THE GEOLOGIC HISTORY

OF THE

SOUTHERN LINE ISLANDS

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ABSTRACT

The Line Islands chain, a major bathymetric feature in the Pacific Basin, is composed of a linear series of parallel submarine ridges and volcanic edifices capped by atolls. Rocks dredged from the previously unsampled southern portion of the chain--the Caroline Island area--have been analyzed for depositional environment, biostratigraphic age, and diagenetic environment. These rocks contain Late Cretaceous and Tertiary faunas.

Drilling on DSDP Legs 17 and 33 revealed that synchronous volcanic edifice building and reef development took place in Late Cretaceous time over a distance of 1270 km along the chain. Rocks dredged from seamounts near Caroline Island contain volcanic debris and shallow-water shell debris of Late Cretaceous age. This association is evidence for the existence of a reef-bearing volcanic edifices with a minimum age of Late Cretaceous near Caroline Island. With the discovery of these seamounts, the known occurrences of Late Cretaceous, reef-capped, volcanic edifices now extend a distance of 2500 km from Kingman Reef to Caroline Island.

Volcanism during middle Eocene time is documented in the southern Line Islands, where Eocene sediments were engulfed and altered by volcanic eruptions. Skeletal debris of shallow-water origin was redeposited in deep-water Paleocene, Eocene, Oligocene, Miocene, and Pliocene strata indicating that reef development was perhaps continuous throughout the Tertiary. Stable isotope geochemistry of carbonate cements indicates subsidence of the Line Islands seamounts during post-Eocene time.

The synchroneity of Late Cretaceous volcanism along 2500 km of the Line Islands argues against the proposition that a single hotspot of the Hawaiian-Emperor type produced the Line Island chain. Volcanic edifices of Cretaceous age are now known to extend from the Line Islands through the Mid-Pacific Mountains to the Marshall Islands and the western margin of the Pacific Plate from Japan to the Marianas. The occurrence of both Cretaceous and Eocene volcanism in the southern Line Islands indicates similarities between the histories of the Line Islands and the Marshall Islands.

TABLE OF CONTENTS

	Page
ACKNOWLEDGEMENTS	iii
ABSTRACT	iv
LIST OF TABLES	x
LIST OF FIGURES	xi
LIST OF PLATES	xiii
INTRODUCTION	1
Background	1
REGIONAL GEOLOGIC SETTING	8
PREVIOUS INVESTIGATIONS	13
STATEMENT OF PROBLEM	18
RESEARCH METHODOLOGY	19
Documentation of Dredge Sites	20
Petrologic Analysis	21
Carbon and Oxygen Stable Isotope Analysis	22
DREDGE SITE LOCATIONS	24
DREDGE-44 RESULTS	27
Bathymetry	27
Rock Descriptions and Interpretations	32
Conclusions	34
DREDGE-45 RESULTS	35
Bathymetry	35
Rock Descriptions and Interpretations	35
Conclusions	47
DREDGE-46 AND 47 RESULTS	49
Bathymetry	49
Rock Descriptions and Interpretations	49
Conclusions	59

	Page
DREDGE-48 RESULTS	60
Bathymetry	60
Rock Descriptions and Interpretations	60
Conclusions	65
DREDGE-50 RESULTS	66
Bathymetry	66
Rock Descriptions and Interpretations	66
Conclusions	71
DREDGE-51 RESULTS	72
Bathymetry	72
Rock Descriptions and Interpretations	72
Conclusions	77
DREDGE-52 RESULTS	78
Bathymetry	78
Rock Descripttions and Interpretations	78
Conclusions	83
CARBON AND OXYGEN STABLE ISOTOPE GEOCHEMISTRY OF CEMENTS IN CENOZOIC LIMESTONES FROM THE SOUTHERN LINE ISLANDS	84
Results	88
Interpretations	91
Implications	93
SUMMARY OF THE GEOLOGIC HISTORY OF THE SOUTHERN LINE ISLANDS CORRELATION WITH THE CENTRAL PACIFIC	97
Reefing History	97
Erosional Events	98
Volcanic Events	101
Phosphatization Events	103
Subsidence History	105
REGIONAL IMPLICATIONS	115
PLATES	126

Page

APPENDIX A: A REVIEW OF STABLE ISOTOPE GEOCHEMISTRY OF CARBONATE CEMENTS 151

APPENDIX B: DESCRIPTION OF DREDGE HAULS AND PISTON CORES 160

APPENDIX C: UNDERWAY GEOPHYSICAL DATA 166

APPENDIX D: SAMPLE DESCRIPTIONS AND PALEONTOLOGIC DATA FROM THE SOUTHERN LINE ISLANDS 175

REFERENCES 182

LIST OF TABLES

Table		Page
1.	Carbon and oxygen stable isotopic composition of Cenozoic limestones from the southern Line Islands	89
2.	Descriptions of rocks dredged during Legs 1 and 2 of the R/V Kana Keoki cruise KK79-08-08 . .	161
3.	Descriptions of piston cores recovered during Leg 1 of the R/V Kana Keoki cruise KK79-08-08 . .	165
4.	Samples studied from the southern Line Islands	176
5.	Distribution of volcanic material, invertebrate fossils and fossil preservation in samples from the southern Line Islands	179
6.	Distribution of Cretaceous to Eocene planktonic foraminifera in samples from the southern Line Islands	180
7.	Distribution of Oligocene to Recent planktonic foraminifera in samples from the southern Line Islands	181

LIST OF FIGURES

Figure		Page
1.	Stratigraphic distribution of Cretaceous mid-plate volcanic rocks at DSDP sites in the Central Pacific	4
2.	Bathymetric chart of the Southern Province of the Line Islands	12
3.	Location of DSDP sites in the area of the Line Islands	15
4.	Track chart of the R/V Kana Keoki and dredge site locations along the Line Islands	26
5.	Seismic reflection profile of site RD-44	29
6.	Bathymetric chart of site RD-44	31
7.	Seismic reflection profile of site RD-45	37
8.	Bathymetric chart of site RD-45	39
9.	Seismic reflection profile of sites RD-46 and 47 . .	51
10.	Bathymetric chart of sites RD-46 and 47 on the flank of Caroline Island	53
11.	Seismic reflection profile of site RD-48	62
12.	Bathymetric chart of sites RD-48 and 49 on the flank of Vostok Island	64
13.	Seismic reflection profile of site RD-50	68
14.	Bathymetric chart of site RD-50 northwest of Flint Island	70
15.	Seismic reflection profile of site RD-51	74
16.	Bathymetric chart of site RD-51	76
17.	Seismic reflection profile of site RD-52 along the Tuamotu Ridge	80
18.	Bathymetric chart of site RD-52 on the Tuamotu Ridge	82

Figure Page

19. Subsidence history diagram of site RD-45 109

20. Line drawing of seismic reflection profile of site RD-45 114

21. Location and extent of reefs of Late Cretaceous age along the Line Islands 117

22. Map of the western Pacific showing the extent and type of Cretaceous volcanism 121

23. Locations of seamounts and guyots of Cretaceous age on the Pacific Plate 123

LIST OF PLATES

Plate		Page
I.	Photomicrographs of rocks from site RD-44	128
II.	Photomicrographs of Cretaceous rocks from site RD-45	130
III.	Cretaceous coquina from site RD-45	132
IV.	Phosphatized and burrowed foraminiferal limestones from site RD-45	134
V.	Volcanic rocks associated with Eocene sediment from sites RD-45 and RD-46	136
VI.	Low-magnesium limestones from site RD-46 and site RD-47	138
VII.	Aragonite dissolution features in rocks from site RD-47	140
VIII.	Photomicrographs of rocks from site RD-46 and site RD-47	142
IX.	Photomicrographs of rocks from site RD-47 and site RD-48	144
X.	Larger foraminifera in rocks from site RD-47	146
XI.	Reworked hyaloclastite from site RD-50	148
XII.	Photomicrographs of volcanic sandstones from site RD-51 and site RD-52	150

INTRODUCTION

The Line Islands chain is a major bathymetric feature composed of a series of parallel submarine ridges, seamounts, and atolls, which extend a distance of 4200 km from southeast of Horizon Guyot to just north of the Tuamotu Islands in the central Pacific Basin. In August, 1979, 19 seamounts were dredged along the Line Islands, of which eight successful dredge hauls were recovered in the southern portion of the chain near Caroline Island. The subject of this dissertation is the geology of the southern Line Islands from a sedimentological perspective using rocks dredged from seamounts near Caroline Island.

Background

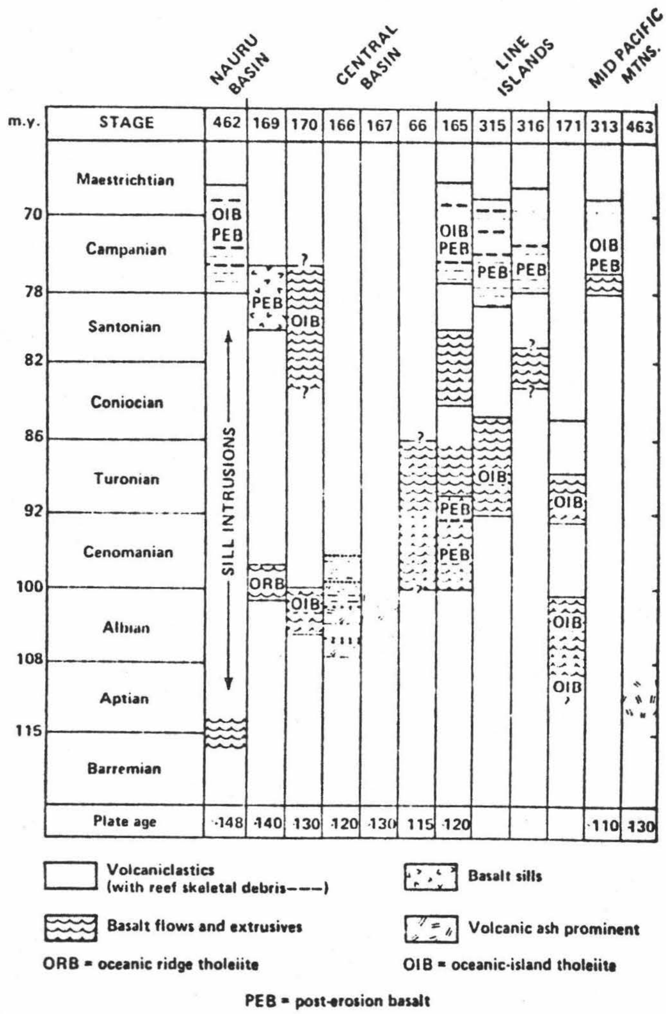
Morgan (1972) considered the Line-Tuamotu chain and the Emperor-Hawaiian chain as temporal and genetic equivalents, formed by plate motion over a fixed mantle hotspot. Required evidence for coeval hotspot traces includes (1) the same age progression of volcanism along the chain, and (2) the bends or elbows in the chains should be contemporaneous. The bend in the Emperor-Hawaiian chain has been dated by the K-Ar method as 42.3 ± 1.6 m.y.B.P. at Yuryaku seamount (Clague et al., 1975). The youngest expressions of these hotspots or melting anomalies is considered to be Loihi, for the Hawaiian chain (Malahoff et al., 1981), and Pitcairn Island, for the Tuamotu extension through the Gambier Islands (Duncan et al., 1974).

Since 1972, various investigations have been conducted to decipher the history of these chains and the validity of the hotspot model. Evidence has accumulated which demonstrates dissimilarities between the two chains. The Emperor-Hawaiian chain appears to fit the Wilson (1963) and Morgan (1972) hotspot model (Jackson, 1976; Scientific Staff, DSDP Leg 55, 1978; Jackson et al., 1980), however the Line Islands do not (Jackson and Schlanger, 1976).

Data derived from two legs of the Deep Sea Drilling Project (DSDP) at Sites 165 (Winterer et al., 1973), 315, and 316 (Schlanger et al., 1976) along the Line Islands, indicate a cessation in oceanic-island basalt flow volcanism by early Campanian time. Recovered skeletal reef debris was dated as Campanian/Maestrichtian (Figure 1). Consequently, Jackson and Schlanger (1976) interpreted these data as synchronous Cretaceous reef development which extended 1270 km along the chain. If continuous subsidence had occurred along the chain with increasing "northward" age, Site 165 would have subsided too deeply for reef growth to have occurred there, as well as simultaneously 1270 km away at Site 316. The reefs indicate that the entire 1270 km was in the photic zone during Campanian/Maestrichtian time.

The lack of both an age progression and a uniform rate of volcanic propagation is also indicated by the radiometric dates of the volcanic rocks (Jackson, 1976; Jarrard and Clague, 1977; Saito and Ozima, 1977). The radiometric ages of volcanic material from north of Christmas Island are older than the most northern Emperor seamount, Meiji (Site 192), which is early Maestrichtian in age (Worsley, 1973; Scholl and

Figure 1. Stratigraphic distribution of Cretaceous mid-plate volcanic rocks at DSDP sites in the central Pacific (from Schlanger and Premoli Silva, 1981).



NAURU BASIN
CENTRAL BASIN
LINE ISLANDS
MID PACIFIC MTNS.
m.y.
STAGE
462
169
170
166
167
66
165
315
316
171
313
463
Maestrichtian
70
Campanian
78
Santonian
82
Coniocian
86
Turonian
92
Cenomanian
100
Albian
108
Aptian
115
Barremian
Plate age
148
140
130
120
130
115
120
110
130
SILL INTRUSIONS
OIB
PEB
ORB
Volcaniclastics (with reef skeletal debris---)
Basalt sills
Basalt flows and extrusives
Volcanic ash prominent
ORB = oceanic ridge tholeiite
OIB = oceanic-island tholeiite
PEB = post-erosion basalt

Creager, 1973). Therefore, if there is a temporal and/or genetic analogue within the Line-Tuamotu chain to the Emperor-Hawaiian chain, it must be south of Christmas Island.

In addition to the hotspot model as mid-plate volcanism forming the Line Islands, plate boundary volcanism either associated with a ridge crest or a transform fault has been called upon by several authors to explain the origin of the Line Islands. Winterer (1976) suggested that the Line Islands formed by volcanism along structural trends associated with an abandoned ridge crest. On the basis of free-air gravity anomaly data, Watts et al. (1980) also suggested that the Line Islands were formed near a ridge crest. Orwig and Kroenke (1980) proposed that the Line Islands were formed by one episode of volcanism, about 85 m.y., along a large transform fault that connected an active spreading ridge south of the Mid-Pacific Mountains to a former East Pacific Rise segment. Farrar and Dixon (1981) proposed that 1700-1900 km of dextral offset occurred between 67 to 40 m.y. along a fracture zone system extending from the Emperor Trough, through the Gardner seamount chain, and the Line Islands.

Epp (1978) proposed more than one mechanism for the origin of the Line Islands. He noted that the petrology and long linear nature of the chain suggested a hotspot origin, although other characteristics of the chain were not typical of hotspot traces. He therefore suggested that the formation of the chain may have been related either to the interaction of the hotspot with an older structural weakness developed at a ridge crest or to the interaction of plate to plate and plate to mantle motion.

Jackson and Schlanger (1976) suggested that during the evolution of the Line Islands, a post-edifice epeirogenic pulse with associated volcanism (i.e., Cretaceous mid-plate volcanism) uplifted the chain into the photic zone. This model would account for the synchronous reef development during the Late Cretaceous along the central Line Islands, with or without the previous subsidence along the chain as required by the hotspot model. This new stage of volcanism, forming post-edifice basalt, comprise the potassic basanites and nephelinites described by Natland (1976).

In the past several years, it has been proposed that Cretaceous mid-plate volcanism has played a major role in the geological development of the Central Pacific. Menard (1964) suggested that a bulge of the mantle resulted in the large regional feature, the Darwin Rise, in the Central Pacific which was associated with large scale volcanism during the Late Mesozoic. DSDP data from the Nauru Basin and the central Line Islands support this idea (Schlanger et al., 1981b; Schlanger and Premoli Silva, 1981). Widespread volcanism is noted to have occurred between 120 and 90 m.y. (Watts et al., 1980) in the Pacific and was associated with major vertical uplift, as documented at Site 462 (Schlanger et al., 1981b; Schlanger and Premoli Silva, 1981). This large scale volcanism and vertical tectonics in the Pacific Basin and other ocean basins during the Cretaceous has been postulated as causing the global Cretaceous transgression (Schlanger et al., 1981b). This postulated implication of Cretaceous mid-plate volcanism may therefore alleviate the requirement of fast spreading rate changes in the world mid-ocean ridge systems as had previously been proposed by Hays and Pitman (1973). Knowledge of the geographical extent of Cretaceous mid-plate volcanism is important in evaluating this problem.

REGIONAL GEOLOGIC SETTING

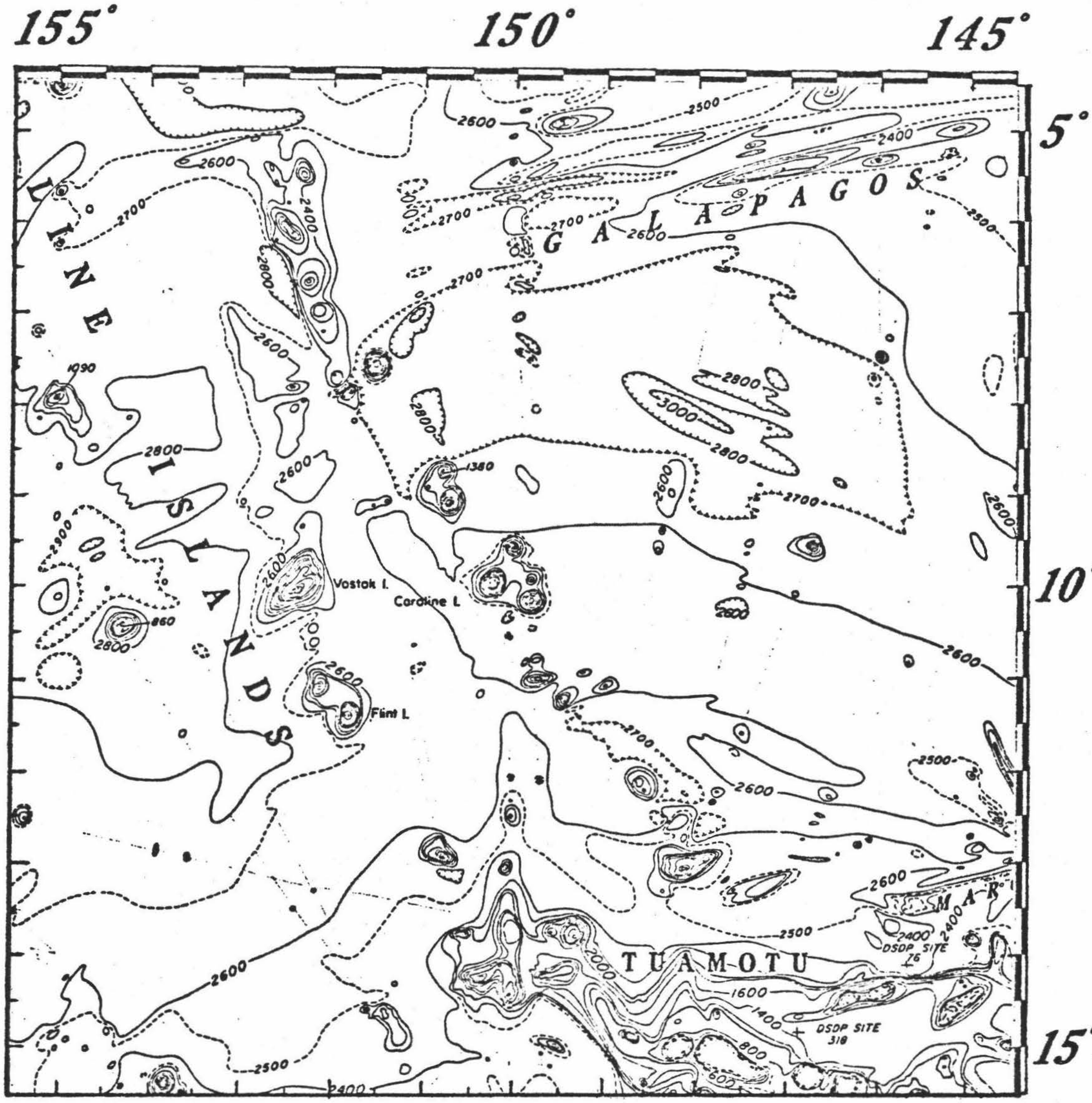
The morphology and regional geologic setting of the Line Islands is described in detail in Winterer (1976), and Jackson and Schlanger (1976). Briefly, the Line Islands appear as a double chain composed of two parallel trends of isolated seamounts and ridges. From Kingman Reef to Christmas Island, this doublet feature disappears, but may exist beneath the thick sedimentary fans surrounding the islands. The Line Islands are located on oceanic crust that does not appear to contain linear magnetic anomalies (Larson and Chase, 1972) that could be used to determine the age of the oceanic crust and aid in plate reconstructions.

