06	0.20	0.08	0.05	0.07
FeO*	8.03	7.43	8.02	6.41	7.50	7.56	7.65	7.40	8.15
MnO	0.21	0.18	0.16	0.15	0.16	0.13	0.17	0.17	0.13
MgO	13.69	13.22	13.31	14.90	12.95	14.65	14.85	13.49	13.19
CaO	21.65	21.15	20.03	20.85	21.40	20.31	20.24	20.97	20.62
Na2O	0.63	0.61	0.76	0.56	0.48	0.51	0.49	0.59	0.69
TOTAL	100.03	100.50	100.31	99.88	100.48	100.41	100.18	100.45	100.22
Si	1.839	1.751	1.734	1.829	1.748	1.814	1.826	1.761	1.743
Al iv	0.161	0.249	0.266	0.171	0.252	0.186	0.174	0.239	0.257
Al vi	0.058	0.124	0.119	0.097	0.129	0.100	0.094	0.122	0.110
Ti	0.043	0.054	0.069	0.032	0.056	0.036	0.032	0.052	0.061
Cr	0.000	0.003	0.001	0.005	0.002	0.006	0.002	0.001	0.002
Fe	0.251	0.230	0.249	0.198	0.232	0.233	0.236	0.229	0.254
Mn	0.007	0.006	0.005	0.005	0.005	0.004	0.005	0.005	0.004
Mg	0.761	0.729	0.736	0.820	0.715	0.805	0.818	0.743	0.732
Ca	0.865	0.839	0.797	0.825	0.849	0.803	0.802	0.831	0.823
Na	0.046	0.044	0.055	0.040	0.034	0.036	0.035	0.042	0.050
TOTAL	4.031	4.029	4.031	4.022	4.022	4.023	4.024	4.025	4.036

LINE ISLANDS CLINOPYROXENES

	59-15I	63-7A	63-7B	63-7C	63-7Dc	63-7Dr	63-7E	63-7F	63-7G
	ph	gm	gm	gm	gm	gm	gm	ph	ph
SiO2	46.30	48.83	48.70	49.16	48.28	45.22	48.32	44.55	44.29
TiO2	2.53	2.45	2.56	1.89	2.66	3.94	2.48	4.08	4.04
Al2O3	8.61	5.84	5.22	5.96	5.67	8.65	5.79	8.99	9.14
Cr2O3	0.03	0.25	0.17	0.48	0.28	0.36	0.46	0.28	0.20
FeO*	8.42	6.47	6.89	5.63	6.45	7.13	5.79	7.45	7.14
MnO	0.16	0.14	0.11	0.09	0.08	0.07	0.11	0.09	0.06
MgO	12.59	13.40	13.73	14.67	13.70	12.55	14.11	11.97	11.94
CaO	20.79	22.54	22.47	22.15	22.66	22.78	22.72	22.54	22.46
Na2O	0.64	0.39	0.41	0.41	0.41	0.45	0.41	0.48	0.47
TOTAL	100.07	100.31	100.26	100.44	100.19	101.15	100.19	100.43	99.74
Si	1.731	1.809	1.810	1.809	1.794	1.678	1.791	1.668	1.667
Al iv	0.269	0.191	0.190	0.191	0.206	0.322	0.209	0.332	0.333
Al vi	0.110	0.064	0.039	0.067	0.042	0.056	0.044	0.065	0.072
Ti	0.071	0.068	0.071	0.052	0.074	0.110	0.069	0.115	0.114
Cr	0.001	0.007	0.005	0.014	0.008	0.011	0.013	0.008	0.006
Fe	0.263	0.200	0.214	0.173	0.200	0.221	0.179	0.233	0.225
Mn	0.005	0.004	0.003	0.003	0.002	0.002	0.003	0.003	0.002
Mg	0.701	0.740	0.760	0.804	0.759	0.694	0.779	0.668	0.670
Ca	0.833	0.894	0.895	0.873	0.902	0.906	0.902	0.904	0.906
Na	0.046	0.028	0.029	0.029	0.029	0.032	0.029	0.035	0.034
TOTAL	4.030	4.005	4.016	0.015	4.016	4.032	4.018	4.031	4.029

APPENDIX C (continued)

CLINOPYROXENE AND AMPHIBOLE COMPOSITIONS OF VOLCANIC ROCKS FROM THE LINE ISLANDS.

LINE ISLANDS CLINOPYROXENES

	63-7H	63-7I
	ph	ph
SiO2	49.00	48.56
TiO2	2.52	2.52
Al2O3	5.32	5.29
Cr2O3	0.29	0.22
FeO*	6.15	6.39
MnO	0.08	0.13
MgO	14.08	14.11
CaO	22.88	22.44
Na2O	0.36	0.42
TOTAL	100.68	100.08
Si	1.808	1.804
Al iv	0.192	0.196
Al vi	0.039	0.036
Ti	0.070	0.070
Cr	0.008	0.006
Fe	0.190	0.199
Mn	0.002	0.004
Mg	0.774	0.781
Ca	0.905	0.893
Na	0.026	0.030
TOTAL	4.014	4.019

LINE ISLANDS AMPHIBOLES

	46-1A	46-1B	46-1C	59-7A	59-7B
	ph	ph	ph	ph	ph
SiO2	40.83	40.81	40.36	39.16	39.24
TiO2	3.88	4.08	3.92	4.89	4.96
Al2O3	11.85	11.94	11.87	13.54	13.70
FeO*	17.46	16.51	17.20	12.99	12.40
MnO	0.24	0.20	0.20	0.14	0.15
MgO	10.18	10.62	10.28	12.03	12.11
CaO	10.59	10.63	10.51	11.58	11.75
Na2O	2.91	2.89	2.88	2.64	2.78
K2O	0.92	0.88	0.91	1.05	1.02
Cr2O3	0.01	0.00	0.00	0.03	0.02
TOTAL	98.87	98.56	98.13	98.05	98.13
Si	6.130	6.118	6.103	5.841	5.835
Al iv	1.870	1.882	1.897	2.159	2.165
Al vi	0.227	0.228	0.218	0.221	0.236
Ti	0.438	0.460	0.446	0.548	0.555
Fe	2.192	2.070	2.175	1.620	1.542
Mn	0.030	0.025	0.026	0.018	0.019
Mg	2.278	2.373	2.316	2.674	2.684
Cr	0.001	0.000	0.000	0.004	0.002
Ca	1.704	1.707	1.703	1.851	1.872
Na	0.847	0.840	0.844	0.763	0.802
K	0.176	0.168	0.175	0.200	0.193
TOTAL	15.893	15.871	15.903	15.899	15.905

LINE ISLANDS AMPHIBOLES

	59-7C	59-7D	59-7E	59-13A	59-13B	59-13C	59-13Dc	59-13Dr	59-13E
	ph	ph	ph	ph	ph	ph	ph	ph	ph
SiO2	39.21	38.39	39.42	38.23	39.36	39.80	37.61	39.75	38.34
TiO2	4.87	4.96	4.81	4.39	4.15	4.03	3.63	4.28	4.32
Al2O3	13.31	13.61	13.36	14.26	14.18	13.59	14.48	14.02	13.86
FeO*	12.51	13.34	12.26	11.98	9.70	11.93	15.02	10.39	12.52
MnO	0.15	0.15	0.15	0.15	0.10	0.12	0.14	0.09	0.17
MgO	11.99	11.45	12.21	12.46	14.15	13.17	10.32	13.71	12.40
CaO	11.62	11.68	11.73	11.35	11.47	11.28	11.42	11.45	11.29
Na2O	2.78	2.77	2.79	2.53	2.46	2.72	2.63	2.54	2.72
K2O	1.06	1.07	1.03	1.62	1.63	1.49	1.54	1.48	1.52
Cr2O3	0.00	0.03	0.00	0.02	0.11	0.01	0.00	0.00	0.03
TOTAL	97.50	97.45	97.76	96.99	97.31	98.14	96.79	97.71	97.17
Si	5.873	5.787	5.880	5.760	5.834	5.903	5.763	5.876	5.782
Al iv	2.127	2.213	2.120	2.240	2.166	2.097	2.237	2.124	2.218
Al vi	0.237	0.205	0.229	0.292	0.311	0.279	0.378	0.319	0.246
Ti	0.549	0.562	0.540	0.497	0.463	0.449	0.418	0.476	0.490
Fe	1.567	1.682	1.529	1.509	1.202	1.480	1.925	1.284	1.579
Mn	0.019	0.019	0.019	0.019	0.012	0.015	0.018	0.011	0.022
Mg	2.676	2.572	2.714	2.798	3.126	2.911	2.356	3.020	2.787
Cr	0.000	0.004	0.000	0.002	0.013	0.001	0.000	0.000	0.004
Ca	1.865	1.887	1.875	1.832	1.822	1.792	1.875	1.813	1.824
Na	0.807	0.810	0.807	0.739	0.707	0.782	0.781	0.728	0.795
K	0.203	0.206	0.196	0.311	0.308	0.282	0.301	0.279	0.292
TOTAL	15.926	15.847	15.909	15.999	15.964	15.991	16.052	15.930	16.039

APPENDIX C (continued)

CLINOPYROXENE, AMPHIBOLE, AND BIOTITE COMPOSITIONS OF 59-13 XENOLITH, LINE ISLANDS.

CLINOPYROXENES

	Ac	Ar	Bc	Br	C
SiO2	47.36	45.36	45.90	46.05	46.02
TiO2	2.00	2.26	2.41	2.46	2.37
Al2O3	7.95	10.00	8.72	9.33	8.67
Cr2O3	0.01	0.01	0.05	0.00	0.09
FeO*	6.71	7.89	6.16	6.66	6.69
MnO	0.13	0.18	0.10	0.12	0.14
MgO	12.00	12.06	11.86	12.01	11.80
CaO	23.24	20.68	23.84	22.09	23.72
Na2O	0.60	1.21	0.61	0.87	0.61
TOTAL	100.00	99.65	99.65	99.59	100.11
Si	1.766	1.702	1.722	1.723	1.722
Al iv	0.234	0.298	0.278	0.277	0.278
AL vi	0.115	0.144	0.108	0.134	0.104
Ti	0.056	0.064	0.068	0.069	0.067
Cr	0.000	0.000	0.001	0.000	0.003
Fe	0.209	0.248	0.193	0.208	0.209
Mn	0.004	0.006	0.003	0.004	0.004
Mg	0.667	0.675	0.663	0.670	0.658
Ca	0.929	0.832	0.958	0.886	0.951
Na	0.043	0.088	0.044	0.063	0.044
TOTAL	4.023	4.057	4.038	4.034	4.040