The immediate region around the Line Islands is magnetically quiet possibly due to the following reasons listed by Winterer (1976): (1) formation of oceanic crust during the Magnetic Quiet Era in Middle and Late Cretaceous time, or (2) massive volcanism during spreading formed a thick crust with no distinct magnetic anomaly, or (3) the older sea floor which may have contained linear magnetic anomalies was flooded and buried by younger lavas. The younger lavas forming the Line Islands and the Mid-Pacific Mountains cover the older oceanic crust on the bight between the Hawaiian and Phoenix magnetic anomalies. The youngest age of the Hawaiian and Phoenix magnetic lineations, which are to the northwest and west of the Line Islands, is estimated at 107 m.y. (Larson and Hilde, 1975). Basement between the Phoenix magnetic lineations and the Line Islands chain at DSDP Site 66 is about 100 m.y. (Winterer, 1973). To the northeast of the Line Islands, beyond the Mendocino Fracture Zone, is anomaly 32, about 70 to 71 m.y. (Van Hinte, 1978; Lowrie and Alvarez, 1981), but directly east of the Line Islands anomaly 32 has not been identified possibly due to the low magnetic paleolatitude of the region during Late Cretaceous time. The Molokai, Clarion, and Galapagos Fracture Zones obliquely intersect the Line Island chain from the east and their extension west of the chain may be obscured due to the presence of the chain. The Clipperton Fracture Zone vanishes at about 300 km east of the chain and is not in direct line with the Nova-Canton Trough to the west of the chain.

Winterer (1976) divides the Line Islands chain into various geographic provinces based on morphology. The Northern Province extends south from Horizon Guyot, in the Mid-Pacific Mountains, to the Clarion Fracture Zone, and consists of a row of long, narrow ridges along the eastern side of the chain and a series of shorter subparallel ridges 150 km to the west. The Central Province extends from the Clarion Fracture Zone to just north of Kingman Reef, and consists of several parallel rows of isolated seamounts. The seafloor is several hundred meters shallower than that of of the Northern Province. DSDP Site 165 is located 50 km west of a guyot in the Central Province. The Islands Province extends from Kingman Reef to the Galapagos Fracture Zone, and consists of a more massive structure of ridges and cones with atolls existing at sea level. From Christmas Island to 2^{o}S Lat. the eastern side of the chain is composed of a main ridge and the western ridge is narrower. DSDP Site 315 is located on the sedimentary fan east of Fanning Island and DSDP Site 316 is located just south of Christmas Island within the Islands Province.

Beyond the Galapagos Fracture Zone to the north end of the Tuamotu Ridge is defined here as the Southern Province of the Line Islands. This area was previously represented on the Scripps chart (Figure 2) as isolated and widely spaced seamounts and islands. Because this portion of the Line Islands has been very poorly surveyed, the bathymetric features are poorly known, except for the exposed islands--Malden, Starbuck, Vostok, Flint, and Caroline. If the 60 and 90 m.y. crustal age isochrons of the Pacific, used by Watts et al. (1980) are interpolated, the age of the seafloor beneath the Southern Line Islands is about 80 m.y.

Figure 2. Bathymetric chart of the Southern Province of the Line Islands. Bathymetric chart prepared by J. Mammerickx et al. for IMR Technical Report Series by Scripps Institution of Oceanography.


155°
150°
145°
5°
10°
15°
LINE ISLANDS
GALAPAGOS
TUAMOTU
MAR
Vostok I.
Caroline I.
Flint I.
DSDP SITE 76
DSDP SITE 318
1090
1380
860
2400
2500
2600
2700
2800
3000
2000
1600
1400
800
600

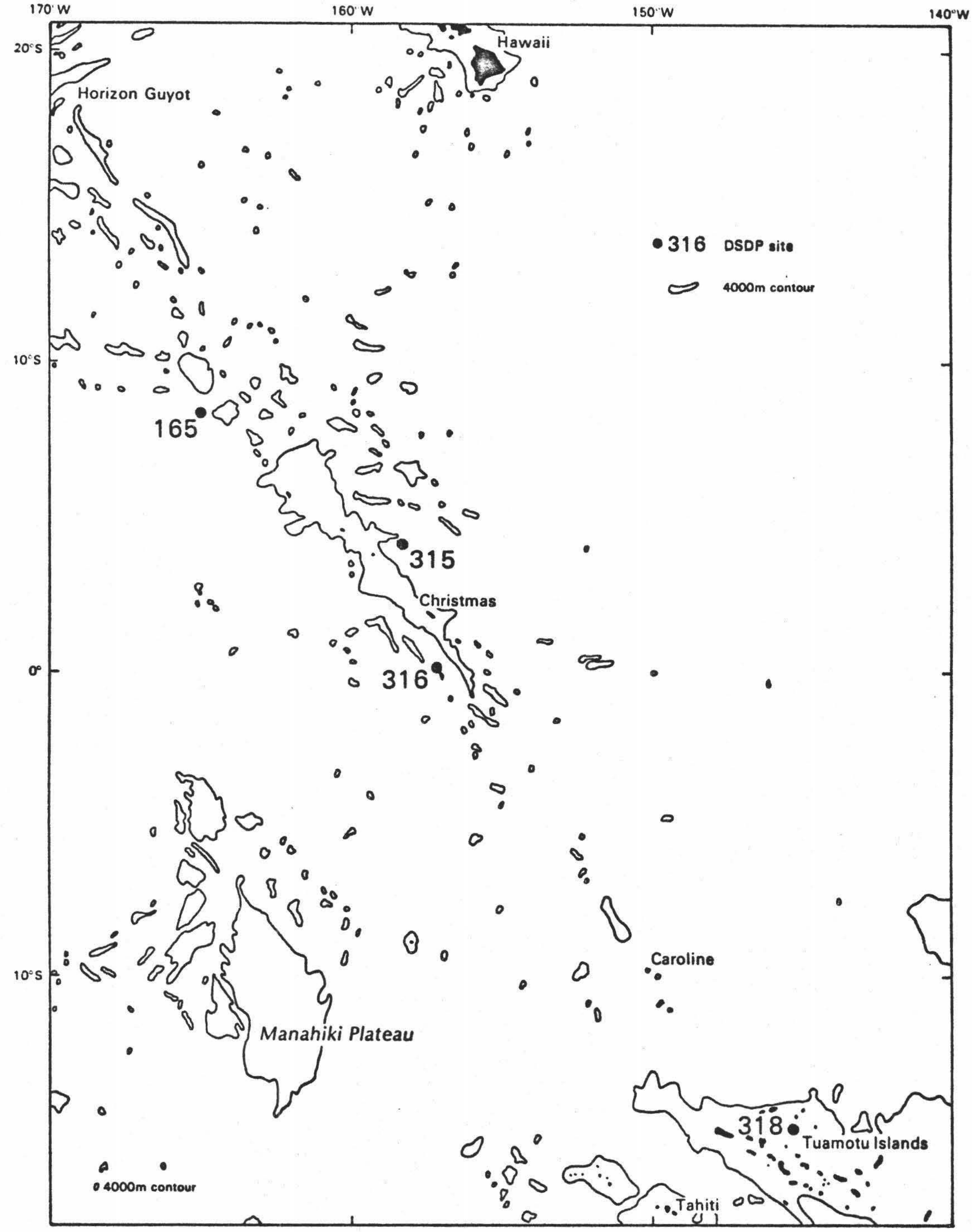
PREVIOUS INVESTIGATIONS

The Southern Province of the Line Islands was not previously sampled. Two legs of the Deep Sea Drilling Project have four drill sites near the study area (Figure 3). Three of these sites are located along the Line Island chain. Site 165 is in the Northern Province and Sites 315 and 316 are in the Island Province. Site 318 is located on the Tuamotu Ridge. These DSDP cores are described in detail in the chapter on Site Reports in Winterer et al. (1973) for Site 165, and Schlanger et al. (1976) for Sites 315, 316, and 318. Below is a general discussion of the results from each drill site.

At Site 165, basement was reached at 480 m below the seafloor. The oldest sediment recovered is Upper Cretaceous, greenish gray volcanic siltstone and marly mudstone. The oldest recovered nannofossils were of the Eiffelithus eximus Zone (76 to 80 m.y.), about 50 m above the lowermost post-edifice basanite. With a conservative accumulation rate of 15 m/m.y., the minimum basement age was calculated as 79 to 83 m.y. (Schlanger et al., 1974). Lanphere and Dalrymple (1976) estimated the age of this post-erosional type basalt as 93 to 100 m.y.

At Site 315, two holes were drilled and only one, 315A, reached basement at 996.3 m below the seafloor. The oldest cored sediment is Upper Cretaceous, green siltstone interlayered with brown mudstone. On the basis of the oldest recovered nannofossils, correlative with Marthasterites furcatus Zone (80 to 87 m.y.), and 15 m/m.y.

Figure 3. Location of DSDP sites in the area of the Line Islands.


170° W
160° W
150° W
140° W
20° S
10° S
0°
10° S
Hawaii
Horizon Guyot
316 DSDP site
4000m contour
165
315
Christmas
316
Caroline
Manahiki Plateau
318
Tuamotu Islands
Tahiti
4000m contour

accumulation rate for 70 m of sediment between the biostratigraphically datable horizon and the oceanic island type basalt flows, an extrapolated minimum basement age of 85 to 92 m.y. was determined (Jackson and Schlanger, 1976). Lanphere and Dalrymple (1976) determined a K/Ar radiometric date of 91.2 ± 2.7 m.y. for these oceanic island type basalts.

At Site 316, basement was not reached and the oldest sediment cored at 837 m below the seafloor was tan claystone of early Campanian age. The oldest recovered nannofossils were of the *Tetralithus aculeus* Zone (77 to 80 m.y.), and Schlanger et al. (1974) determined an extrapolated minimum basement age of 81 to 83 m.y.

Five lithologic units are described in these cores. Unit 5, the lowermost, consists of thin-bedded, red claystones that were probably derived from submarine weathered basalt basement. Unit 4 consists of green volcaniclastic graded and massive conglomerates and breccias and foram-rich limestones.

The volcaniclastic material consists essentially of altered volcanic glass, feldspars, mafic minerals, and clays formed by the alteration of volcanogenic material. The unit formed from debris and turbidity flows and exhibits graded bedding and current structures. The upper portion of the unit, the foram-rich limestone, contains *Pseudorbitoides*, *Asterorbis*, and *Sulcoperculina* (larger foraminifera), fragments of coralline algae and rudists. This redeposited skeletal debris originated on shallow water carbonate banks which existed in the photic zone.

Unit 3 consists of brown chert, and limestones with abundant burrows. Unit 2, composed of purple, green, blue, and white calcareous oozes and chalks is thin-bedded. Unit 1 contains brown radiolarian-rich ooze interbedded with white and orange calcareous-rich ooze which is laminated and thin-bedded. In the three upper units, which are basically composed of pelagic carbonate, redeposited Cretaceous shallow-water debris is found within pelagic material of Oligocene age. Various hiatuses interrupt the Cenozoic section.

At Site 318, on the Tuamotu sedimentary pedestal, basement was not reached, and the oldest sediment cored at 745 m below the seafloor was Lower Eocene, foraminiferal volcanogenic sandstone. The oldest nannofossils recovered are of the NP 13 Zone, and therefore yield a minimum basement age of 49 to 51 m.y. for the oceanic island type basalt. Unit 5 consists of green and greenish-gray clayey limestones, siltstones, and sandstones which are graded and contain shallow water faunas eroded from nearby edifices. Unit 4 composed of yellowish-gray and pale greenish nanno-foram limestones with chert nodules has fucoid burrows, slumped beds, and redeposited layers. Unit 3 contains yellowish-gray foram-nanno firm chalk with redeposited shallow-water material. Unit 2 is white, bluish-white, and greenish-white foram-nanno firm ooze to chalk with some graded layers of palagonite grains. Unit 1 is pale orange nanno-foraminiferal ooze. Pelagic sedimentation occurred from early Eocene time through to the present with skeletal reef debris entering the stratigraphic units as turbidites during the middle Eocene and early Miocene time.

STATEMENT OF PROBLEM

The Line-Tuamotu chain was proposed by Morgan (1972) as a temporal and genetic equivalent to the Emperor-Hawaiian chain. Data from DSDP Legs 17 and 33 indicate that the Line Islands north of Christmas Island are older than the most northern Emperor Seamount, Meiji. Therefore if there is a temporal equivalent to the Emperor Seamounts within the Line Islands, the analogue must be between Christmas Island and the Tuamotu Ridge.

Prior to the 1979 R/V Kana Keoki cruises there were no rocks collected from the segment between Christmas Island and the Tuamotu Ridge. Specifically, the seamounts and islands in the Caroline Island area were "poorly surveyed and unsampled, and the relationship to the rest of the Line Islands chain may be genetic or only a fortuitous alignment" (Winterer, 1976, p. 735).

The quantity and diversity of the sedimentary rocks recovered in the Southern Province of the Line Islands during our 1979 cruise permitted an extensive paleontological and sedimentological investigation. The rocks contain both fossils and volcanic rock fragments, thereby enabling one to date volcanic episodes as well as periods of reef growth. This type of information pertaining to the evolution of this province can help determine the genetic relationship with the northern Line Islands, and place constraints on models suggested for the origin of the Line Islands.

RESEARCH METHODOLOGY

A major goal of this study is to establish minimum ages of volcanism in the Line Islands. By determining the biostratigraphic age of the fossils associated with volcanic fragments, a minimum age of the volcanic fragments can be derived for that sedimentary rock. An indirect approach is biostratigraphic dating of reef material whose existence implies the presence of a volcanic edifice that facilitated the growth of reefs in the photic zone. This reef material may be found as redeposited larger foraminifera within chalks formed from turbidites or as limestone breccias composed of reef debris. Ages obtained by these methods aid in discriminating between tectonic models.

Another aspect of this research includes the investigation of carbonates for subaerial weathering characteristics as possible evidence of vertical tectonics. Techniques used to determine subaerial diagenetic alteration include petrographic examination of the hand specimens and thin sections, and geochemical analysis of the cements for carbon and oxygen stable isotopes. If these limestones have been subaerially exposed and the biostratigraphic age does not correlate with a known sea level drop (as documented by Vail and Hardenbol, 1979), then vertical tectonic uplift as a precursor to subaerial alteration is implied.

Documentation of Dredge Sites

Continuous underway geophysical data used in this study are 3.5 KHz echo sounding and variable frequency seismic reflection. All data from cruises KK79-08-08-01 and -02 are controlled by satellite navigation and dead reckoning. Good satellite fixes arrived on the average about every three hours.

All bathymetric data were corrected for variations in sound velocity in seawater by using Matthews Tables (Matthews, 1939). The first reflection return was picked, excluding obvious side echos, as bathymetric data assumed to mark true depth. The sound signal from the 3.5 KHz transducer mounted on the ship travels downward in a 30 degree beam through the water. In 5 km water depth, this cone covers an area 1294 m in diameter. Any bathymetric highs within this cone can give a first return as a false sounding, and consequently yield a shallower topography than actually beneath the ship.

For each dredge site in the Caroline Island vicinity, track charts were plotted and merged with the contoured bathymetry. The location of the dredge haul was annotated on the chart. The seismic reflection profiles used were recorded in the frequency band between 40 and 120 Hz. Documentation of the position of the dredge haul on the seamount was denoted on the seismic reflection profiles by the depth range during the dredging operation.

Petrologic Analysis

The collected samples were catalogued, cut, and thin sectioned for petrographic analysis. Faunal assemblages were identified in thin section and used to determine the biostratigraphic age of the sediment, and paleoenvironment. The planktonic foraminiferal zonation schemes used are Blow (1969) for the Neogene, Hardenbol and Berggren (1978) for the Paleogene, and Premoli Silva and Boersma (1977) from DSDP Leg 39 for the Cretaceous. The absolute ages for the Cretaceous zonations are derived from the DSDP Leg 39 scheme merged with the radiometric dates used in Van Hinte (1978).

A scanning electron microscope was used for studying diagenetic characteristics and surveying for nannofossils when the planktonic foraminifera were not well preserved for identification. A small subsample of the rock with a fresh, broken surface was mounted on an aluminum sample stub. The sample was then coated with gold-palladium in a vacuum evaporator and examined in a Cambridge S4-10 Scanning Electron Microscope.

Diagenetic characteristics such as cements, casts and molds, and recrystallization were also noted in examination of hand specimens and thin sections. Employing the electron microscope, cathodoluminescence was conducted to determine if more than one generation of carbonate cement had developed in some samples which were analyzed for the stable isotope geochemistry of the cement. X-ray diffraction, using a Norelco diffractometer with a high energy Ni-filtered, Cu-Kα radiation source and/or carbonate staining by the method of Warne (1962), modified by

Burkett (1972) was required to determine the mineralogy of various components of the rocks.