LINE ISLANDS: 59-13 XENOLITH

	AMPHIBOLES				BIOTITES				
	A	B	C	D	A	B	Ca	Cb	D
SiO2	39.67	39.58	41.21	39.50	35.10	36.79	35.95	36.26	36.29
TiO2	3.16	3.03	2.43	2.49	2.77	2.96	2.81	2.81	2.99
Al2O3	15.46	15.49	13.37	15.53	17.41	16.45	17.02	17.32	17.39
FeO*	11.42	13.20	15.54	13.84	17.88	14.33	17.50	17.70	16.46
MnO	0.08	0.01	0.20	0.12	0.09	0.08	0.09	0.08	0.07
MgO	12.53	11.78	10.97	11.22	13.30	15.76	13.40	13.35	13.78
CaO	11.70	11.87	11.32	11.53	0.00	0.01	0.01	0.01	0.00
Na2O	2.86	2.82	3.09	2.83	0.61	0.79	0.61	0.71	0.66
K2O	0.91	0.94	1.01	0.88	9.05	8.82	8.97	9.03	8.74
Cr2O3	0.06	0.02	0.01	0.02	0.06	0.12	0.06	0.07	0.05
TOTAL	97.85	98.83	99.15	97.76	96.27	96.11	96.42	97.34	96.43
Si	5.861	5.841	6.115	5.902	5.513	5.671	5.613	5.609	5.662
Al iv	2.139	2.159	1.885	2.098	2.487	2.329	2.387	2.391	2.378
Al vi	0.553	0.535	0.453	0.602	0.736	0.660	0.745	0.757	0.798
Ti	0.351	0.336	0.271	0.280	0.327	0.343	0.330	0.327	0.348
Fe	1.411	1.629	1.928	1.729	2.349	1.847	2.285	2.290	2.133
Mn	0.010	0.012	0.025	0.015	0.012	0.010	0.012	0.010	0.009
Mg	2.759	2.591	2.426	2.498	3.113	3.621	3.118	3.078	3.182
Cr	0.007	0.002	0.001	0.002	0.007	0.015	0.007	0.009	0.006
Ca	1.852	1.877	1.800	1.846	0.000	0.001	0.002	0.002	0.000
Na	0.819	0.807	0.889	0.820	0.186	0.236	0.185	0.213	0.198
K	0.171	0.177	0.191	0.168	1.813	1.735	1.787	1.782	1.727
TOTAL	15.933	15.966	15.984	15.960	16.543	16.468	16.471	16.478	16.401

REFERENCES

Allegre, C. J., Treuil, M., Minster, J. F., Minster, B., and Allegre, F., 1977, Fractional crystallization processes in volcanic suites, Contrib. Miner. Petrol., v. 60, 57-75.

Anderson, D. L., 1975, Chemical plumes in the mantle, Bull. Geol. Soc. Amer., v. 86, 1593-1600.

Anderson, D. L. and Grew, P. L., 1977, Stress corrosion theory of crack propagation with applications to geophysics, Rev. Geophys. Space Phys., v. 15, 77-104.

Aoki, K. I., 1964, Clinopyroxenes from alkaline rocks of Japan, Amer. Miner., v. 49, 1199-1223.

Aumento, F., 1968, The Mid-Atlantic ridge near 45^{o}N, II - Basalts from Confederation Peak, Can. Jour. Earth Sci., v. 5, 1-21.

Baker, P. E., 1969, Petrology of the volcanic rocks of St. Helena Island, south Atlantic, Bull. Geol. Soc. Amer., v. 80, 1283-1310.

Baker, P. E., Buckley, F., and Holland, J. G., 1974, Petrology and geochemistry of Easter Island, Contrib. Miner. Petrol., v. 44, 85-100.

Baldwin, B., Coney, P. J., and Dickinson, W. R., 1974, Dilemma of a Cretaceous time scale and rates of sea floor spreading, Geology, v. 2, 267-274.

Bass, M. N., Moberly, R., Rhodes, J. M., Shih, C. Y., and Church, S. E., 1973, Volcanic rocks cored in the central Pacific, Leg 17, D. S. D. P., Init. Rep. of the Deep Sea Drilling Project, v. 17, 429-446.

Batiza, R., 1977, Petrology and chemistry of Guadalupe Island: an alkalic seamount on a fossil ridge crest, Geology, v. 5, 760-764.

Batiza, R., Rosendahl, B. R., and Fisher, R. L., 1977, Evolution of oceanic crust, 3.-Petrology and geochemistry of basalts from the East Pacific Rise and the Siqueiros Transform Fault, Jour. Geophys. Res., v. 82, 265-276.

Beeson M. H., 1976, Petrology, mineralogy, and geochemistry of the East Molokai Volcanic Series, Hawaii, U. S. G. S. Prof. Paper, no. 961, 1-53.

Best, M. G., 1974, Mantle-derived amphibole within inclusions in alkalic-basaltic lavas, Jour. Geophys. Res., v. 79, 2107-2113.

Betz, F. and Hess, H. H., 1942, The floor of the north Pacific Ocean, Geograph. Rev., v. 32, 99-116.

Boettcher, A. L. and O'Neil, J. R., 1980, Stable isotope, chemical, and petrographic studies of high-pressure amphiboles and micas: evidence for metasomatism in the mantle source regions of alkali basalts and kimberlites, Amer. Jour. Sci., v. 280-A, 594-621.

Bonatti, E., Honnorez, J., and Ferrara, G., 1971, Peridotite-gabbro-basalt complex from the equatorial Mid-Atlantic Ridge, Phil. Trans. Roy. Soc. Lond., v. A-268, 385-402.

Bonatti, E., Harrison, C. G. A., Fisher, D. E., Honnorez, J., Schilling, J.-G., Stipp, J. J., and Zentilli, M., 1977, Easter volcanic chain (southeast Pacific): a mantle hot line, Jour. Geophys. Res., v. 82, 2457-2478.

Carmichael, I. S. E., Turner, F. J., and Verhoogen, J., 1974, "Igneous Petrology", McGraw-Hill, Inc., New York.

Clague, D. A., 1974, The Hawaii-Emperor Seamount Chain: it's origin, petrology, and implications for plate tectonics, Ph. D. Dissertation, Univ. Calif., San Diego.

Clague, D. A. and Jarrard, R. D., 1973, Tertiary Pacific Plate motion deduced from the Hawaiian-Emperor Chain, Bull. Geol. Soc. Amer., v. 84, 1135-1154.

Clague, D. A., Dalrymple, G. B., and Moberly, R., 1975, Petrology and K-Ar ages of dredged volcanic rocks from the western Hawaiian ridge and southern Emperor Seamount Chain, Bull. Geol. Soc. Amer., v. 86, 991-998.

Coish, R. A. and Taylor, L. A., 1979, The effects of cooling rate on texture and pyroxene chemistry in D. S. D. P. Leg 34 basalt: a microprobe study, Earth Planet. Sci. Let., v. 42, 389-398.

Coombs, D. S., 1963, Trends and affinities of basaltic magmas and pyroxenes as illustrated on the DIOPSIDE-OLIVINE-SiO_2 diagram, Miner. Soc. Amer., Spec. Paper 1, 227-251.

Coombs, D. S. and Wilkinson, J. F. G., 1969, Lineages and fractionation trends in undersaturated volcanic rocks from the East Otago Volcanic Province (New Zealand) and related rocks, Jour. Petrol., v. 10, 440-501.

Crough, S. T. and Jarrard, J. D., 1981, The Line-Marquesas Swell, Jour. Geophys. Res., v. 86, 11,763-11,771.

Dalrymple, G. B., and Lanphere, M. A., 1969, "Potassium-Argon Dating: Principles, Techniques, And Applications To Geochronology", Freeman and Company, Inc., San Francisco.

Dalrymple, G. B. and Lanphere, M. A., 1971, $^{40}Ar/^{39}Ar$ techniques of K-Ar dating: a comparison with the conventional technique, Earth Planet. Sci. Let., v. 12, 300-308.

Dalrymple, G. B., Lanphere, M. A., and Jackson, E. D., 1974, Contributions to the petrology and geochronology of volcanic rocks from the leeward Hawaiian Islands, Bull. Geol. Soc. Amer., v. 85, 727-738.

Dalrymple, G. B., Lanphere, M. A., and Clague, D. A., 1980, Conventional and $^{40}Ar/^{39}Ar$ K-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 Hawaii-Emperor Chain, Init. Rep. of the Deep Sea Drilling Project, v. 55, 659-676.

Deer, W. A., Howie, R. A., and Zussman, J., 1966, "An Introduction To The Rock-Forming Minerals", Longman Group, LTD., London.

Demange, J., Metrier, M., and Varet, J., 1979, Petrology of Mururoa and Fangataufa Atoll, South Pacific, Haw. Symp. on Intraplate Volc. and Submar. Volc., p. 10, abstract.

Donaldson, C. H., Usselman, T. M., Williams, R. J., and Lofgren, G. E., 1975, Experimental modelling of the cooling history of Apollo 12 olivine basalts, Proc. Sixth Lunar Sci. Conf., 843-869.

Duncan, R. A., 1983, Overprinted volcanism in the Line Islands and Pacific plate motion since 100 M.Y. (abs.), EOS Trans. AGU, v. 64, 843.

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

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

Farrar, E. and Dixon, J. M., 1981, Early Tertiary rupture of the Pacific plate: 1700 km of dextral offset along the Emperor Trough-Line Islands lineament, Earth Planet. Sci. Let., v. 53, 307-322.

Flanagan, F. L. (ed.), 1976, Descriptions and analyses of eight new U. S. G. S. rock standards, U. S. G. S. Prof. Paper, no. 840.