Information pertaining to the post-depositional environment is important as potential evidence of the vertical tectonic history of the area.

Carbon and Oxygen Stable Isotope Analysis

Stratigraphic and petrographic evidence has typically been used to elucidate the diagenetic history of limestones. Limestones can exhibit petrographic evidence of cementation in a series of diagenetic environments (Folk, 1974; Longman, 1980). Isotopic studies of the various cements and components of the limestones may support or clarify the petrographic observations. Allan and Matthews (1977) have demonstrated from the isotopic compositions of surface and subsurface limestones from Barbados that $\delta^{13}C$ and $\delta^{18}O$ data are useful diagenetic and stratigraphic tools. Because this study is conducted using dredged material and therefore lacking direct evidence of the lithostratigraphy, the application of stable isotope geochemistry to carbonate cements can aid in determining the diagenetic environment. Appendix A contains a discussion of the principles underlying the basic relationships of carbon and oxygen isotopes to the marine environment, along with their interaction with dissolved CO_2 in pore waters, degradation of organic material, methane production, and hydrocarbons. A short review is also included on observed isotopic compositions of carbonates in selected diagenetic environments.

Carbonate rocks suspected of having been subaerially exposed were subsampled for mass spectrometric analysis. Between 5 to 15 mg of low-Mg calcite cement was removed from the rock with a dentist drill, taking care not to contaminate the sample with skeletal debris.

Extraction of carbon dioxide from the carbonate samples was accomplished by following the procedure outlined by McCrea (1950). The carbonate was reacted with orthophosphoric acid under vacuum for nine hours at 25°C water bath. The sample gas was extracted from the reaction vessel, purified, and dried by standard techniques involving a series of liquid nitrogen and dry ice traps on input into the mass spectrometer.

Analysis for isotopic composition was performed using a Nucleide 3-60 RMS mass spectrometer. All mass spectrometer corrections were made according to Craig (1957) and Deines (1970). The isotopic data are expressed in delta notation with respect to the PDB standard CO_2:

$$\delta^{13}C = 1000\ [(R_x/R_s) -1]$$

in per mil, where R is

$$^{13}C/^{12}C \quad (\text{or } ^{18}O/^{16}O \text{ for } \delta^{18}O)$$

and where x and s refer to the sample and standard respectively. The daily reproducibility of the instrument was ± 0.05‰ $\delta^{13}C$ and ± 0.1‰ $\delta^{18}O$. The reproducibility of three duplicate subsamples from stalagtitic calcite from Bisbee, Arizona was ± 0.06‰ $\delta^{13}C$ and ± 0.11‰ $\delta^{18}O$ as overall precision.

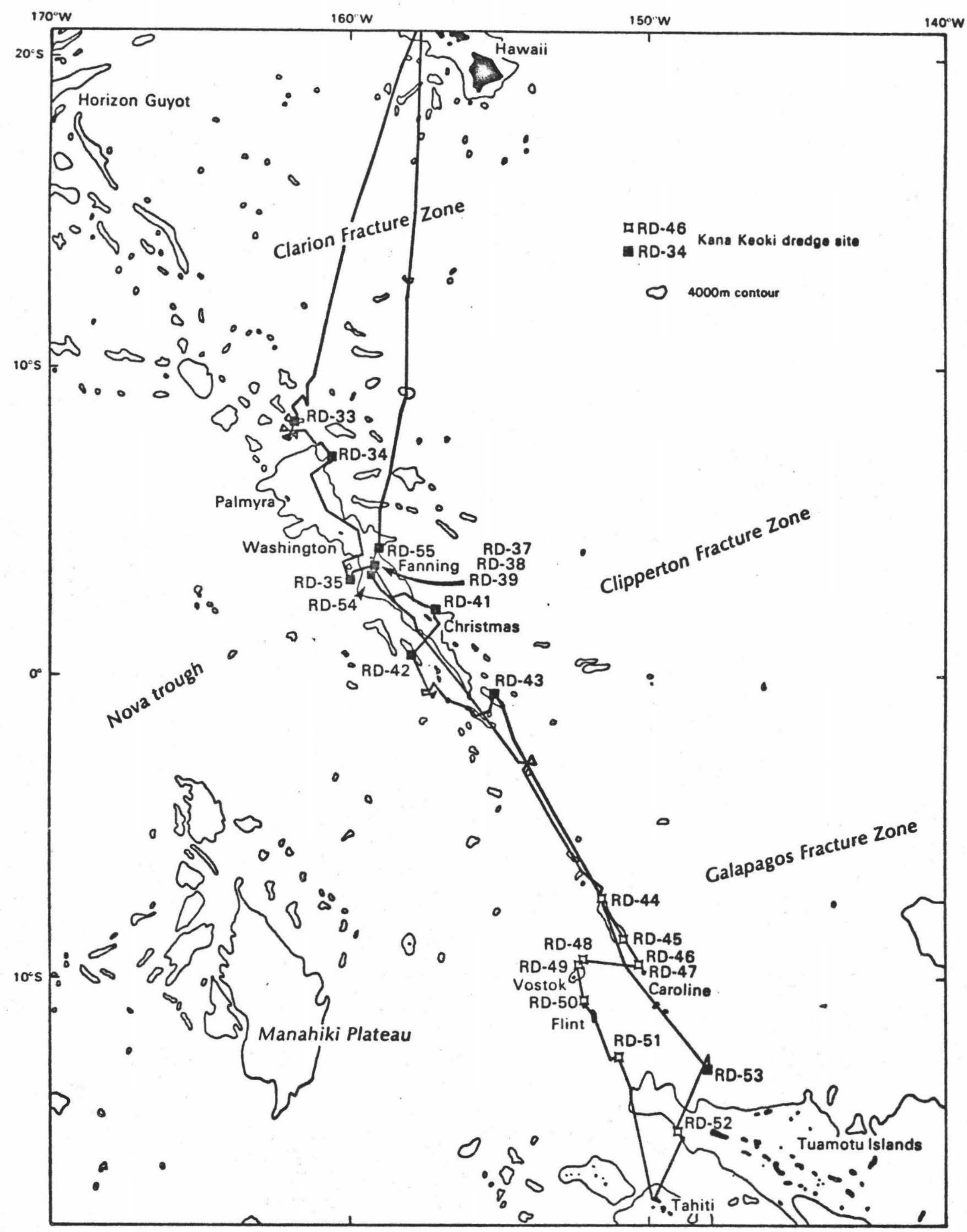
DREDGE SITE LOCATIONS

The first leg of the R/V Kana Keoki cruise to the Line Islands departed Honolulu on August 8, 1979 at 0100 Greenwich Mean Time (GMT) and arrived in Papeete, Tahiti on September 2, 1979 at 23:30 GMT. A total of 19 dredge hauls and six piston cores were attempted during the first leg. Seven successful dredge hauls recovered sedimentary rock from the Southern Province of the Line Islands (Figure 4).

The second leg of the cruise departed Papeete on September 7, 1979 at 0100 GMT and arrived in Honolulu on September 19, 1979 at 2100 GMT. Four dredge hauls were attempted during this leg. Two of these dredge sites were in the study area but RD-53 recovered only Mn-crusts with brown clay containing a few radiolarians of middle Pliocene to Recent age.

Results from all of the dredge sites and piston cores from the first and second legs are summarized in Appendix B. Eight successful dredge sites yielded sedimentary rocks in the Southern Province of the Line Islands (Figure 4) and comprise the material used in this study. Appendix C contains bathymetric, gravity, and magnetic profiles for both legs of the cruise. Appendix D contains tables listing the samples studied, and charts displaying the distribution of planktonic foraminifera, larger benthonic foraminifera, other shallow water debris, and volcanic material in the samples investigated from the Southern Province of the Line Islands.

Figure 4. Track chart of cruises of the R/V Kana Keoki and dredge site locations along the Line Islands. Rock dredge (RD) locations used in this study are denoted by open squares.



170°W
160°W
150°W
140°W
20°S
10°S
0°
10°S
Hawaii
Horizon Guyot
Clarion Fracture Zone
RD-46
RD-34
Kana Keoki dredge site
4000m contour
RD-33
RD-34
Palmyra
Washington
RD-55
Fanning
RD-37
RD-38
RD-39
Clipperton Fracture Zone
RD-35
RD-54
RD-41
Christmas
RD-42
RD-43
Nova trough
Galapagos Fracture Zone
RD-44
RD-45
RD-48
RD-46
RD-47
RD-49
Vostok
Caroline
RD-50
Flint
Manahiki Plateau
RD-51
RD-53
RD-52
Tuamotu Islands
Tahiti

DREDGE-44 RESULTS

Bathymetry

On the 27 of August 1979, the R/V Kana Keoki was underway for a dredge site at 7°30′S and 151°30′W marked on the Scripps chart as an isolated, conical seamount. Arrival at the location revealed that the seamount is not isolated, but is on the northern edge of a ridge that rises from a surrounding seafloor depth of 5450 m. The seismic reflection profile (Figure 5) displays three distinct steps or terraces on the northwestern flank of the seamount. Bathymetric contours show that the breaks in slope appear to trend NW-SE and do not encircle the seamount (Figure 6). These steps are not interpreted as coralline or wavecut terraces, but as normal faults, possibly lystric faults (L.W. Kroenke, personal communication), from which the fault block has slumped down the flank of the seamount. Very similar geomorphologic features are seen today at the Hilina Pali on the island of Hawaii, the north shore of Molokai, and the Nuuanu Pali on Oahu (Moore, 1964). Terrace-like features on the flanks of seamounts in the Hawaiian chain have been suggested as the result of submarine landslides (Moore, 1964), and as "due to vertical movements associated with aging of the lithosphere, reheating of the lithosphere by midplate volcanism, isostatic sinking related to the new volcanic load, and local tectonic movements" (Campbell et al., 1979, p. 117).

Figure 5. Seismic reflection profile of site RD-44, a seamount on the northern edge of the newly discovered ridge in the Southern Province of the Line Islands. Note step-like features on the northwest flank. Abyssal sea floor depth is greater than 5400 m. The location of RD-44 dredge haul is represented by a thick bar. Horizontal lines on the record represent seconds of two-way travel time and uncorrected water depth in meters. Bracketed bar indicates a horizontal scale of 10 km.

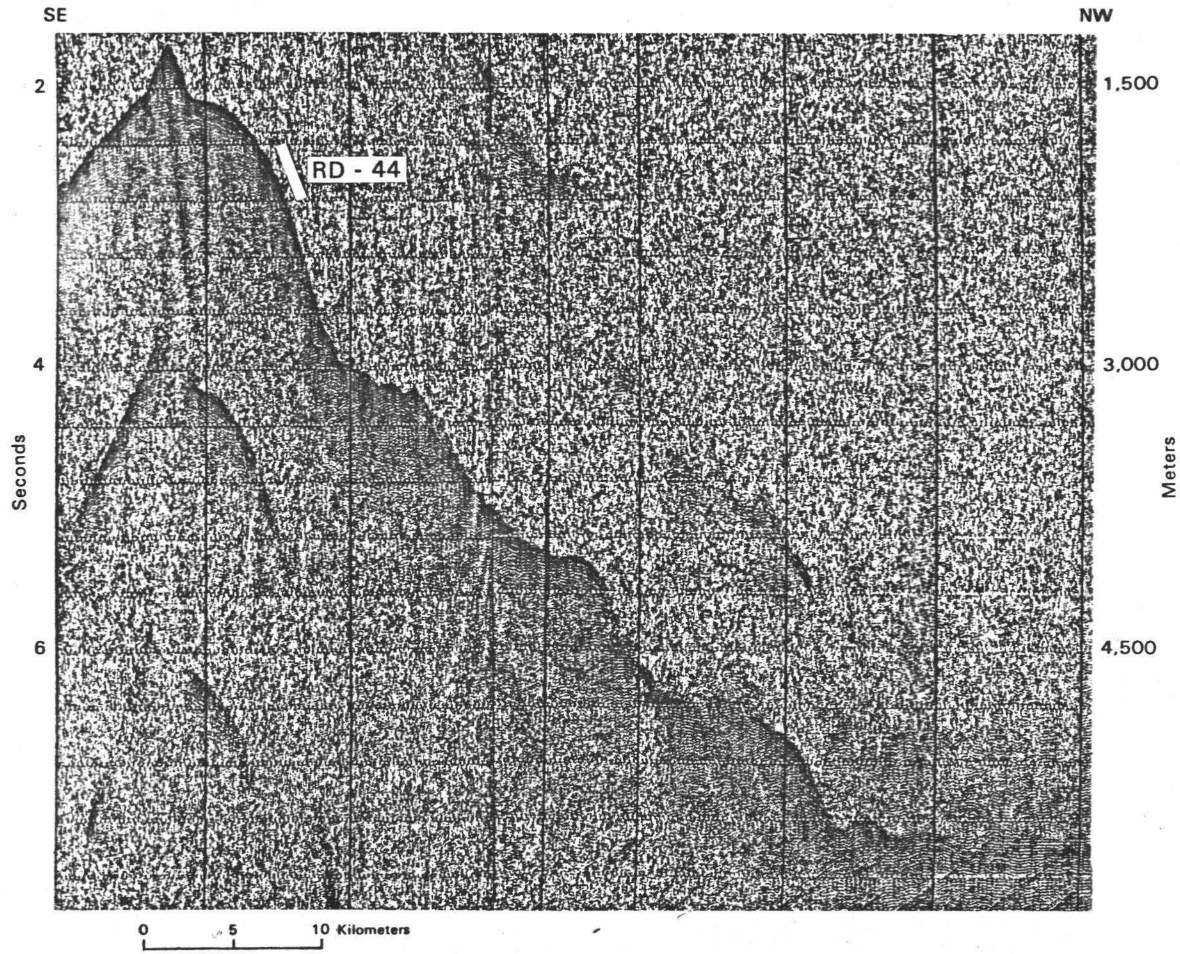
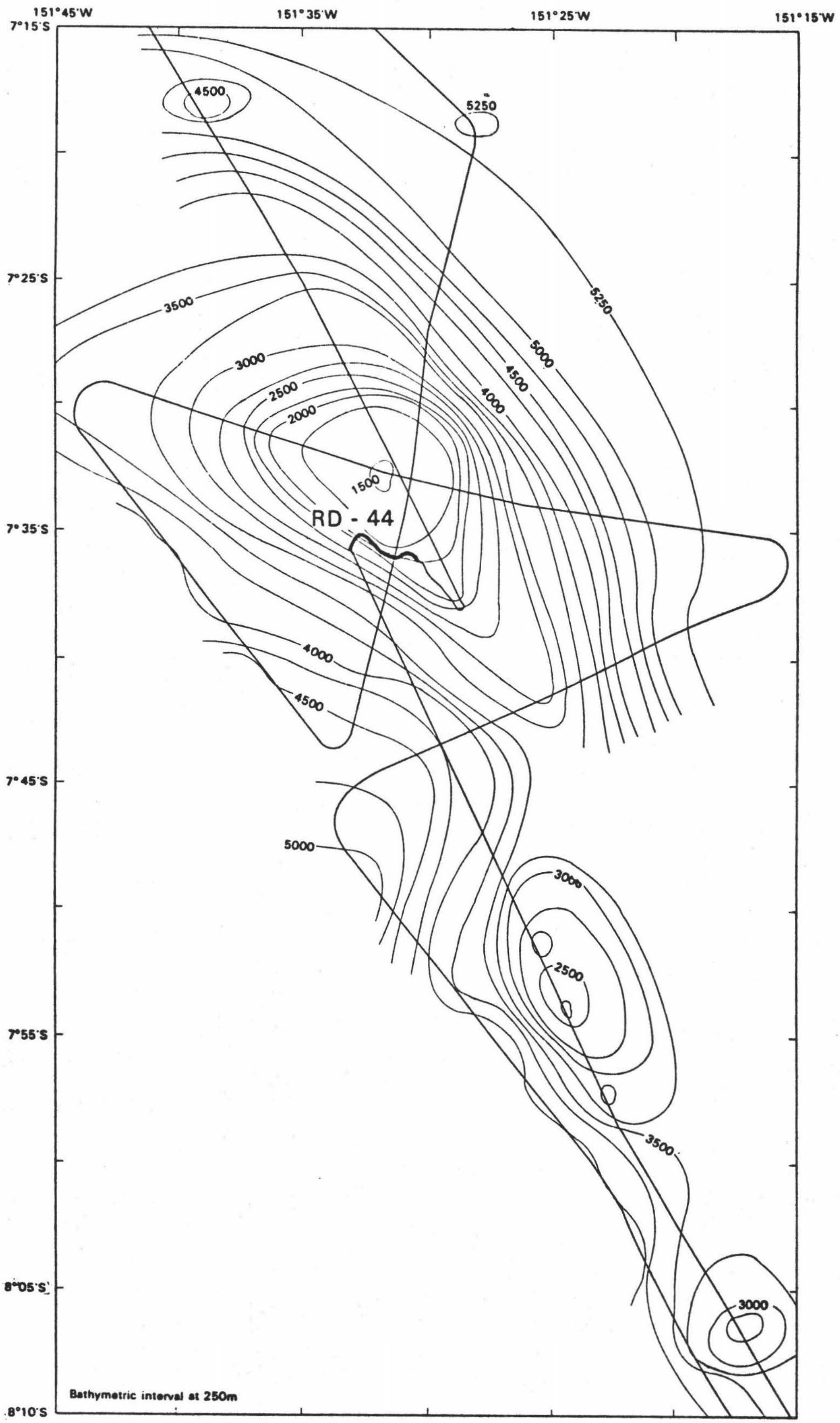

SE
NW
RD - 44
2
4
6
Seconds
1,500
3,000
4,500
Meters
0
5
10 Kilometers

Figure 6. Bathymetric chart of site RD-44, showing the track of the R/V Kana Keoki and location of the dredge site. Depth contour interval is 250 m.


151°45'W
151°35'W
151°25'W
151°15'W
7°15'S
7°25'S
7°35'S
7°45'S
7°55'S
8°05'S
8°10'S
4500
5250
5250
3500
5000
4500
4000
3000
2500
2000
1500
RD - 44
4000
4500
5000
3000
2500
3500
3000
Bathymetric interval at 250m

Sedimentary rocks were dredged from 2100 to 1800 m water depth, near the top of the southern flank, of this elongate seamount, that extends to within 1177 m of sea level (Figure 6).

Rock Descriptions and Interpretations

Sedimentary rocks recovered from site RD-44 include: (1) a phosphatized volcanic conglomerate; and (2) volcanic breccias.

The phosphatized volcanic conglomerate (Plate I, A) contains a few manganese-rimmed pebbles that are composed of fine-grained, highly-altered volcanic rock fragments, recrystallized rare specimens of globotruncanids of Campanian/Maestrichtian age and fragments of macrofossils (rudists?). These reworked Upper Cretaceous sedimentary pebbles are associated with subrounded, one to five millimeter diameter grains of basalt. This poorly-sorted, sandy gravel is unstratified and ungraded, floating in a phosphatic foraminiferal micritic matrix containing miliolids and planktonic foraminifera of late Paleocene age (Zone P4).

The conglomerate is coated and being infiltrated by manganese forming a 4 cm thick crust. A phosphatized bioclast (Plate I, B), partially encroached upon by manganese dendrites, has a microstructure composed of infilled chambers and/or canals. There are no spines or septa projecting into a body cavity, as in a coral, and no spicules within the skeletal wall, as in an axial canal of a sponge. This bioclast is interpreted as a fragment of a rudist because of the robust skeletal walls, and the arrangement and orientation of the chambers and/or pores.

The manganese rind on the volcanic conglomerate also is fractured and infilled with planktonic foraminiferal limestone (Plate I, A) containing rare volcanic rock fragments. The planktonic foraminifera are of middle Eocene age, Zone P10.

Interpretation of this rock yields a complex history. The association of globotruncanids with volcanic rock fragments within the sedimentary pebbles signify the existence of a volcanic edifice by Campanian/Maestrichtian time. The inclusion of the macrofossil fragments within the Upper Cretaceous sedimentary pebbles and in the manganese rim indicate the existence of Cretaceous rudist reefs on this volcanic edifice. The miliolids associated with planktonic foraminifera of late Paleocene age reveal that a neritic-shelf environment existed on the seamount during Paleocene time. The roundness of the volcanic pebbles and the association with the same planktonic foraminifera indicate erosion of an edifice by the late Paleocene.

Using a descriptive scheme designed by Walker (1975), this conglomerate is interpreted as being deposited by a slump or debris flow. The deposit was then lithified, phosphatized, and developed a manganese rim. The manganese grew inward and outward on the deposit, and was fractured and infilled with Eocene sediment.

There are two kinds of volcanic breccias recovered in RD-44. One is very dense with little porosity, loosely packed, containing dark gray basalt fragments, with little vesicularity. Each fragment is surrounded by a layer of fibrous zeolites within a phosphatized micritic matrix containing rare molds from Cretaceous planktonic foraminifera, such as globotruncanids and heterohelicids (Plate I, C). The relationship of the volcanic rock fragments with planktonic foraminifera place a minimum age of Campanian/Maestrichtian on these volcanic rocks.

The second type of volcanic breccia is porous and composed of highly altered, red, volcanic rock fragments, with zeolitic rims building a clast-supported framework (Plate I, D). The phosphatized micritic matrix contains a few specimens of planktonic foraminifera of Paleocene age. These volcanic fragments therefore are interpreted as Paleocene or older.

Conclusions

This seamount existed as a volcanic edifice near sealevel upon which reefs grew in Late Cretaceous (Campanian/Maestrichtian) time. In late Paleocene time, a neritic-shelf environment existed and the edifice was being eroded. By middle Eocene time, pelagic sedimentation was dominant.

DREDGE-45 RESULTS

Bathymetry

North of Caroline Island a 300 km long ridge topped with seamounts was discovered to extend between sites RD-44 and RD-45. The seismic reflection profile is of the southern portion of this ridge on approach to site RD-45 (Figure 7). The base of the seamounts on the ridge are typically 1000 m shallower than the base of the seamount on the ridge at site RD-44. This ridge trends parallel to and appears to be part of the Line Islands chain. Dredge RD-45 was recovered from 1300-1450 m water depth near the top of the western flank of a seamount that rises to 1228 m below sea level (Figure 8).

Rock Descriptions and Interpretations

Sedimentary rocks recovered from site RD-45 include: (1) partly phosphatized foraminiferal limestone containing volcanic rock fragments; (2) phosphatized, matrix-supported conglomerates; (3) rudistid coquina; (4) volcanic breccia; (5) phosphatized and intensively burrowed foraminiferal limestone containing volcanic rock fragments; and (6) a peperite.

The partially phosphatized pelagic limestone contains rounded volcanic rock fragments 0.3 to 9 mm in diameter and recrystallized planktonic and benthonic foraminifera (Plate II, A). The phosphatized limestone, in addition to containing individual volcanic rock fragments, is in contact with a palagonitized volcanic rock. On the basis of this association of planktonic foraminifera of late Campanian

Figure 7. Seismic reflection profile of site RD-45, a seamount on the southern portion of the newly discovered ridge in the Southern Province of the Line Islands. The location of RD-45 dredge haul is represented by a thick bar. Horizontal lines on the record represent seconds of two-way travel time and uncorrected water depth in meters. Bracketed bar indicates a horizontal scale of 10 km.

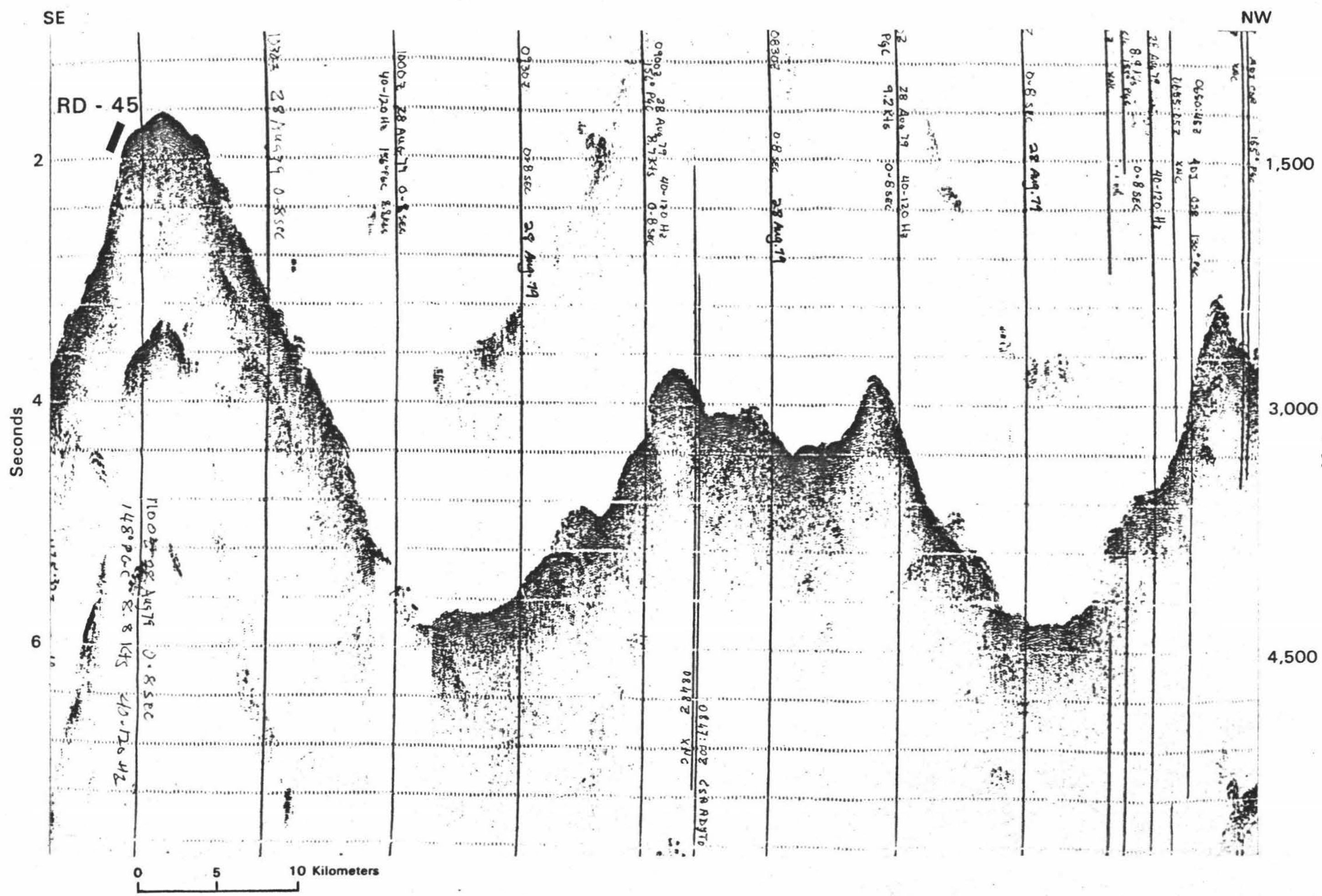
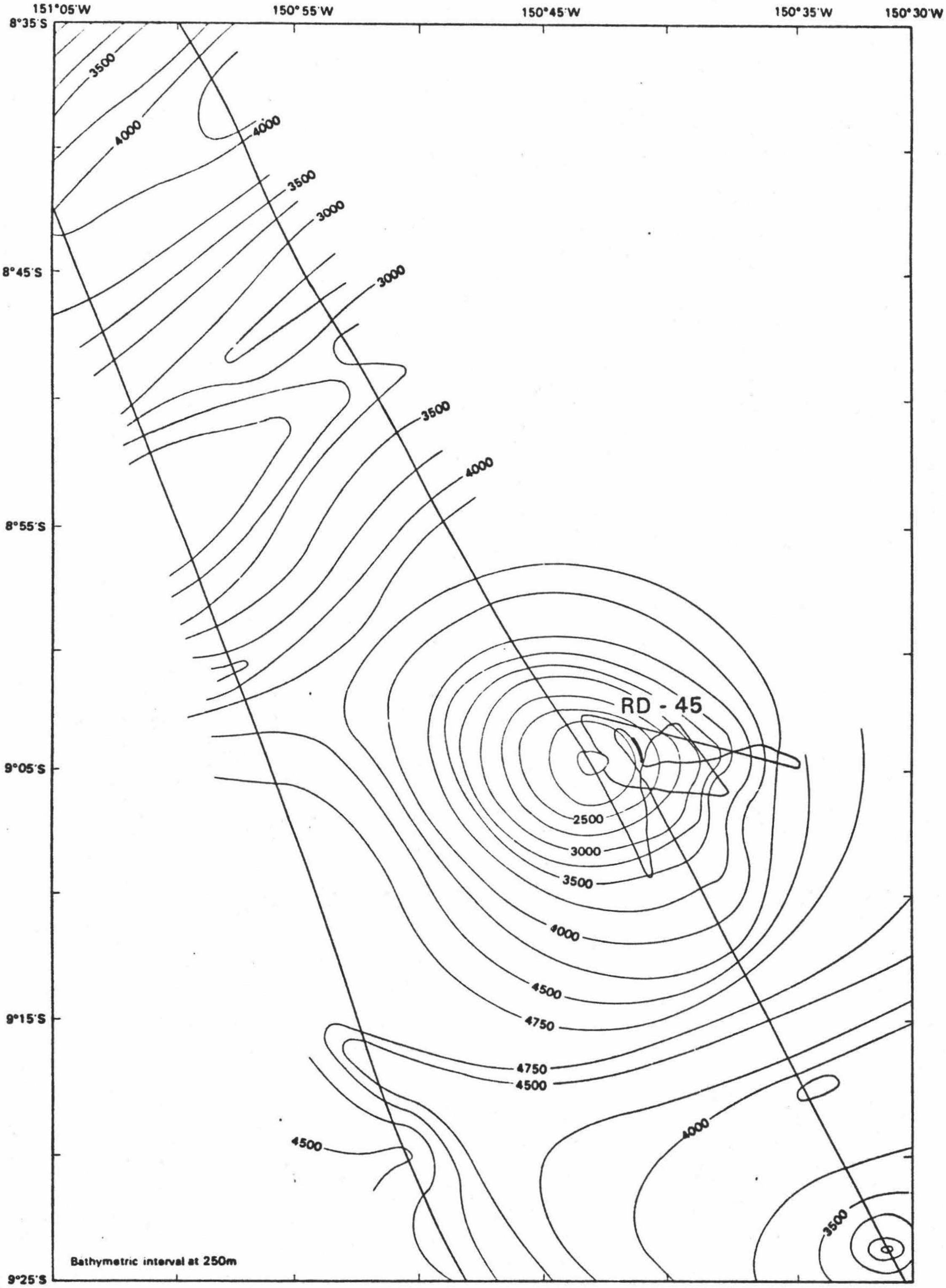

SE
NW
RD - 45
Seconds
2
4
6
Meters
1,500
3,000
4,500
0
5
10 Kilometers

Figure 8. Bathymetric chart of site RD-45, showing the track of the R/V Kana Keoki and location of the dredge site. Depth contour interval is 250 m.


151°05'W
150°55'W
150°45'W
150°35'W
150°30'W
8°35'S
8°45'S
8°55'S
9°05'S
9°15'S
9°25'S
3500
4000
4000
3500
3000
3000
3500
4000
RD - 45
2500
3000
3500
4000
4500
4750
4750
4500
4500
4000
3500
Bathymetric interval at 250m

age with rounded volcanic rock fragments, a minimum age of the volcanic rocks is established as late Campanian. The limestone was deposited on the upper flank of the seamount during normal pelagic sedimentation.

Some of these partly phosphatized limestones contain a planktonic foraminiferal assemblage similar to the late Campanian assemblage (Appendix D, Table 6), but a few marginotruncanids also are included. This early Campanian assemblage includes upper-slope benthonic foraminifera (Cita, 1966; Sliter and Baker, 1972), such as Stensioina (Plate II, B), and Spiroplectammina (Plate II, C). The association of upper-slope benthonic foraminifera and planktonic foraminifera of early Campanian age with rounded volcanic fragments documents the existence of a volcanic edifice with a minimum age of early Campanian yielding an upper-slope benthonic environment.

The phosphatized, matrix-supported conglomerates are composed of rounded volcanic rock fragments, predominately hawaiites and mugearites (M.P. Smith, personal communication), in a limestone matrix of late middle Maestrichtian age, correlative with the Globotruncana contusa Zone. In thin section these rocks are seen as fossiliferous volcanic arenites (Plate II, D). The matrix is chalky and porous and displays burrows filled with Tertiary planktonic foraminifera. Foraminiferal tests imbedded in the matrix are commonly filled with mud. SEM and x-ray diffraction studies show the infillings, as well as the matrix, to be a porous, fine-grained aggregate of euhedral crystals of apatite, three to four microns long. As the result of diagenesis, the foraminiferal tests appear as outlines and molds in the phosphatized matrix (Plate II, E). The volcanic pebbles are rounded; some were coated with manganese rims, probably before they were deposited within the matrix. The degree of rounding of these volcanic rock fragments and their association with foraminifera correlative with the G. contusa Zone is interpreted as indicating erosion of the volcanic edifice during latest Cretaceous time.

In addition to the rocks containing Cretaceous material of deep-water and upper-slope origin, dredge RD-45 also contained limestones of shallow-water origin. The coquina (Plate III, A) is composed of shallow-water shell debris, calcareous algae and medium-grained sand to cobble size volcanic rock fragments. Thin sections show well-sorted, highly abraded, and preferentially oriented molluscan fragments. One of the molluscan fragments is incorporated within an algal ball of shallow-water origin (Plate III, B). These mechanically sorted, abraded, molluscan and volcanic rock fragments are moderately cemented; grain interstices lack fine-grained infilling.

Another important component of this rock is fragments of rudists (Plate III, D). These mollusks thrived and formed carbonate banks or reefs during the Cretaceous and became extinct at the end of the Cretaceous. The fragments are assigned to the Family Radiolitidae, which ranges in age from the Barremian through the Maestrichtian. Because of the degree of fragmentation of the shells, the rudists could be identified only to the family level. Rare specimens of planktonic globotruncanid foraminifera of Campanian/Maestrichtian age (Plate III, C) found among shell debris indicate that this deposit is

Campanian/Maestrichtian in age. The presence of planktonic foraminifera mixed with shallow water skeletal debris suggests deposition in a fore-reef environment.

A volcanic breccia recovered in dredge RD-45 is very similar in appearance to a type recovered in dredge RD-44 (Plate I, D). Highly altered, red, volcanic rock fragments with zeolitic rims compose the clast-supported framework. A sparse infilling of phosphatized micrite contains rare planktonic foraminifera of Paleocene age. These volcanic rock fragments are therefore Paleocene or older and were deposited in an environment where currents permitted little infilling by Paleocene foraminiferal ooze. Phosphatization occurred after the infilling.

Slightly phosphatized foraminiferal limestones with patches of thin manganese coatings contained planktonic foraminifera of middle Eocene age (Zone P11, and Zone P10?-P11), and rare fragments of altered volcanic glass scattered through a phosphatized micritic matrix (Plate IV, A). The tests are well-preserved, although some tests have been infilled with phosphatized mud. On the basis of the association of the planktonic foraminifera of middle Eocene age with altered volcanic glass, the age of the volcanic glass is established as middle Eocene or older. These phosphatized foraminiferal limestones contain no evidence of reef skeletal debris, and are not a winnowed deposit, and therefore are interpreted as pelagic deposits.

An interesting post-depositional feature of these pelagic deposits is the abundant unfilled burrows or trace fossils lined with a thin, patchy coating of manganese. The predominant trace fossil is characterized by tunnels and shafts (Plate IV, B) of variable diameter with an irregular network (Plate IV, C) and fit the morphological classification of *Thalassinoides* (Frey, 1975). These burrowing systems are believed to be developed by a variety of decapods or other crustaceans.

The excellent preservation of the burrows, and the lack of abundant infilling indicates synsedimentary lithification and the development of an omission surface (Bromley, 1975) as a hardground. Burrows created early in the lithification process appear as long regular shafts or tunnels with Y-shaped branching patterns (Plate IV, B). As lithification proceeded with nondeposition, the burrows became increasingly restricted and contorted (Plate IV, C). The change in morphology of *Thalassinoides* during the formation of chalk hardgrounds has been described in detail in Bromley (1967) and Kennedy (1967).

Thalassinoides, until very recently, was widely held to represent relatively shallow water environments (Farrow, 1966; Frey, 1975). It is typically described in intertidal paleoenvironments, and is ubiquitous in shelf-sea chalks, commonly associated with hardgrounds. Kern and Warme (1974) reported the occurrence of *Thalassinoides* in the Upper Cretaceous Point Loma Formation and interpreted the environment of deposition as a bathyal, mass grain-flow environment. Link and Nilsen (1980) reported *Thalassinoides* with other trace fossils representing an outer-shelf to slope depths associated with turbidites in the Rocks Sandstone, an Eocene deep-sea fan deposit in northern Santa Lucia Range, California. Bottjer (1981) noted the presence of Thalassinoides in an Upper Cretaceous deep-sea fan deposit in Simi Hills, California. In all reports, Thalassinoides is associated with primarily high-energy environments, whether it be an intertidal environment, hardground, or turbidity currents in deep-sea fans.

The existence of Thalassinoides in deep-sea fans from California may be due to other factors in addition to the high-energy environments. For example, the Californian deposits have abundant terrigenous input and thus differ significantly from true open ocean deposits.