Flower, M. F. J., 1973, Trace-element distribution in lavas from Anjouan and Grande Comore, western Indian Ocean, Chem. Geol., v. 12, 81-98.

Fodor, R. V., Keil, K., and Bunch, T. E., 1975, Contributions to the mineral chemistry of Hawaiian rocks-IV. Pyroxenes in rocks from Haleakala and West Maui volcanoes, Maui, Hawaii, Contrib. Miner. Petrol., v. 50, 173-195.

Garcia, M. O., 1975, Clinopyroxene composition, an indicator of magma type in altered volcanic rocks, Geol. Soc. Amer. Abs. w/ Progs., v. 7, p. 1082-1083.

Gast, P. W., 1968, Trace element fractionation and the origin of tholeiitic and alkaline magma types, Geochim. Cosmochim. Acta, v. 32, 1057-1086.

Gramlich, J. W., 1970, Improvements in the potassium-argon dating method and their application to studies of the Honolulu Volcanic Series, Ph. D. Dissertation, Univ. Hawaii, Honolulu.

Green, D. H., 1971, Composition of basaltic magmas as indicators of conditions of origin: application to oceanic volcanism, Proc. Roy. Soc. Lond., v. A-268, 707-725.

Green, D. H., Edgar, A. D., Beasley, P., Kiss, E., and Ware, N. G., 1974, Upper mantle source for some hawaiites, mugearites, and benmoreites, Contrib. Miner. Petrol., v. 48, 3-43.

Griffin, W. L. and Murthy, V. R., 1969, Distribution of K, Rb, Sr, and Ba in some minerals relevant to basalt genesis, Geochim. Cosmochim. Acta, v. 33, 1389-1414.

Haggerty, J. A., Schlanger, S. O., and Premoli-Silva, I., 1981, Cretaceous volcanism in the southern Line Islands, EOS Trans., v. 62, p. 381, abstract.

Haggerty, J. A., Schlanger, S. O., and Premoli-Silva, I., 1982, Late Cretaceous and Eocene volcanism in the southern Line Islands and implications for hotspot theory, Geology, v. 10, 433-437.

Hart, S. R., 1970, Chemical exchange between sea water and deep ocean basalts, Earth Planet. Sci. Let., v. 9, 269-279.

Hart, S. R. and Aldrich, L. T., 1967, Fractionation of potassium/rubidium by amphiboles: implications regarding mantle composition, Science, v. 155, 325-327.

Hart, S. R., Erlank, A. J., and Kable, E. J. D., 1974, Sea floor basalt alteration: some chemical and Sr-isotopic effects, Contrib. Miner. Petrol., v. 44, 219-230.

Hekinian, R., 1972, Volcanics from the Walvis Ridge, Nat. Phys. Sci., v. 239, 91-93.

Hekinian, R., 1974, Petrology of the Ninety East Ridge (Indian Ocean) compared to other aseismic ridges, Contrib. Miner. Petrol., v. 43, 125-147.

Hekinian, R. and Thompson, G., 1976, Comparative geochemistry of volcanics from rift valleys, transform faults, and aseismic ridges, Contrib. Miner. Petrol., v. 57, 145-162.

Henderson, L. J. and Gordon, R. G., 1982, Fixed hot spots and recurrent volcanism along the Line Islands chain, Geol. Soc. Amer. Abstr. Programs, v. 14, 513.

Henoc, J. and Tong, M., unpublished manuscript, "Automation Of The Electron Microprobe", C. N. E. T., CAMECA.

Holloway, J. B. and Burnham, C. W., 1972, Melting relations of basalt with equilibrium water pressure less than total water, Jour. Petrol., v. 13, 1-29.

Hubbard, N. J., 1969, A chemical comparison of ocean ridge, Hawaiian tholeiitic, and Hawaiian alkalic basalts, Earth Planet. Sci. Let., v. 5, 346-352.

Hughes, D. J. and Brown, G. C., 1972, Basalts from Madeira: a petrochemical contribution to the genesis of oceanic alkali rock series, Contrib. Miner. Petrol., v. 37, 91-109.

Humphris, S. E. and Thompson, G., 1978, Hydrothermal alteration of oceanic basalts by seawater: greenschist-facies metamorphism of Mid-Atlantic Ridge pillow basalts, Geochim. Cosmochim. Acta, v. 42, 107-125.

Jackson, E. D., 1976, Linear volcanic chains on the Pacific Plate, Amer. Geophys Un., Geophys. Mono. 19, 319-335.

Jackson E. D. and Wright, T. L., 1970, Xenoliths in the Honolulu Volcanic Series, Jour. Petrol., v. 11, 405-430.

Jackson, E. D., Bargar, K. E., Fabbi, B. P., and Heropoulos, C., 1976, Petrology of basaltic rocks drilled on Leg 33 of the D. S. D. P., Init. Rep. of the Deep Sea Drilling Project, v. 33, 571-613.

Jackson, E. D. and Schlanger, S. O., 1976, Regional syntheses: Line Islands Chain, Tuamotu Island Chain, and Manihiki Plateau, Central Pacific Ocean, Init. Rep. of the Deep Sea Drilling Project, v. 33, 915-927.

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 D. S. D. P. Leg 55, the Hawaii-Emperor hot-spot experiment, Init. Rep. of the Deep Sea Drilling Project, v. 55, 5-31.

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, 57-76.

Kay, R. W. and Gast, P. W., 1973, The rare earth content and origin of alkali-rich basalts, Jour. Geology, v. 81, 653-682.

Kelts, K. and McKenzie, J. A., 1976, Cretaceous volcanogenic sediments from the Line Islands Chain: diagenesis and formation of K-feldspar, D. S. D. P. Leg 33, Hole 315A and 316, Init. Rep. of the Deep Sea Drilling Project, v. 33, 789-831.

Kesson, S. and Price, R. C., 1972, The major and trace element chemistry of kaersutite and its bearing on the petrogenesis of alkaline rocks, Contrib. Miner. Petrol., v. 35, 119-124.

Kushiro, I., 1960, Si-Al relation in clinopyroxenes from igneous rocks, Amer. Jour. Sci., v. 258, 548-554.

Lanphere, M. A. and Dalrymple, G. B., 1976, K-Ar ages for basalts from DSDP Leg 33: Sites 315 (Line Islands) and 317 (Manihiki Plateau), Init. Rep. of the Deep Sea Drilling Project, v. 33, 649-653.

Lanphere, M. A., Dalrymple, G. B., and Clague, D. A., 1980, Rb-Sr systematics of basalts from the Hawaiian-Emperor volcanic chain, Init. Rep. of the Deep Sea Drilling Project, v. 55, 695-706.

Larson, R. L. and Chase, C. G., 1972, Late Mesozoic evolution of the western Pacific Ocean, Bull. Geol. Soc. Amer., v. 83, 3627-3644.

Larson, R. L. and Pitman, W. C. III, 1972, World-wide correlation of Mesozoic magnetic anomalies and its implications, Bull. Geol. Soc. Amer., v. 83, 3645-3662.

Larson, R. L., Smith, S. M., and Chase, C. G., 1972, Magnetic lineations of Early Cretaceous age in the western equatorial Pacific Ocean, Earth Planet. Sci. Let., v. 15, 315-319.

Leake, B. E., 1978, Nomenclature of amphiboles, Amer. Mineral., v. 63, 1023-1052.

LeBas, M. J., 1962, The role of aluminum in igneous clinopyroxenes with relation to their parentage, Amer. Jour. Sci., v. 260, 267-288.

Leeman, W. P., Murali, A. V., Ma, M.-S., and Schmitt, R. A., 1977, Mineral constitution of mantle source regions for Hawaiian basalts - rare earth evidence for mantle heterogeneity. In: Magma Genesis, State of Oregon, Dept. of Geology and Mineral Resources Bull., v. 96, 169-183.

Lofgren, G., Donaldson, C. H., Williams, R. J., Mullins, O., and Usselman, T. M., 1974, Experimentally reproduced textures and mineral chemistry of Apollo 15 quartz normative basalts, Proc. Fifth Lunar Sci. Conf., suppl. 5, Geochim. Cosmochim. Acta, v. 1, 549-567.

Ludden, J. N., 1978, Magmatic evolution of the basaltic shield volcanoes of Reunion Island, Jour. Volc. Geotherm. Res., v. 4, 171-198.

Ludden, J. N. and Thompson, G., 1979, An evaluation of the behavior of the rare earth elements during the weathering of sea-floor basalt, Earth Planet. Sci. Let., v. 43, 85-92.

Macdonald, G. A., 1968, Composition and origin of Hawaiian lavas, Geol. Soc. Amer., Memoir 116, 477-522.

Macdonald, G. A. and Powers, H. A., 1946, Contribution to the petrography of Haleakala Volcano, Hawaii, Bull. Geol. Soc. Amer., v. 57, 115-124.

Macdonald, G. A. and Katsura, T., 1964, Chemical composition of Hawaiian lavas, Jour. Petrol., v. 5, 82-133.

Macdonald, G. A. and Abbott, A., 1970, "Volcanoes In The Sea", Univ. of Hawaii Press, Honolulu.

Macdonald, G. A., Powers, H. A., and Katsura, T., 1973, Interlaboratory comparison of some chemical analyses of Hawaiian volcanic rocks, Bull. Volcan., v. 36, 127-139.

Malahoff, A., 1971, Magnetic lineations over the Line Islands Ridge, Bull. Geol. Soc. Amer., v. 82, 1977-1982.

Matsuda, J.-I., 1980, Low Sr isotopic ratios of alkali basalts from the Line Islands in the Pacific Ocean, Geochem. Jour., v. 14, 41-46.

McDougall, I., 1971, Volcanic island chains and sea floor spreading, Nat. Phys. Sci., v. 231, 141-144.

Melson, W. G., Jarosewich, E., and Cifelli, R., 1967, Alkali olivine basalt dredged near St. Paul's Rocks, Mid-Atlantic Ridge, Nature, v. 215, 381-382.