Other studies of specifically deep-sea trace fossils have not revealed the presence of Thalassinoides in deep-sea, open ocean deposits. Chamberlain (1975) conducted a study of 109 DSDP sites in the Pacific Ocean and Thalassinoides was not among the identified trace fossil assemblages. Edkale and Berger (1978) investigated modern abyssal organism traces in bottom photographs and box cores collected on the Ontong Java Plateau in 1597 to 4441 m water depth and also did not find Thalassinoides. Ricketts and Calvin (1972, from Farrow, 1966) have noted that burrowing decapods, which form contemporary Thalassinoides, are abundant in the upper part of the intertidal zone of bays, estuaries, and lagoons along the Pacific coast.

The occurrence of Thalassinoides at site RD-45 is most likely due to a high-energy environment which formed an omission surface on the upper flank of the seamount. The absence of Thalassinoides in DSDP cores and boxcores from the deep seafloor of the Pacific suggests that the RD-45 deposit, which does contain Thalassinoides, is similar to the shelf-sea chalks with associated hardgrounds occurring in 500 m depths or less. These shelf-sea chalks and hardgrounds are also typically phosphatized.

One of these burrowed phosphatized foraminiferal limestones has a centimeter-thick manganese rim and is fractured (Plate IV, D). Manganese has migrated along and lines these fractures, and manganese dendrites appear to grow outward from the fractures thereby emphasizing the appearance of these microfractures. The fractures typically terminate in a burrow and were formed after lithification. There is no evidence of dissolution or of microfaulting along the fractures. The microfractures are interpreted as the result of stress that was initially absorbed by compaction of the unfilled burrows but because of the rigidity of this densely lithified sediment, it fractured.

The last of the rock types recovered from site RD-45 is an alkalic basalt with anastomosing fractures (Plate V, A) filled with phosphatized limestone also containing planktonic foraminifera of middle Eocene age (Zone P10?-P11). No geopetal structure or stratification is evident in this phosphatized filling. In thin section (Plate V, B), an opaque, basaltic glass (tachylite) is observed closest to the sediment, whereas farther away from the sediment the basalt is progressively more crystalline. Fragments of tachylite form a disjointed rim (Plate V, C), and are evidence of a chilled rim that has brecciated in place within the sediment. Foraminifera do not persist in the finer veins; they may have been destroyed by heat or phosphatization. The features shown are typical of a peperite, a kind of hyaloclastite, in which basaltic glass fragments are scattered through sediment. Peperite is attributed to the intrusion or extrusion of basaltic magma into or onto moist, soft sediment (Macdonald, 1939; Schmincke, 1967). The absence of sideromelane (Plate V, F) or its alteration product palagonite, and instead, the presence of tachylite, suggests that the chilling was not very rapid as would be expected for quenching in water. Because the extrusion was onto unconsolidated middle Eocene sediment, the age of this volcanic event is middle Eocene (Zone P10?-P11) or slightly younger.

The exterior of this peperite was coated with layers of manganese which harbored some pockets of loose, unconsolidated calcareous sediment. Inspection of this carbonate sediment revealed a subrecent assemblage of planktonic foraminifera and a few rare specimens of benthonic foraminifera. An Eocene <u>Cibicides</u> (I. Premoli Silva, personal communication) and <u>Planulina</u> cf. <u>marialana</u> variety <u>gigas</u> Keijzer were noted.

Today these genera of benthonic foraminifera are found in restricted depth ranges. Saidova (1966) compiled a synthesis of the distribution of the most common Pacific foraminiferal genera according to depth and latitude. The <u>Cibicides</u>-<u>Amphistegina</u> benthonic assemblage characterizes shallow water to 500 m water depth from 20°N to 40°S latitude. Cibicides commonly lives in carbonate-rich shallow to middle shelf environments.

Sliter and Baker (1972) compiled a synthesis of the upper depth limits and the characteristic occurrence of modern benthonic foraminiferal genera along the eastern Pacific margin from twelve previous studies by experts in the field. Planulina is noted to occur in middle and outer shelf environments and therefore inhabits relatively shallow depths. The occurrence of both of these benthonic foraminifera on the exterior of the middle Eocene peperite may indicate the existence of a middle to outer shelf benthonic environment on the seamount in post-middle Eocene time.

Conclusions

The sedimentary rocks recovered from site RD-45 are diverse and range in age from early Campanian to middle Eocene. The dredged seamount existed as a volcanic edifice with an upper-slope benthonic environment (less than 1000 m water depth) by early Campanian time. Rudist reefs or banks grew in the photic zone on this volcanic edifice and were being eroded and deposited in a fore-reef slope environment during Campanian/Maestrichtian time. During late middle Maestrichtian time the edifice was being eroded. The Paleocene volcanic breccia with sparse infilling may indicate the continuation of erosional currents. During Eocene time pelagic sedimentation resumed.

The occurrence of altered vesicular volcanic fragments with planktonic foraminifera of middle Eocene age and the incorporation of middle Eocene sediment in the peperite is evidence of a volcanic event during middle Eocene time. This seamount therefore has a history of recurrent volcanism; one event took place during or prior to Late Cretaceous time and a second event occurred during middle Eocene time.

Post-middle Eocene time, the pelagic sediment was burrowed by crustaceans and lithified, some became fractured. A middle to outer shelf benthonic environment may also have existed on the upper flank of the seamount in post-middle Eocene time.

A phosphatization event or events occurred during the history of this seamount, although the timing of the event(s) cannot be resolved with these data.

DREDGE-46 AND 47 RESULTS

Bathymetry

On the 28th of August 1979, the R/V Kana Keoki was underway for Caroline Island. Two successful dredge hauls were recovered, RD-46 from 1400-1500 m water depth and RD-47 from 2400-2700 m water depth (Figure 9). Both dredge sites are located on the upper flank of the northeastern slope of the island (Figure 10).

The topography of the seafloor changes slightly between the eastern and western trends of islands in the Southern Province of the Line Islands. The seismic reflection profile (Figure 9) reveals a change from a smooth bottom reflection to a rough bottom topography as the R/V Kana Keoki approached the western chain.

Rock Descriptions and Interpretations

The sedimentary rocks recovered from RD-46 include: (1) phosphatized foraminiferal limestone; (2) limestone breccia; (3) incrustate limestones; and (4) corals. Sedimentary rocks recovered from site RD-47, 1000 m further downslope than site RD-46, include: (1) limestone microbreccias; (2) limestone breccias; and (3) paracoquinites. The classification scheme used in this report for the carbonate rocks and the associated reef complex facies is from the work of Schlanger (1964) on the petrology of limestones from Guam.

Figure 9. Seismic reflection profile of sites RD-46 and 47, a transect along the northern slope of Caroline Island upon departure from dredge sites. Note change in bottom topography as R/V Kana Keoki approaches the western set of islands in the Southern Province of the Line Islands chain. The location of dredge hauls RD-46 and RD-47 are represented by thick bars. Horizontal lines on the record represent seconds of two-way travel time and uncorrected water depth in meters. Bracketed bar indicates a horizontal scale of 10 km.

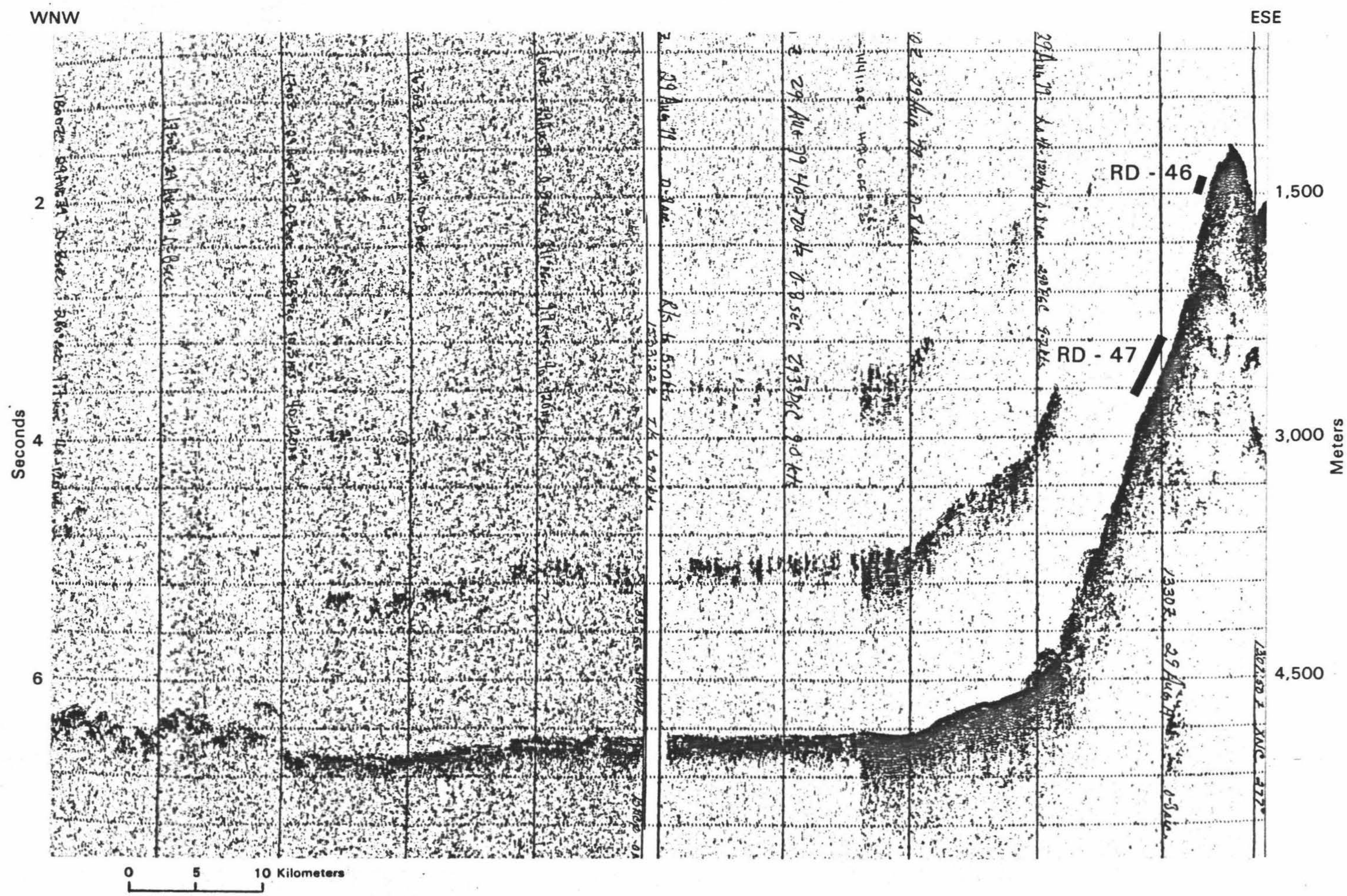
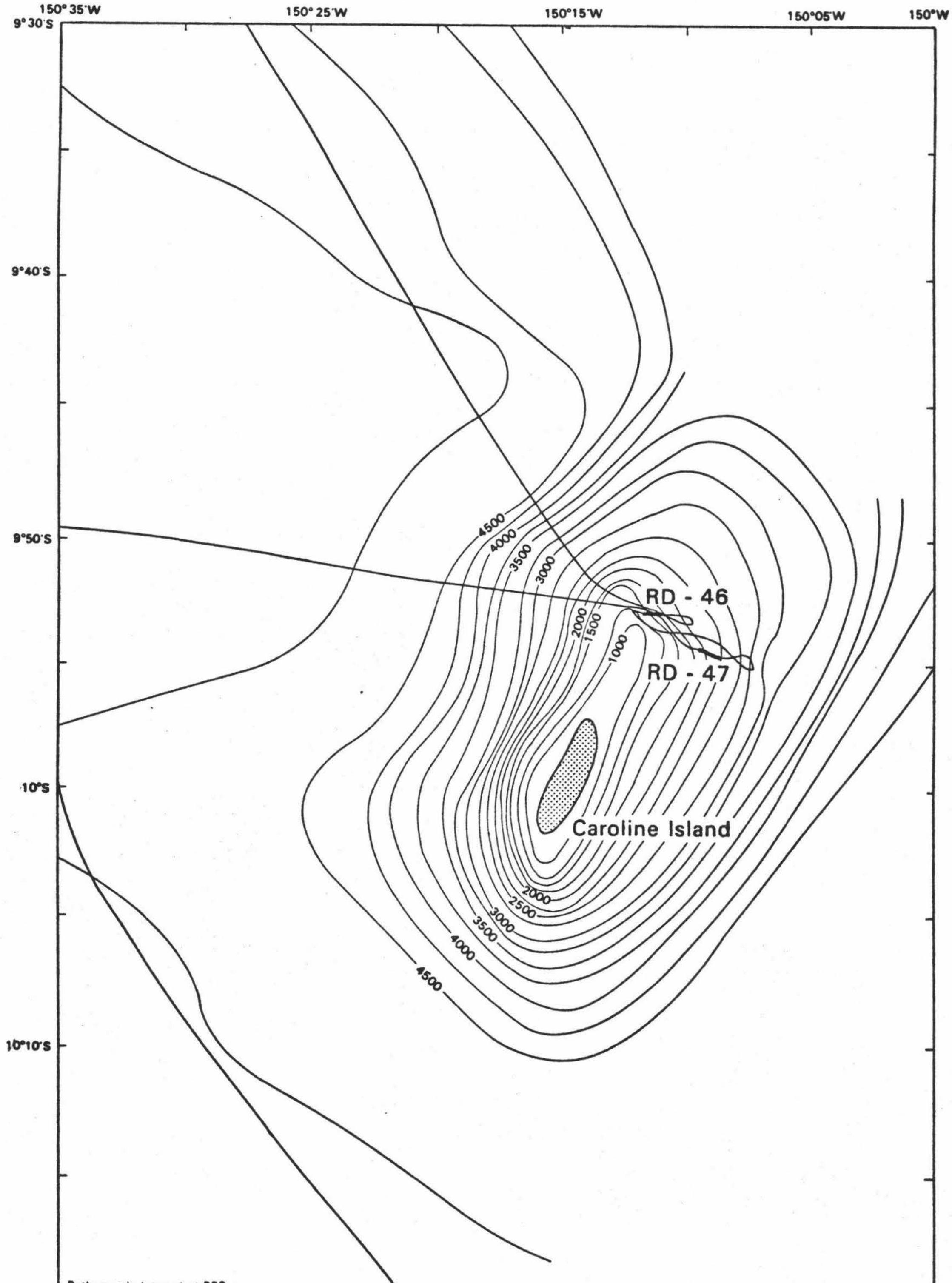

WNW
ESE
RD - 46
RD - 47
Seconds
2
4
6
Meters
1,500
3,000
4,500
0
5
10 Kilometers

Figure 10. Bathymetric chart of sites RD-46 and 47 on the flank of Caroline Island, showing the track of the R/V Kana Keoki and the location of dredge sites. Bathymetric contour interval is 250 m.


150° 35'W
150° 25'W
150°15'W
150°05'W
150°W
9° 30'S
9°40'S
9°50'S
10°S
10°10'S
10°20'S
RD - 46
RD - 47
Caroline Island
4500
4000
3500
3000
2000
1500
1000
2000
2500
3000
3500
4000
4500
Bathymetric interval at 250m

The phosphatized foraminiferal limestone from site RD-46 contains rounded volcanic rock fragments, 3 to 4 mm in diameter, and recrystallized planktonic foraminifera (Plate V, D). This phosphatized limestone is also in contact with a grey volcanic rock that is rimmed in manganese and fractured. Miliolids are found concentrated within the fracture near the manganese rim (Plate V, E). The planktonic foraminifera of Eocene age associated with the volcanic fragments establish a minimum age of volcanism as Eocene. The existence of the miliolids in the fracture denotes the existence of a neritic-shelf type environment in the geologic past (Eocene?). The limestone was deposited on the upper slope of Caroline Island during normal pelagic sedimentation.

The limestone breccia (Plate VI, A) from site RD-46 is composed of foraminiferal-algal paracoquinite and predominantly of foraminiferal microbreccia with some coral cobbles. The foraminiferal-algal paracoquinite (Plate VIII, A) contains broken tests of several genera of large foraminifera such as Lepidocyclina, Operculina, Heterostegina, and Amphistegina, whereas miliolids and globogerinids are rare. Fragments of coralline algae are abundant, and fragments of gastropods, mollusks, echinoids, bryozoans and pebbles of foraminiferal microbreccia (Plate VIII, B) are scattered throughout. Recrystallization of the fine-grained matrix has occurred as well as the dissolution of various skeletal particulates. The development of secondary porosity is easily observed from the outlines of unfilled micritic envelopes. Syntaxial overgrowth is visible on the echinoid fragments. The skeletal debris shows a preferred orientation and suddenly grades into a dense foraminiferal microbreccia. The microbreccia is composed predominantly of planktonic foraminifera of early Miocene age (Zone N 4-6), with fragments of larger foraminifera and unidentifiable skeletal debris. The pebbles of foraminiferal microbreccia included within the paracoquinite also contain planktonic foraminifera of early Miocene age. This portion of the rock described thus far, is separated from the remainder of the rock by a thin layer of manganese (Plate VI, A).

The other portion of the rock is composed of a dense foraminiferal microbreccia with cobbles of recrystallized and reversed corals (Plate VIII, A), and pebbles of pre-existing foraminiferal microbreccia. The microbreccias are primarily composed of planktonic foraminifera of early Miocene age, and fragments of large foraminifera. Some of the pebbles within the microbreccia display irregular outlines that blend with the surrounding medium. This is a typical feature observed when poorly lithified clasts are redeposited in a mud matrix, and may indicate movement of semilithified sediment.

The fossils incorporated within this rock indicate the existence of an early Miocene reef, and the abundance of planktonic foraminifera indicates deposition as a deep-water facies.

The association of the three types of particulate limestones in this rock may be interpreted as deposition by the following mechanisms. The orientation of the skeletal debris indicates that the paracoquinite was deposited by a current. The sudden gradation into the foraminiferal microbreccia may therefore indicate that the current was generated by a gravity flow, and consequently incorporated pre-existing pebbles of foraminiferal microbreccia within the paracoquinite. The third area within the rock, composed of foraminiferal microbreccia with coral cobbles, was semilithified sediment which may have been redeposited by slumping. The depositional environment appears to have been unstable. If these interpretations are correct, then the feature marked by the thin layer of manganese may be a scour or tool mark. The process of scouring and filling can result from massive transport by a slump or sediment-laden water from a current or grain-flow.

From a casual observation of this faint, black manganese demarcation in the hand specimen, one might incorrectly conclude that the feature is a stylolite. However, pressure solution at points of contact of skeletal debris or of planktonic foraminiferal tests along the boundary are absent. The fossils are not truncated. The manganese deposition occurred later, from the migration of manganese along the discontinuity or lithology boundary.

Several varieties of incrustate limestone were recovered from site RD-46. Algal-coral, sclerosponge-coral, algal, and coral incrustate limestones are composed of skeletons of these binding organisms which coat and entrap fine-grained detritus. The predominant encrusting foraminifera are Acervulina, Homotrema, Carpenteria, and Rupertina. The rare specimens of planktonic foraminifera which were deposited in these incrustate limestones are of Miocene to Recent age. Incrustate limestones are associated with the reef-wall facies.