Melson, W. G., Thompson, G., and VanAndel, T. H., 1968, Volcanism and metamorphism in the Mid-Atlantic Ridge, 22^{0} north latitude, Jour. Geophys. Res., v. 73, 5925-5941.

Melson, W. G. and Thompson, G., 1973, Glassy abyssal basalts, Atlantic Ocean floor near St. Paul's Rocks: petrography and composition of secondary clay minerals, Bull. Geol. Soc. Amer., v. 84, 703-716.

Menard, H. W., 1973, Depth anomalies and the bobbing motion of drifting volcanoes, Jour. Geophys. Res., v. 78, 5128-5137.

Moore, J. G., 1966, Rate of palagonitization of submarine basalt adjacent to Hawaii, U. S. G. S., Prof. Paper, no. 55-D, 163-171.

Morgan, W. J., 1971, Convective plumes in the lower mantle, Nature, v. 230, 42-43.

Morgan. W. J., 1972a, Deep mantle convection plumes and plate motions, Amer. Assoc. Petrol. Geol., v. 56, 203-213.

Morgan, W. J., 1972b, Plate motions and deep mantle convection, Geol. Soc. Amer., Memoir 132, 7-22.

Muir, I. D. and Tilley, C. E., 1964, Basalts from the northern part of the rift zone of the Mid-Atlantic Ridge, Jour. Petrol., v. 5, 409-434.

Natland, J. H., 1975, Petrologic studies of linear island chains: I-The Samoan Chain; II-The Line Islands, Ph. D. Dissertation, Univ. Calif., San Diego.

Natland, J. H., 1976a, Petrology of volcanic rocks dredged from seamounts in the Line Islands, Init. Rep. of the Deep Sea Drilling Project, v. 33, 749-777.

Natland, J. H., 1976b, Possible volcanologic explanations for the origin of flat-topped seamounts and ridges in the Line Islands and Mid-Pacific Mountains, Init. Rep. of the Deep Sea Drilling Project, v. 33, 779-787.

Nisbet, E. G. and Pearce, J. A., 1977, Clinopyroxene composition in mafic lavas of different tectonic settings, Contrib. Miner. Petrol., v. 63, 149-160.

O'Nions, R. K. and Pankhurst, R. J., 1974, Petrogenetic significance of isotope and trace element variations in volcanic rocks from the Mid-Atlantic, Jour. Petrol., v. 15, 603-634.

Orwig, T. L. and Kroenke. L. W., 1980, Tectonics of the eastern Central Pacific Basin, Marine Geology, v. 34, 29-43.

Ozima, M., Saito, K., Honda, M., and Aramaki, S., 1977, Sea water weathering effects on K-Ar age of submarine basalts, Geochim. Cosmochim. Acta, v. 41, 453-461.

Philpotts, J. A., Schnetzler, C. C., and Hart, S. R., 1969, Submarine basalts; some K, Rb, Sr, Ba, rare earth, H_2O, and CO_2 data bearing on their alteration, modification by plagioclase, and possible source materials, Earth Planet. Sci. Let., v. 7, 293-299.

Philpotts, J. A. and Schnetzler, C. C., 1970, Phenocryst-matrix partition coefficients for K, Rb, Sr, and Ba, with applications to anorthite and basalt genesis, Geochim. Cosmochim. Acta, v. 34, 307-322.

Sager, W. W., 1981, Paleomagnetism of Line Islands and Musicians Seamounts, EOS Trans., v. 62, p. 381, abstract.

Sager, W. W., Davis, G. T., Keating, B. H., and Philpotts, J. A., 1982, A geophysical and geologic study of Nagata Seamount, Northern Line Islands, Jour. Geomagn. Geoelectr., v. 34, 283-305.

Sager, W. W. and Keating, B. H., 1984, Paleomagnetism of Line Islands seamounts: evidence for Late Cretaceous and Early Tertiary volcanism, Jour. Geophys. Res., v. 89, 11,135-11,151.

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, Amer. Geophys. Un., Geophys. Mono. 19, 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. Let., v. 33, 353-369.

Schilling, J.-G. and Winchester, J. W., 1969, Rare earth contribution to the origin of Hawaiian lavas, Contrib. Miner. Petrol., v. 23, 27-37.

Schlanger, S. O., Jenkyns, H. C., and Premole-Silva, I., 1981, Volcanism and vertical tectonics in the Pacific Basin related to global Cretaceous transgressions, Earth Planet. Sci. Let., v. 52, 435-449.

Schlanger, S. O., Garcia, M. O., Keating, B. H., Naughton, J. J., Sager, W. W., Haggerty, J. A., Philpotts, J. A., and Duncan, R. A., 1984, Geology and geochronology of the Line Islands, Jour. Geophys. Res., v. 89, 11,261-11,272.

Schnetzler, C. C., Thomas, H. H., and Philpotts, J. A, 1967a, The determination of barium in G-1 and W-1 by isotope dilution, Geochim. Cosmochim. Acta, v. 31, 95-96.

Schnetzler, C. C., Thomas, H. H., and Philpotts, J. A., 1967b, Determination of rare earth elements in rocks and minerals by mass spectrometric, stable isotope dilution technique, Analyt. Chem., v. 39, 1888-1890.