The only other sedimentary rocks recovered from this dredge site are corals, probably talus debris from the present reef.

From site RD-47, a more diverse collection of carbonate rocks and ages were obtained. The following descriptions and interpretations are grouped by age and reef facies.

A foraminiferal microbreccia (Plate VIII, C), a foraminiferal-algal breccia, and a foraminiferal microparacoquinite, all contain planktonic foraminifera of Oligocene age and some with additional younger elements (Miocene) typically on the outer carbonate rims of these rocks. The breccia is poorly sorted and contains broken, abraded tests of large foraminifera, especially Lepidocyclina up to 5 mm in length, and Melobesieae algae up to 8 mm in diameter. In the foraminiferal microbreccia, one of the Lepidocyclina tests is identifiable to the subgenus Polylepidina, which is known to range in age from middle to late Eocene time. Fragments of echinoids, bryozoans, recrystallized corals and algae are also included. The microbreccia has the same composition but the skeletal debris is less than 2 mm in size. Tests of globogerinids are scattered throughout the fine-grained matrix. The foraminiferal paracoquinite contains the same skeletal debris, although the globigerinids are not as common. The debris is better-sorted and graded. These Oligocene rocks are typical of a fore-reef and fore-reef slope transitional facies with evidence of the erosion of Eocene strata.

Lower Miocene foraminiferal microbreccias (Plate VIII, D), foraminiferal-algal breccias, and a foraminiferal paracoquinite from a fore-reef and fore-reef slope transitional facies also were recovered from site RD-47. The descriptions and compositions are similar to the Oligocene facies. One distinct difference between the Oligocene and Lower Miocene facies is the inclusion of additional genera of large foraminifera. Spiroclypeus (Plate X, A) is part of a pre-existing rock fragment redeposited in a Lower Miocene facies. In another rock (Plate VI, B and C) of the Lower Miocene strata, Cycloclypeus (Plate X, B) is incorporated. One of the Lepidocyclina tests is identifiable to the subgenus level of Eulepidina which is known to be associated with strata from the Upper Eocene to the Middle Miocene. Specific genera of the family Homotrematidae, such as Victoriella, ranging from Upper Eocene to Miocene strata, and Sporadotrema, ranging from the Eocene to present, could be identified in these Lower Miocene strata from site RD-47.

Another distinct difference between the Oligocene and Miocene facies, is the inclusion of cobbles of paracoquinites (Plate IX, A) within the Lower Miocene foraminiferal microbreccias. These paracoquinites are moderately sorted with a recrystallized mud matrix (Plate X, C). Other "whole rock" paracoquinites contain abraded tests of Lepidocyclina (Plate X, D) up to 10 mm in length with a preferred orientation. The incorporation of pre-existing rock fragments in many of the Lower Miocene rocks may indicate erosion of reef beyond the typical shedding of shallow-water debris downslope.

A Middle Miocene foraminiferal microbreccia (Plate IX, B) and Pliocene foraminiferal microbreccia were also recovered from site RD-47. These limestones contain abundant planktonic foraminifera and the skeletal debris rarely exceeds 1.5 mm in length. The Middle Miocene microbreccia also contains well-rounded, recrystallized corals that may indicate erosion of the reef. The increase in the degree of abrasion of the skeletal debris and the abundance of planktonic foraminifera indicate an increase in distance from the source of the skeletal debris. The rocks are typical of a very deep, fore-reef slope environment, the fore reef transitional facies.

Conclusions

The sedimentary rocks recovered from the upper flank on the northeastern slope of Caroline Island range in age from Eocene to Recent. This feature existed as a volcanic edifice by late Eocene time within the photic zone as indicated by the presence of miliolids of Eocene? age recovered from the upper flank, and more strongly indicated by the presence of the larger foraminifera *Lepidocyclina* (*Polylepidina*) recovered in sedimentary rocks from the lower flank. Erosion of Eocene strata and the growth of reefs occurred during Oligocene time. The reefing history appears to have been continuous from the Oligocene to the present. The occurrence of well-rounded, recrystallized coral fragments, and pre-existing rock fragments, in a deep, fore-reef transitional facies may indicate erosion of the reefs during Miocene time.

DREDGE-48 RESULTS

Bathymetry

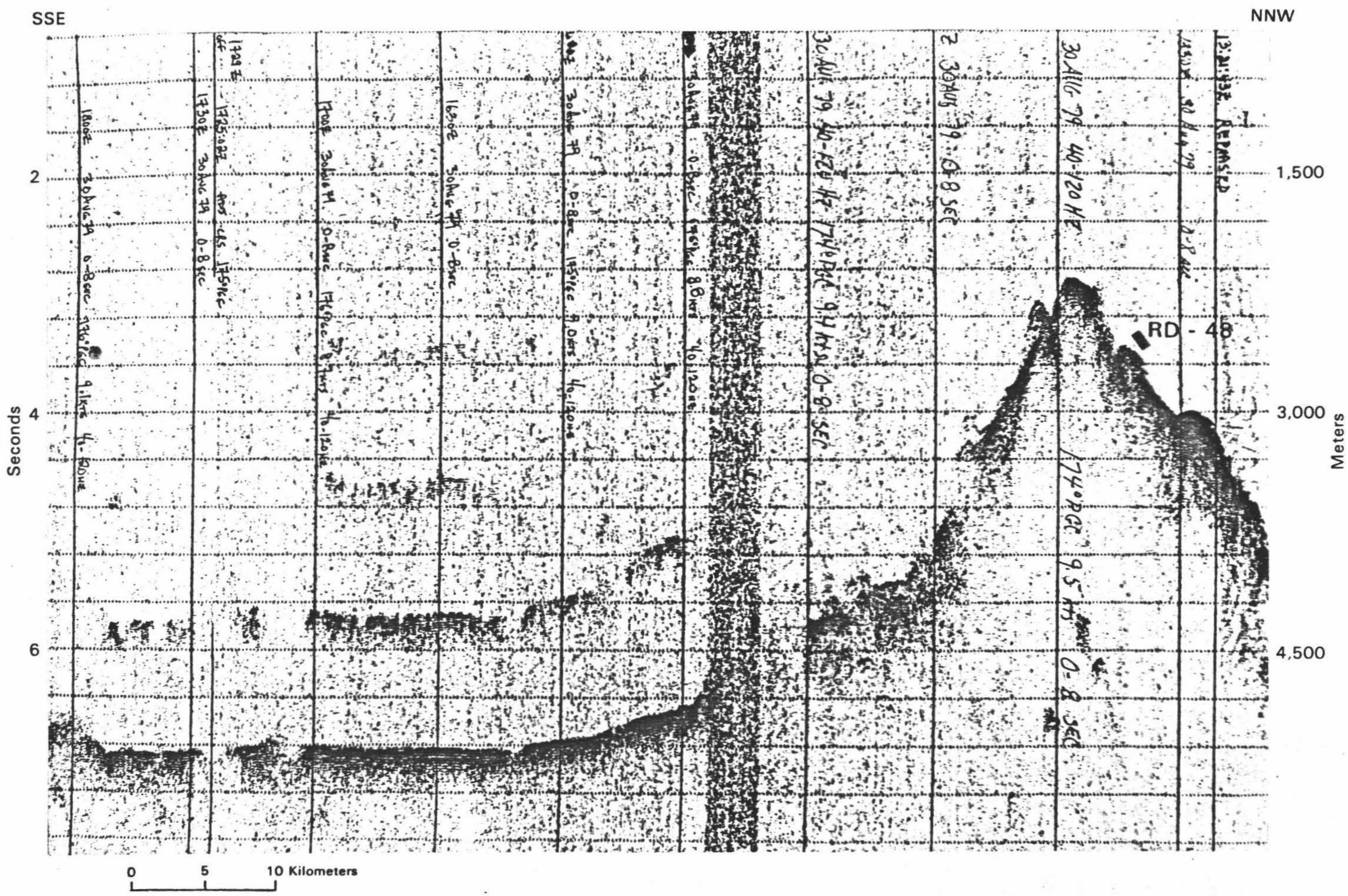
On the 30th of August 1979, the R/V Kana Keoki attempted two dredge hauls on the northern slope of Vostok Island. Sedimentary rocks were recovered from 2500 m water depth at site RD-48 (Figure 11). Another attempt for a dredge haul, at site RD-49 on the lower flank (Figure 12), was unsuccessful.

Rock Descriptions and Interpretations

The sedimentary rocks recovered from site RD-48 include: (1) a coral breccia; and (2) a foraminiferal paracoquinite.

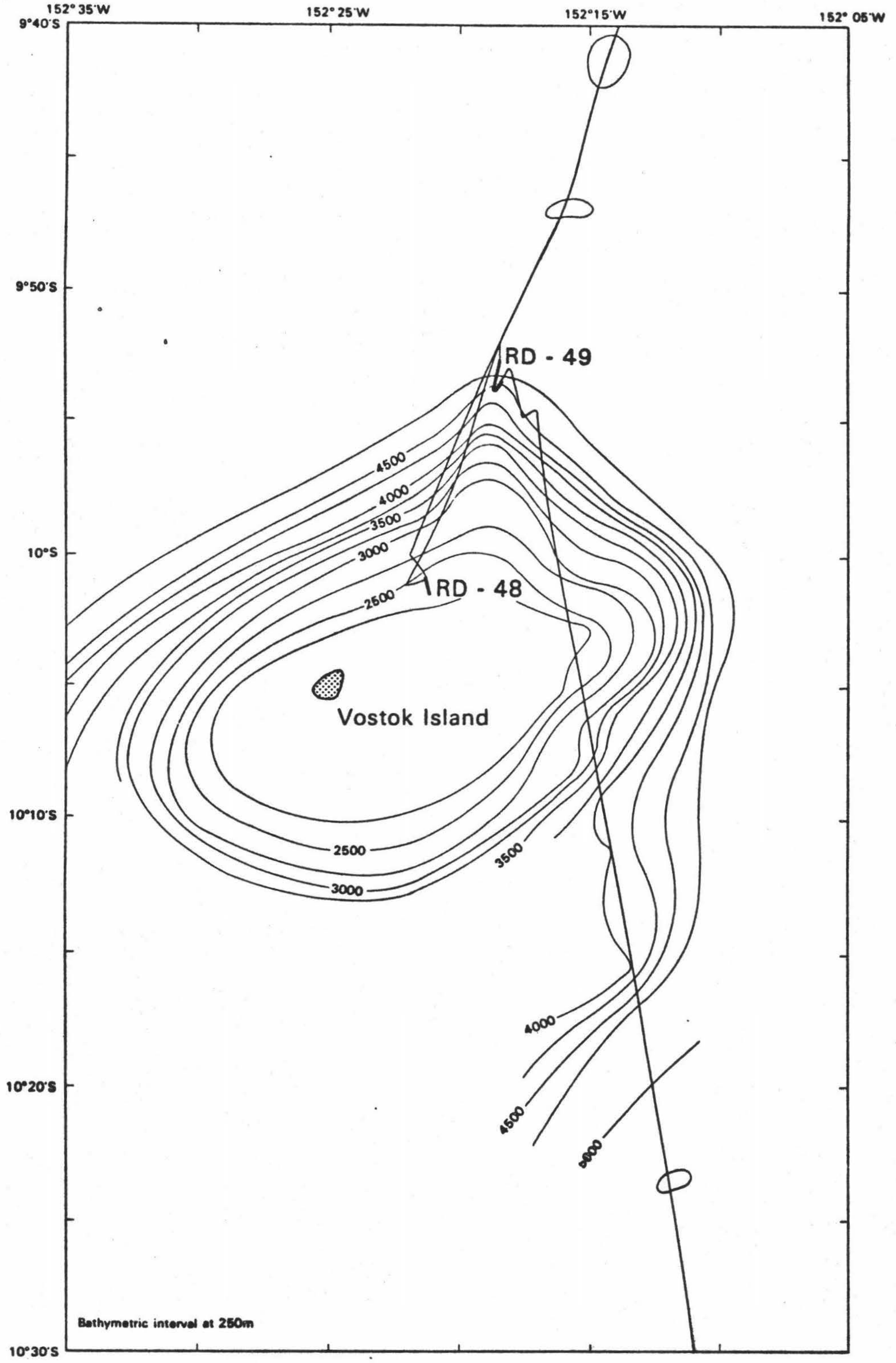
The coral breccia (Plate IX, C) is poorly sorted and contains rounded blocks of completely recrystallized coral up to 4 cm in diameter. Some mud has infilled the interseptal spaces of the coral, but is not recrystallized. A stratification or geopetal framework is exhibited by the concentration of sand-size skeletal debris in pockets of the mud matrix between large coral fragments. The broken and abraded skeletal debris is composed of gastropods, echinoids, bryozoans, Lithothamnium, Heterostegina, Operculina, Acervulina, and Rupertina. This debris is floating in pockets of the fine-grained mud matrix along with miliolids, calcispheres, and rare specimens of planktonic foraminifera of Pliocene/Pleistocene age. From the abundance of the sand size skeletal debris, the fragmentation of large foraminifera, and the rounding of the coral fragments, this rock is interpreted as deposition in a fore-reef slope environment.

Figure 11. Seismic reflection profile of site RD-48, a transect along the eastern slope of Vostok Island. The location of dredge haul RD-48 is represented by a thick bar. Horizontal lines on the record represent seconds of two-way travel time and uncorrected water depth in meters. Bracketed bar indicates horizontal scale of 10 km.



SSE
NNW
Seconds
2
4
6
Meters
1,500
3,000
4,500
RD - 48
0
5
10 Kilometers

Figure 12. Bathymetric chart of sites RD-48 and 49 on the flank of Vostok Island, showing the track of the R/V Kana Keoki and the location of dredge sites. Bathymetric contour interval is 250 m.


152° 35'W
152° 25'W
152°15'W
152° 05'W
9°40'S
9°50'S
10°S
10°10'S
10°20'S
10°30'S
RD - 49
RD - 48
Vostok Island
4500
4000
3500
3000
2500
2500
3000
3500
4000
4500
5000
Bathymetric interval at 250m

The foraminiferal paracoquinite (Plate IX, D) is composed of tests of Heterostegina, Operculina, and planktonic foraminifera of Pliocene age. Some Amphistegina and fragments of Lithothamnium are also present. This rock is interpreted as being deposited in a deep, fore-reef environment.

Conclusions

Vostok existed with fully developed reefs by Pliocene time.

DREDGE-50 RESULTS

Bathymetry

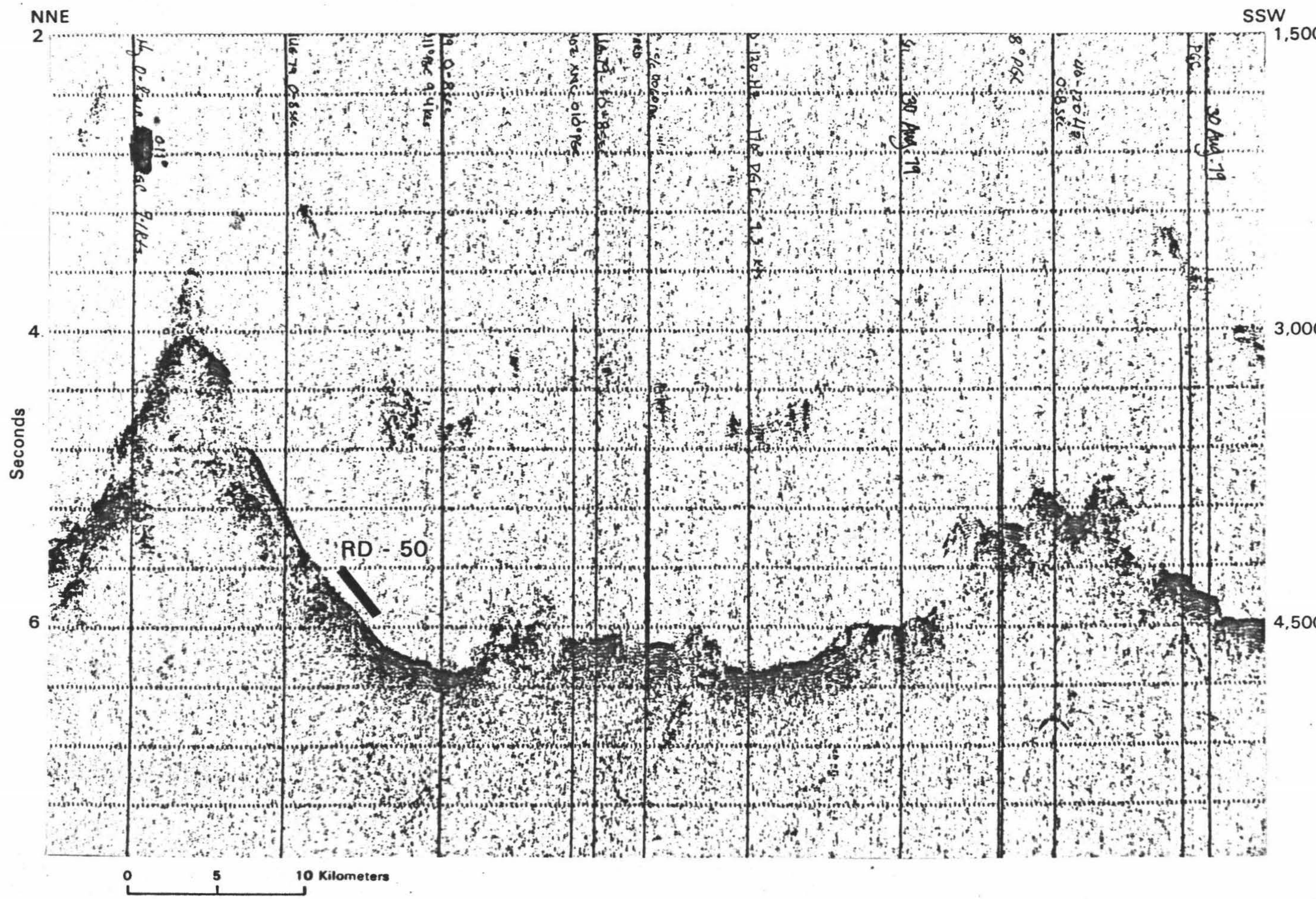
On the 31st of August 1979, the R/V Kana Keoki recovered dredge haul RD-50 from 4250 to 4400 m water depth on the lower flank of a seamount (Figure 13). The seamount is at least 20 km in diameter and located 30 km northwest of Flint Island (Figure 14) in the Southern Province of the Line Islands. The dredge site is on the northern slope of this seamount.

Rock Descriptions and Interpretations

The only type of rock recovered from site RD-50 is a red-brown, stratified, medium to coarse grained volcanic sandstone that has been burrowed (Plate XI, A). The volcanic debris is composed of highly altered glass shards (Plate XI, B and C) which have been reworked by currents. With the addition of water from submarine alteration, the glass shards become palagonitized and zeolites and clays form as alteration products (Furnes, 1974). Scanning electron microscopy beautifully shows the fiberous zeolitic rim surrounding the palagonitized glass (Plate XI, D).

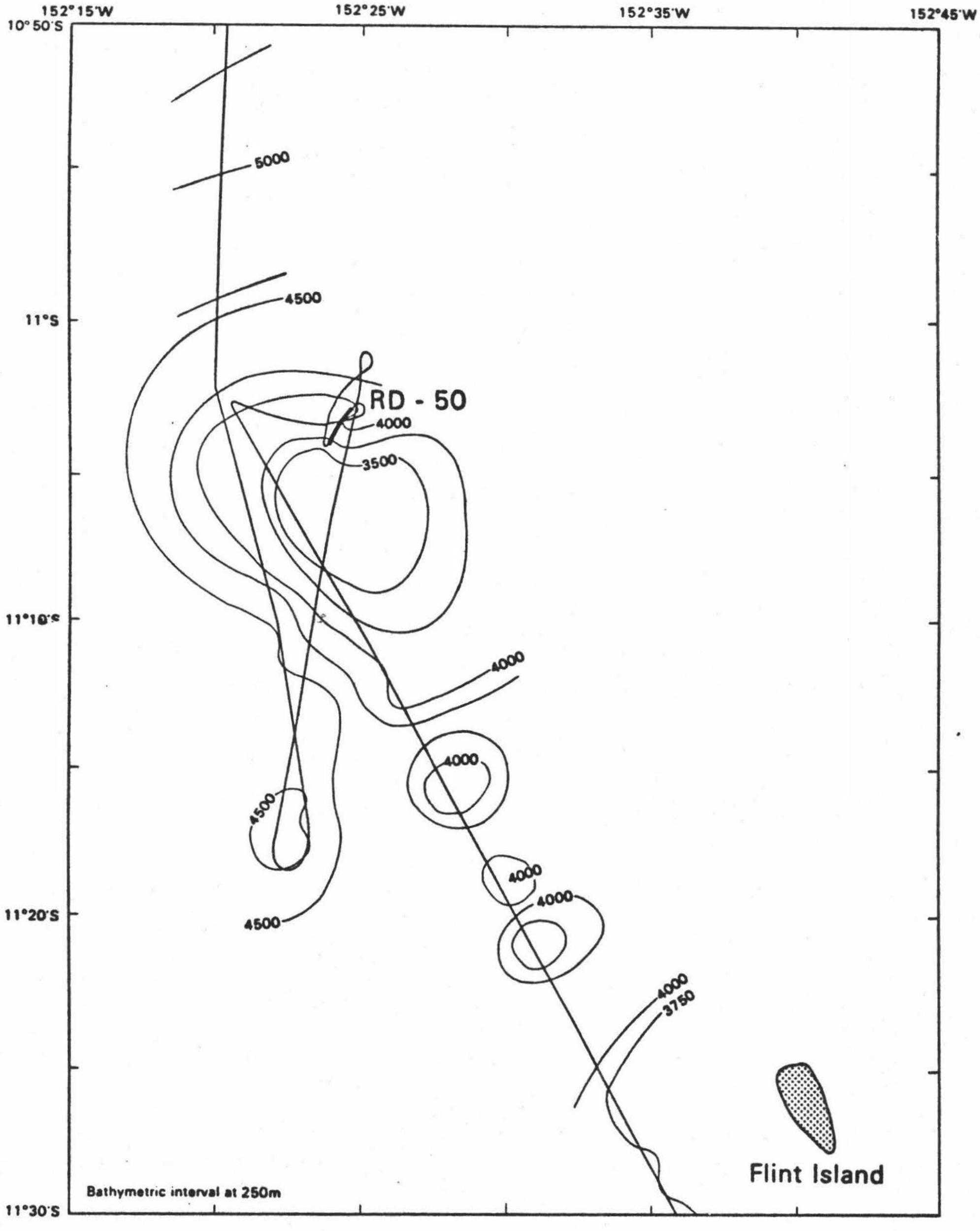
This rock is interpreted as a reworked hyaloclastite showing stratification (Honnorez, 1963). The hyaloclastite was composed of non-vesicular glass which probably formed by rapid quenching in water without a pillow lava or lava flow being formed (Honnorez and Kirst, 1975).

Figure 13. Seismic reflection profile of site RD-50, heading north across a seamount that is northwest of Flint Island. The location of dredge haul RD-50 on the lower flank of the seamount is represented by a thick bar. Horizontal lines on the record represent seconds of two-way travel time and uncorrected water depth in meters. Bracketed bar indicates a horizontal scale of 10 km.



NNE
SSW
2
4
6
Seconds
1,500
3,000
4,500
Meters
RD - 50
0
5
10 Kilometers

Figure 14. Bathymetric chart of site RD-50 northwest of Flint Island, showing the track of the R/V Kana Keoki and the location of dredge site. Bathymetric contour interval is 250 m.


152°15'W
152°25'W
152°35'W
152°45'W
10°50'S
11°S
11°10'S
11°20'S
11°30'S
5000
4500
RD - 50
4000
3500
4000
4000
4500
4500
4000
4000
4000
3750
Flint Island
Bathymetric interval at 250m

Conclusions

No planktonic foraminifera were found among the volcanic debris, however, planktonic foraminifera of Miocene age were found within the infilled burrows. The association of these Miocene planktonic foraminifera with the volcanic debris establishes a minimum age of volcanism as Miocene.

DREDGE-51 RESULTS

Bathymetry

On the 1st of September 1979, the R/V Kana Keoki recovered dredge haul RD-51 in 3000 to 3200 m water depth on the flank of a seamount that is 40 km in diameter (Figure 15). The dredge site is on the eastern slope of this seamount (Figure 16) which rises to at least 2100 m below sea level and is located 322 km north of the Tuamotu Ridge.

Rock Descriptions and Interpretations

Only volcanic sandstone was recovered from site RD-51, although it is distinctly different from the volcanic sandstone recovered from site RD-50. The volcanic sandstone from site RD-51 is composed of highly-altered, vesicular glass fragments (Plate XII, A) that have been redeposited in a matrix containing planktonic foraminifera of middle Eocene age (Zone P12-14). This has been overlain by phosphatized foraminiferal and radiolarian sediment (Plate XII, B), also Zone P12 to 14, and then by a centimeter thick manganese crust. The highly vesicular nature of this palagonitized volcanic debris indicates that this may have been a very shallow submarine eruption which was rapidly quenched in water.

Figure 15. Seismic reflection profile of site DR-51,heading east across the flank of a seamount located 322 km north of the Tuamotu Ridge. The location of RD-51 represented by a thick bar. Horizontal lines on the record represent seconds of two-way travel time and uncorrected water depth in meters. Bracketed bar indicates horizontal scale of 10 km.

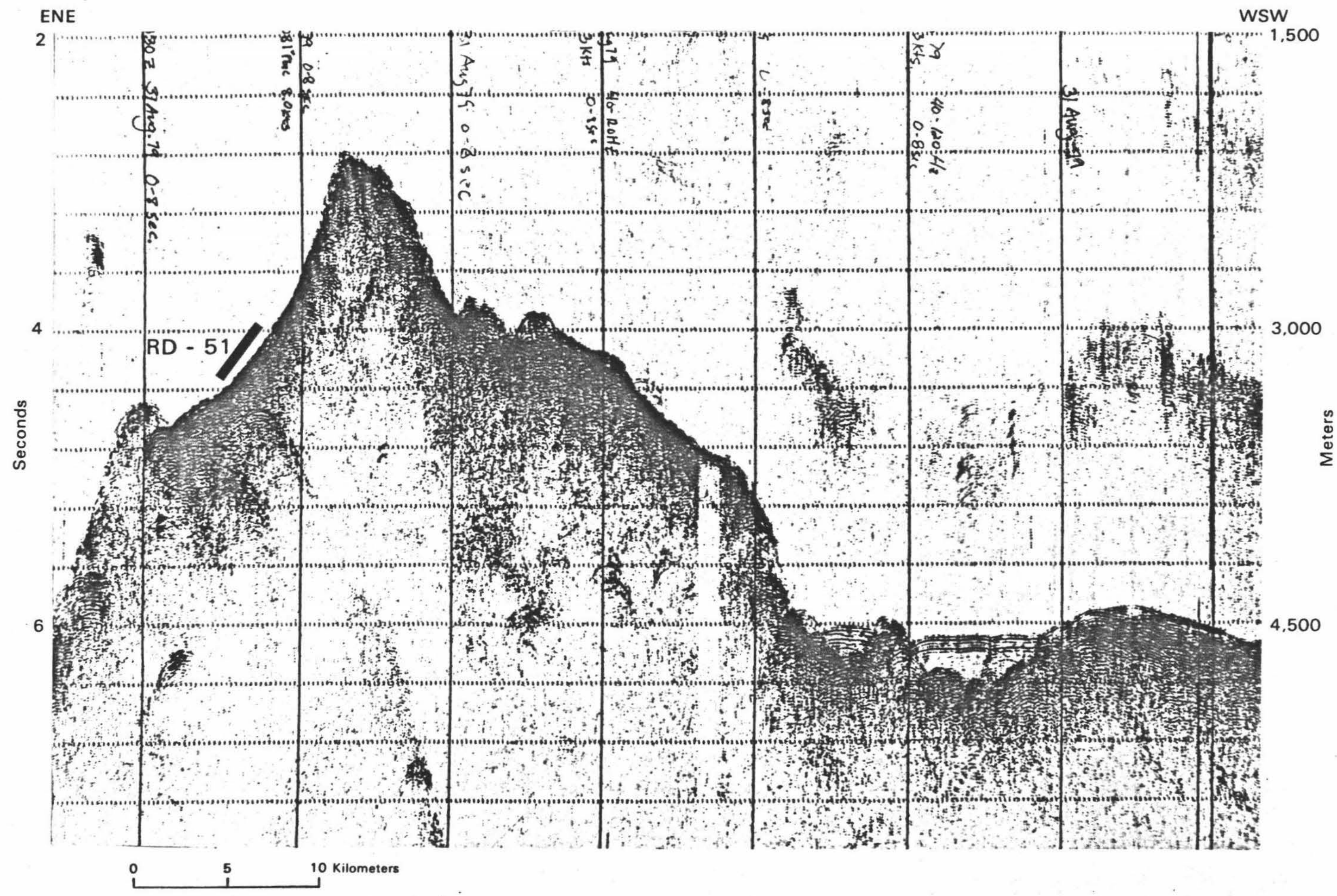
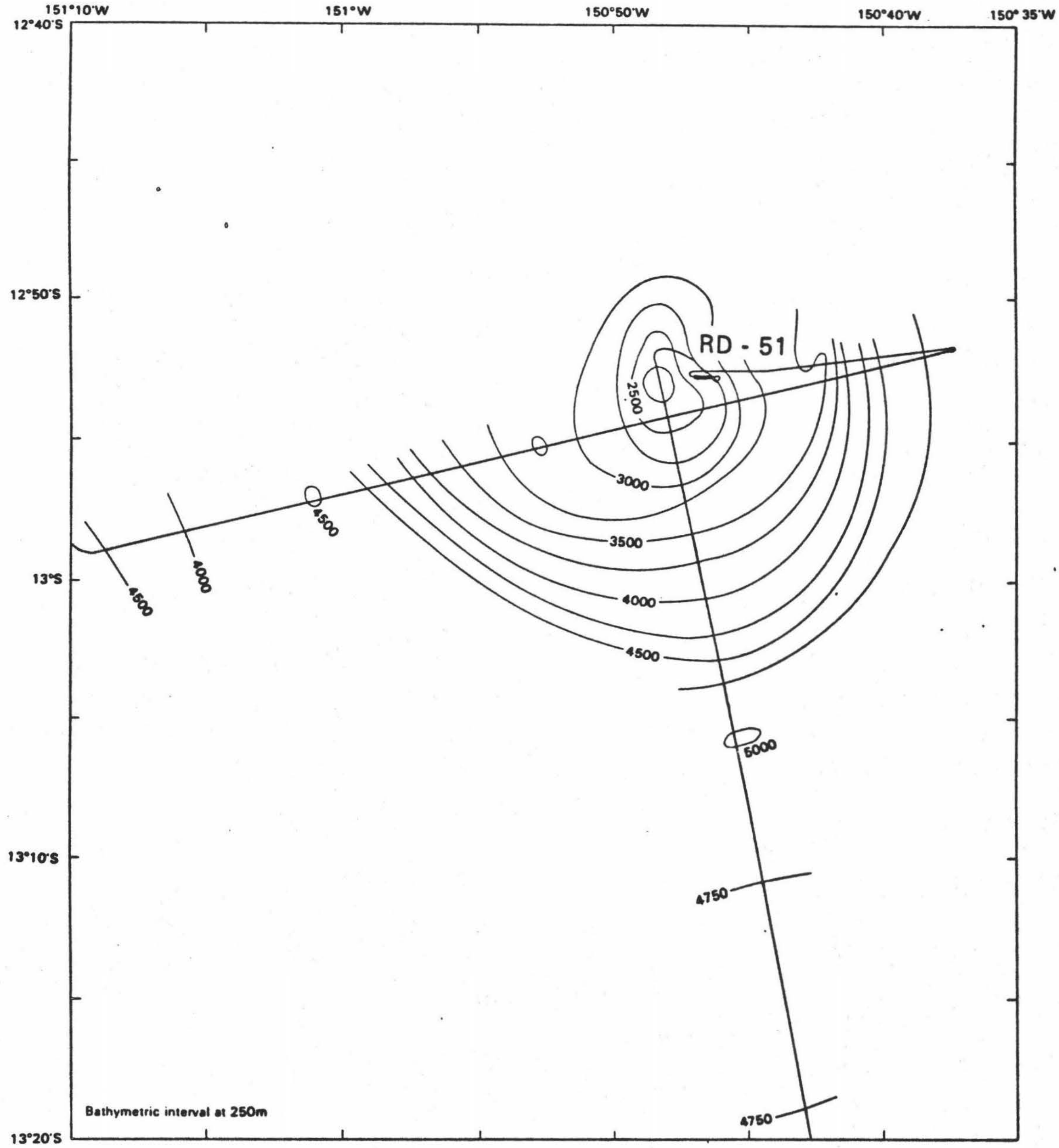

ENE
WSW
2
4
6
Seconds
1,500
3,000
4,500
Meters
RD - 51
0
5
10 Kilometers

Figure 16. Bathymetric chart of site RD-51, showing the track of the R/V Kana Keoki and location of the dredge site. Depth contour interval is 250 m.



151°10'W
151°W
150°50'W
150°40'W
150°35'W
12°40'S
12°50'S
13°S
13°10'S
13°20'S
RD - 51
2500
3000
3500
4000
4500
4500
4000
4500
5000
4750
4750
Bathymetric interval at 250m

Conclusion

The middle Eocene planktonic foraminifera associated with the volcanic debris establishes a minimum age of volcanism as middle Eocene. The highly vesicular volcanics may indicate a shallow-water eruption.

DREDGE-52 RESULTS

Bathymetry

After the dredging operation at site RD-51, the R/V Kana Keoki headed south for the Tuamotu Ridge. A planned dredge attempt on the Tuamotu Ridge was abandoned due to rough seas, and the ship continued southward for a port call in Tahiti. On Leg 2 of the Line Islands cruise, a successful dredge was recovered from 3400 m water depth (Figure 17) from the southern flank of the Tuamotu Ridge (Figure 18). The seismic reflection profile (Figure 17) displays distinct steps or terraces similar to those appearing on the seamount of site RD-44. From the limited bathymetric data, the author cannot detect a trend or the extent of these step-like terraces.

Rock Descriptions and Interpretations

A greenish-gray, graded, volcanogenic sandstone with altered volcanic fragments, ranging from 1 to 4 mm in diameter, was recovered from site RD-52. Some of the altered volcanic fragments, yellow or brown palagonite with tachylite, appear to have been fragments from pillow rims (Plate XII, C), while others are fragments of altered aphyric vesicular basalt exhibiting flow texture (Plate XII, D). No planktonic foraminifera or any shallow-water, skeletal debris was observed in thin sections or in examination of a disaggregated sample.

Figure 17. Seismic reflection profile of site RD-52 along the Tuamotu Ridge. Note change in orientation of the profile due to a change in course of the ship from southwest heading northeast to a due west direction. The step-like features on the seismic profile are not an artifact from the change in course. The location of dredge haul RD-52 is represented by a thick bar. Horizontal lines on the record represent seconds of two-way travel time and uncorrected water depth in meters. Bracketed bar indicates a horizontal scale of 10 km.