Schnetzler, C. C. and Philpotts, J. A., 1968, Partition coefficients of rare-earth elements and barium between igneous matrix material and rock-forming mineral phenocrysts-I. In: "Origin And Distribution Of The Elements", L. H. Ahrens (ed.), Pergamon Press, New York.

Schnetzler, C. C. and Philpotts, J. A., 1970, Partition coefficients of rare-earth elements between igneous matrix material and rock-forming mineral phenocrysts-II, Geochim. Cosmochim. Acta, v. 34, 331-340.

Scholl, D. W. and Creagar, J. S., 1973, Geologic synthesis of Leg 19 (DSDP) results; for north Pacific, Aleutian Ridge, and Bering Sea, Init. Rep. of the Deep Sea Drilling Project. v. 19, 897-913.

Scientific Staff, 1974, Leg 33-Deep Sea Drilling Project: testing a hot-spot theory, Geotimes, v. 19, 16-20.

Shaw, H. R., 1973, Mantle convection and volcanic periodicity in the Pacific: evidence from Hawaii, Bull. Geol. Soc. Amer., v. 84, 1505-1526.

Shaw, H. R. and Jackson, E. D., 1973. Linear island chains in the Pacific: result of thermal plumes or gravitational anchors, Jour. Geophys. Res., v. 78, 8634-8652.

Shibata, T., Thompson, G., and Frey, F. A., 1979, Tholeiitic and alkali basalts from the Mid-Atlantic Ridge at 43^{O}N, Contrib. Miner. Petrol., v. 70, 127-141.

Shipboard Scientific Party-Leg 9, 1972, Shipboard Report-Site 76, Init. Rep. of the Deep Sea Drilling Project, v. 9, 21-41.

Shipboard Scientific Party-Leg 17, 1973, Site Report-Site 165, Init. Rep. of the Deep Sea Drilling Project, v. 17, 43-102.

Shipboard Scientific Party-Leg 33, 1976, Site Report-Site 318, Init. Rep. of the Deep Sea Drilling Project, v. 33, 301-357.

Solomon, S. C., Sleep, N. H., and Jurdy, D. M., 1977, Mechanical models for absolute plate motions in the Early Tertiary, Jour. Geophys. Res., v. 82, 203-212.

Strong, D. F., 1972, The petrology of the lavas of Grand Comore, Jour. Petrol., v. 13, 181-217.

Sun, S.-S. and Hanson, G. N., 1975, Evolution of the mantle: geochemical evidence from alkali basalt, Geology, v. 3, 297-302.

Sutton, G. H., Manghnani, M. H., and Moberly, R. (eds.), 1976, "The Geophysics Of The Pacific Ocean Basin And Its Margin", Amer. Geophys. Un., Geophys. Mono. 19, Washington, D. C..

Thompson, G., 1973, A geochemical study of low temperature interaction of sea-water and oceanic igneous rocks, EOS Trans., v. 54, 1015-1019.

Thompson, G. and Melson, W. G., 1972, The petrology of oceanic crust across fracture zones in the Atlantic Ocean: evidence of a new kind of sea-floor spreading, Jour. Geology, v. 80, 526-538.

Thompson, R. N., 1974, Some high-pressure pyroxenes, Miner. Mag., v. 39, 768-787.

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

Vallance, T. J., 1974, Pyroxenes and the basalt-spillite relation. In: "Spillites And Spillitic Rocks", G. C. Amstutz (ed.), Springer-Verlag, New York.

Varne, R. and Graham, A. L., 1971, Rare earth abundances in hornblende and clinopyroxene of a hornblende lherzolite xenolith: implications for upper mantle fractionation processes, Earth Planet. Sci. Let., v. 13, 11-18.

Wass, S. Y., 1979, Multiple origins of clinopyroxenes in alkali basaltic rocks, Lithos, v. 12, 115-131.

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, 532-537.

White, W. M. and Schilling, J.-G., 1978, The nature and origin of geochemical variation in Mid-Atlantic Ridge basalts from central north Atlantic, Geochim. Cosmochim. Acta, v. 42, 1501-1516.

Wilson, J. T., 1963a, A possible origin of the Hawaiian Islands, Can. Jour. Physics, v. 41, 863-870.

Wilson, J. T., 1963b, Evidence from islands on the spreading of the ocean floor, Nature, v. 197, 536-538.

Winterer, E. L., 1976a, Anomalies in the tectonic evolution of the Pacific, Amer. Geophys. Un., Geophys. Mono. 19, 269-278.

Winterer, E. L., 1976b, Bathymetry and regional setting of the Line Islands Chain, Init. Rep. of the Deep Sea Drilling Project, v. 33, 731-747.

Worsley, T. R., 1973, Calcareous nannofossils, Init. Rep. of the Deep Sea Drilling Project, v. 19, 741-750.

Zielinski, R. A., 1975, Trace element evaluation of a suite of rocks from Reunion Island, Indian Ocean, Geochim. Cosmochim. Acta, v. 39, 713-734.

Zielinski, R. A. and Frey, F. A., 1970, Gough Island: evaluation of a fractional crystallization model, Contrib. Miner. Petrol., v. 29, 242-254.