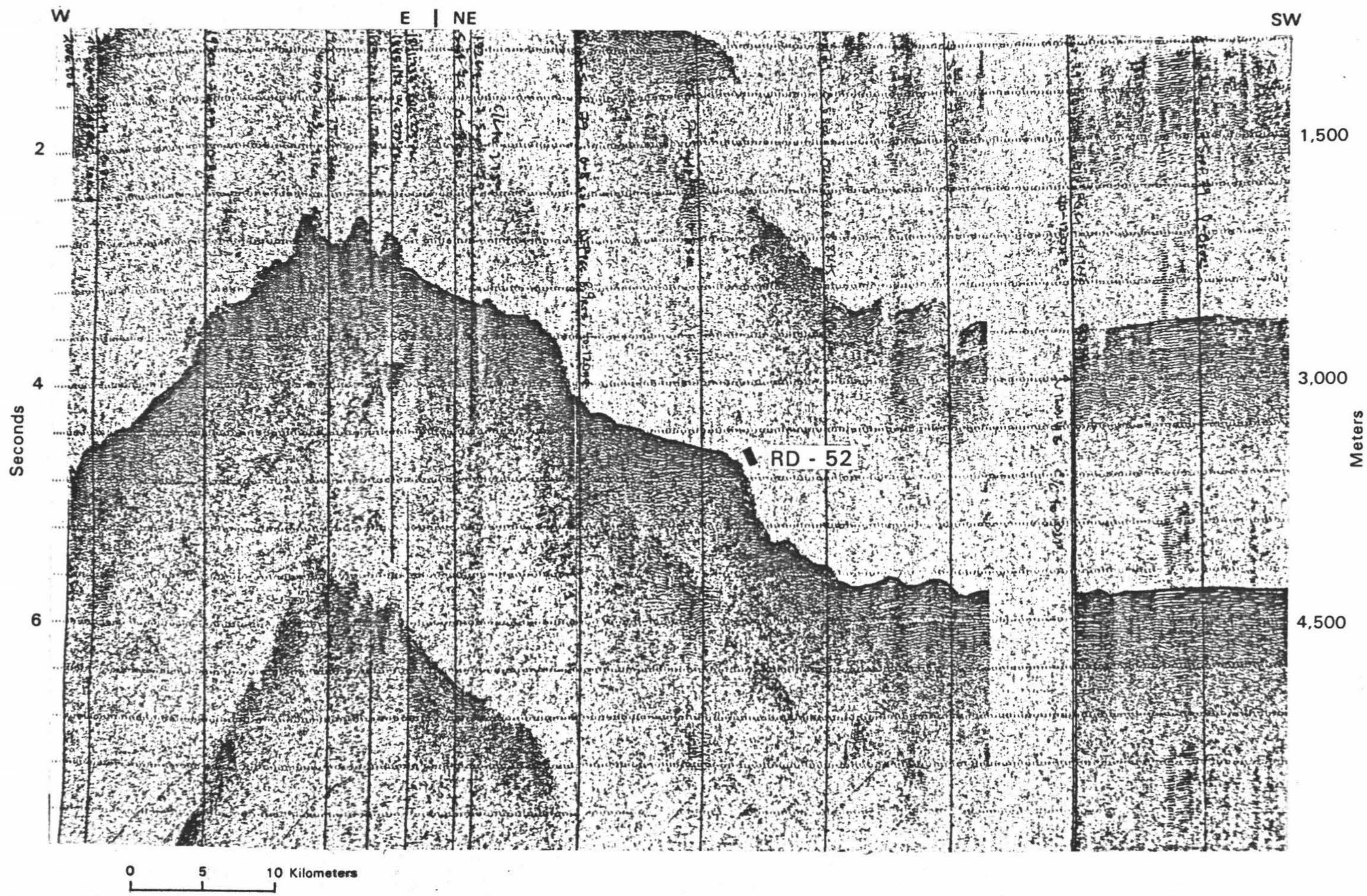
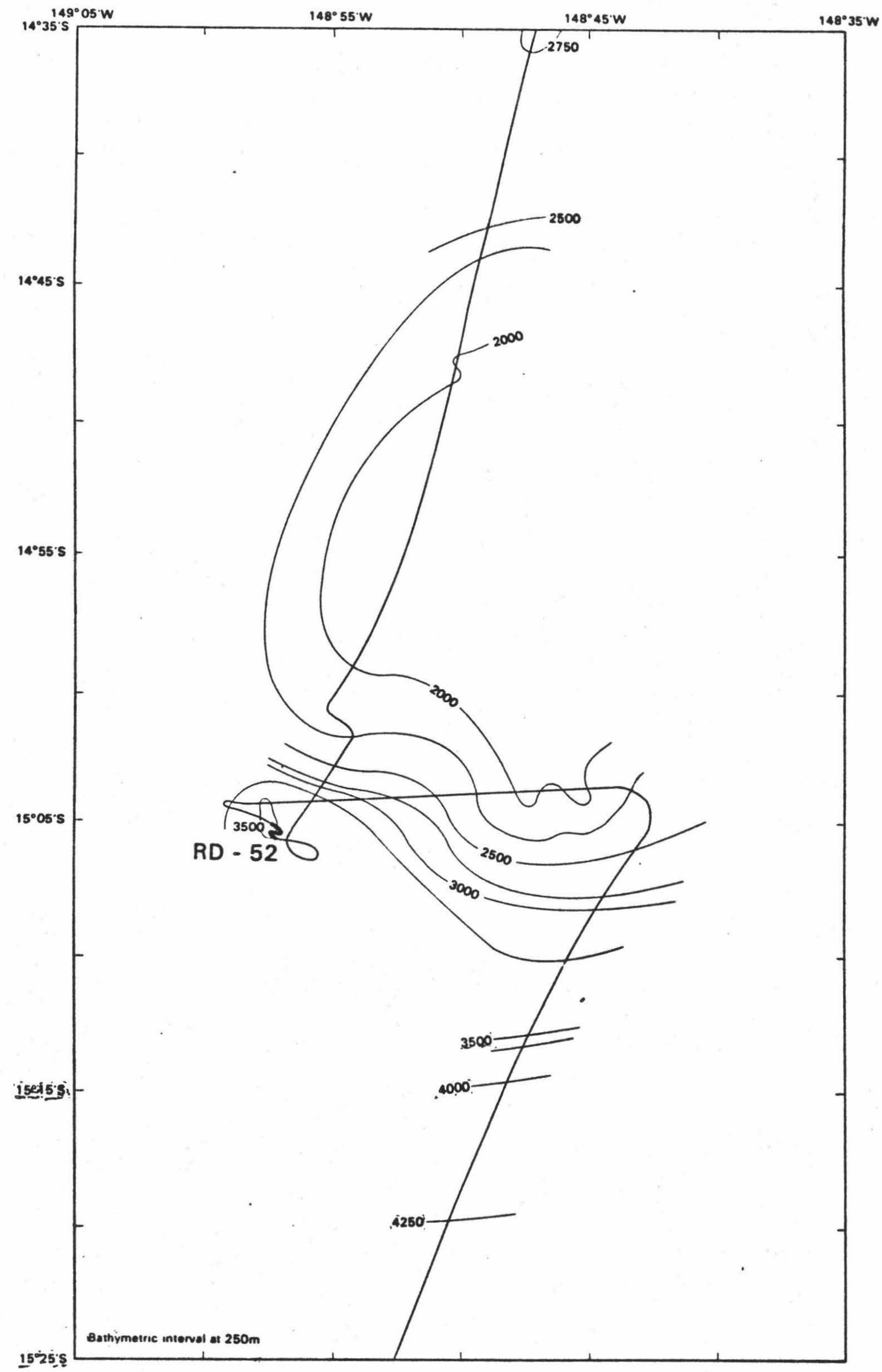

W
E
NE
SW
2
4
6
Seconds
1,500
3,000
4,500
Meters
RD - 52
0
5
10 Kilometers

Figure 18. Bathymetric chart of site RD-52 on the Tuamotu Ridge, showing the track of the R/V Kana Keoki and the location of dredge site. Bathymetric contour interval is 250 m.


149° 05'W
148° 55'W
148° 45'W
148° 35'W
14°35'S
14°45'S
14°55'S
15°05'S
15°15'S
15°25'S
2750
2500
2000
2000
2500
3000
3500
RD - 52
3500
4000
4250
Bathymetric interval at 250m

Conclusions

The volcanic debris is graded and subangular and is therefore interpreted as having been deposited by currents not far from the source area. The volcanogenic sandstone recovered from this dredge site may possibly correlate with the volcaniclastic sediment in lithostratigraphic Unit 5 from DSDP Site 318, however insufficient data do not permit a strong correlation.

CARBON AND OXYGEN STABLE ISOTOPE GEOCHEMISTRY OF CEMENTS IN CENOZOIC LIMESTONES FROM THE SOUTHERN LINE ISLANDS

By deciphering the diagenetic history of limestones from sites RD-46, 47, and 48, valuable information can be obtained about the geologic history of the Southern Province of the Line Islands. The Oligocene, Miocene, and Plio/Pleistocene limestones from those sites have similar diagenetic features. On the exterior of many of the hand specimens, abundant molds of corals, and occasionally molds of gastropods, are displayed (Plate VII). The outer surface of some samples are coated with a flowstone or travertine-like deposit (Plate VI, B). On cut surfaces, the rocks appear very dense with observable molds of corals (Plate VI, C), or reversed corals (Plate VIII, A), and recrystallized corals (Plate VI, A; Plate IX, C). The samples are very indurated to the degree of a brittle limestone. In fact, when hammered on some of the limestones will ring.

From x-ray diffraction analysis, these rocks are composed of low-Mg calcite (less than 5 mol percent of magnesium) and a questionable trace of aragonite. Carbonate staining revealed only the presence of low-Mg calcite, no aragonite. High-Mg calcite was not observed during staining or x-ray diffraction analysis. These rocks are nearly pure low-Mg calcite.

In thin section, a particularly common feature is syntaxial overgrowth on echinoid fragments in paracoquinites (Plate VIII, A) and in microbreccias (Plate VIII, D). In the paracoquinites and microparacoquinites, much of the mud is now equant calcite (Plate VIII, B) with crystals coarsening toward the center of the pores (Plate X, C). Occasionally, isopachous bladed calcite cement may surround a skeletal fragment. These cements also are developed in localized areas within the microbreccias. Some coral fragments have undergone complete replacement of the aragonite by equant calcite (Plate IX, C). In other cases, the aragonite has been leached and a "reversed" coral composed of the micritic mud infill remains (Plate VIII, A).

Other obvious dissolution characteristics are the development of moldic and vuggy porosity. In the paracoquinites and the microparacoquinites (Plate VIII, A; Plate IX, A) sand size grains have been dissolved and only the micritic envelope remains. Not only have grains been dissolved, but also missing are areas of the mud matrix that appear as vugs in the microbreccia (Plate VIII, C and D; Plate IX, D; Plate X, A and B). These rocks therefore are interpreted as having been in an environment undersaturated with respect to carbonate.

On the basis of the observed mineralogy and petrology, these diagenetic textures appear similar to the freshwater phreatic characteristics listed by Longman (1980, p. 474) in a review article on the diagenesis of carbonates. Excluding the occurrence of micritic mud, and micritic envelopes on grains, these rocks do not display any of the typical marine phreatic diagenetic characteristics listed by Longman (1980, p. 464).

Little research has been conducted on lithification and diagenesis of sediments on Pacific seamounts. Before accepting a freshwater phreatic history as generating the petrographic characteristics and mineralogic composition of these rocks, several other factors should be considered.

Could these samples have been subaerially exposed? Considering global cycles of sealevel change during the Tertiary (Vail et al., 1977; Vail and Hardenbol, 1979), these deep fore-reef slope deposits could only be subaerially exposed if a major sealevel drop occurred during or after the time of their deposition. Another mechanism that may possibly permit subaerial exposure of the limestones would be tectonic uplift. If the uplift was of a large enough magnitude, the uplift alone could expose the limestones, or in conjunction with a sealevel drop, the combination could expose fore-reef slope deposits. Because little is known about the tectonics of this area, uplift cannot be ruled out as a potential mechanism for subaerial exposure of these limestones.

Are there any other diagenetic environments undersaturated with respect to carbonate besides the freshwater phreatic environment? In the marine realm, there are carbonate dissolution environments associated with the carbonate compensation depth (CCD) and the lysocline, but both occur at water depths much greater than those from which the limestones were dredged. A marine carbonate dissolution environment at shallower depths is associated with the aragonite compensation depth, below which aragonite dissolution would not be compensated by the rate of supply. Berner and Honjo (1981) commented that seawater below a few hundred meters in the present day Pacific is undersaturated with respect to aragonite. (In the Atlantic Ocean, this does not occur till 1000 to 2000 m water depth.) Berger (1970) conducted aragonite dissolution experiments with pteropod samples in the Pacific. After four months of exposure seawater, there was strong evidence of dissolution at 500 m water depth and complete disappearance at 3000 m. With removal of organic coatings and four months of exposure in the central equatorial Pacific, the aragonite had completely dissolved at 750 m water depth. The samples from sites RD-46, 47, and 48 were recovered from below 750 m water depth.

Therefore there are two feasible environments that are undersaturated with respect to carbonate, which may generate the diagenetic textures and cements exhibited in these samples. By using stable isotope geochemistry of the cements, one can distinguish between subaerial environments and the marine realm. Allen and Matthews (1977) have demonstrated the use of stable isotope geochemistry as a stratigraphic tool to distinguish subaerial environments from the marine environment. Isotopically light carbon dioxide from soil gases dissolved in the groundwater will impart a negative carbon isotopic signature in subaerial cements. Carbonate deposited in isotopic equilibrium with sea water will be zero or have a positive carbon isotopic signature.

In order to discriminate between a subaerial freshwater phreatic environment and aragonite dissolution at depth in the marine realm, five rocks were analyzed for carbon and oxygen stable isotopic composition of the cements. Several samples were taken from within each rock, including clasts of different ages from within the same rock.

Results

Carbon and oxygen stable isotopic compositions of 20 samples from five carbonate rocks of Oligocene, Miocene, and Plio/Pleistocene age are listed in Table 1. Note that all of the carbon isotope ratios are very positive, none of these carbon isotope ratios are less than one, suggesting that the cements were produced in the marine environment.

The oxygen isotopic compositions of the cements may be converted to isotopic temperatures. The author chose to use the equation of Shackleton and Kennett (1975), but with the average $\delta^{18}O$ water value as +0.8‰ relative to modern as suggested by Matthews and Poore (1981). Assuming 28°C as tropical sea surface temperature, none of the isotopic temperatures match or approach this shallow-water value, and therefore indicate cements generated in the marine realm.

TABLE 1

CARBON AND OXYGEN STABLE ISOTOPIC COMPOSITION OF CENOZOIC LIMESTONES FROM THE SOUTHERN LINE ISLANDS

SAMPLE	AREA	AGE	$\delta^{13}C_{PDB}$	$\delta^{18}O_{PDB}$	°C (δw=0.72)
KK79-46-03	foraminiferal-algal paracoquinite	N.4-6	+2.6	+2.3	10.2
	pebble of foraminiferal microbreccia	N.5	+2.1	+2.2	10.6
	coral mold in foraminiferal microbreccia	N.4-6	+2.1	+2.6	9.0
	clear spar in vugs in foraminiferal microbreccia	N.4-6	+2.7	+2.7	8.6
	Intergranular spar in foraminiferal microbreccia	N.4-6	+2.3	+2.6	9.0
	recrystallized coral in foraminiferal microbreccia	N.4-6	+2.7	+0.8	16.6
	echinoid fragment in foraminiferal-algal paracoquinite		+2.3	+2.2	10.6
KK79-47-01	foraminiferal microbreccia	top of N.7 or N.8	+1.9	+2.2	10.6
	coral mold in foraminiferal microbreccia	top of N.7 or N.8	+2.3	+2.6	9.0
KK79-47-08	flowstone-like deposit on exterior of sample		+2.2	+3.2	6.6
	intergranular spar in foraminiferal microbreccia	N.8	+2.3	+3.2	6.6
	coral mold in foraminiferal microbreccia	N.8	+2.2	+2.8	8.2
	clast of paracoquinite	N.5?	+2.4	+2.0	11.5
KK78-47-09	clast of paracoquinite	N.5-8	+1.4	+2.9	7.8
	foraminiferal microbreccia	N.8	+2.7	+2.2	10.6
	micritic cement	N.8	+2.9	+2.5	9.4

TABLE 1. (Continued) CARBON AND OXYGEN STABLE ISOTOPIC COMPOSITION OF CENOZOIC LIMESTONES FROM THE SOUTHERN LINE ISLANDS

SAMPLE	AREA	AGE	$\delta^{13}C_{PDB}$	$\delta^{18}O_{PDB}$	°C (δw=0.72)
KK79-47-11	foraminiferal microbreccia	P.19	+1.4	+2.7	8.6
	micritic cement		+2.3	+2.8	8.2
	foraminiferal microbreccia	N.4?	+2.6	+4.9	0.3
KK79-48-01	recrystallized coral	Plio/Pleistocene	+2.3	-0.6	22.9

$$T°C = 16.9 - 4.38 (\delta c - \delta w) + 0.10 (\delta c - \delta w)^2$$

from Shackleton and Kennett (1975).

$\delta c = \delta^{18}O$ of the calcite

$\delta w = 0.72$

Interpretations

If the cements weere formed subaerially in a closed system, or without much influence from soil gases, positive carbon values could be produced (Allen and Matthews, 1977), but the values would be very close to zero. The fact that the carbon isotope ratios of the Cenozoic cements are positive and never less than one, points to a marine origin for these Cenozoic cements. Further, if the cements were formed subaerially, with or without the influence of soil gases, the oxygen isotope ratios would typically be negative reflecting the warm temperatures of groundwater in tropical islands or atolls. The fact that the oxygen isotope ratios of these Cenozoic limestones are positive (with the exception of KK79-48-01) indicates cool temperatures, and a marine origin for the cements.

Mink (1964) conducted a study of groundwater temperatures in a tropical island environment with caprock inhibiting the movement of seawater in and out of the island. He found that on the island of Oahu, the average temperature of meteoric infiltration water is 19.7°C and that within the basal freshwater lens the temperature may increase 1.1°C, and continues to increase in the transition zone. A temperature of 23.3°C was found at 400 m depth in the lower portion of the transition zone in southern Oahu. Seawater at the same depth was 8.5°C. On atolls, where the caprock is absent, the temperature of the sub-lens saline water would not continue to increase. The work of Swartz (1958) on Enewetak and Bikini atolls showed that above 1000 m depth there is a striking similarity between thermal profiles in deep wells and the surrounding ocean. The thermal profile of the wells mimic the thermal profile of the adjacent ocean as the result of unrestricted movement of seawater into the islands. The upper 100 m of the drill hole E-1, Enewetak Atoll, has water temperatures of 24 to about 28°C, and the ocean water temperature ranges from 26 to about 28°C for the same depth range (Swartz, 1958, p. 737). The work of Noshkin et al. (1976, p. 532) shows that the middle of the transition zone on Engebi Island, in Enewetak Atoll, is at 10 m water depth. By 100 m water depth, one should be through the remainder of the transition zone and into seawater. The isotopic temperatures calculated for the cements in the Cenozoic limestones from the southern Line Islands average about 8 to 10°C and therefore do not suggest cements that were precipitated in a warm freshwater lens or transition zone. These Cenozoic limestones contain tropical reef faunas and therefore warm, surface-water temperatures would be expected in the geologic past. A tropical, sea-surface temperature of 8 to 10°C is unlikely.

On the basis of the mineralogy, petrology, and stable isotope geochemistry of the cements in the Oligocene, Miocene and Plio/Pleistocene limestones from sites RD-46, 47, and 48, the diagenetic dissolution textures and low-Mg calcite cements are interpreted as being generated in the marine environment. The isotopic data obtained from these samples do not indicate evidence for subaerial exposure of these Oligocene, Miocene, or Plio/Pleistocene fore-reef slope deposits.

Implications

Matthews and Poore (1981) utilized a $\delta^{18}O_{water}$ value which is +0.8‰ relative to modern sea water (-0.08‰) for interpreting the Tertiary $\delta^{18}O$ record. This value was derived from average late Pleistocene conditions. By assuming this $\delta^{18}O_{water}$ value for the Tertiary, and a constant tropical seasurface temperature of 28°C, the paleotemperatures for the Tertiary are generated which do not assume an ice-free earth prior to middle Miocene time. Much evidence has accumulated which indicates that glaciation existed during the Oligocene on Antarctica (Le Masurier, 1972; Margolis, 1977). The author feels this logic and approach is better than the approach used by Savin (1977) and others which assume an ice-free earth prior to middle Miocene time.

The oxygen isotopic composition of the cement is a function of the isotopic composition of the surrounding medium and the temperature when the cement was precipitated. If carbonate dissolves, the oxygen will rapidly equilibrate with the surrounding seawater. Assuming that the chosen $\delta^{18}O_{water}$ value was appropriate, the derived isotopic temperatures should be indicative of the temperature of lithification and formation of the cements.

The isotopic temperatures in Table I compared with a water column temperature profile from GEOSECS Station 263, at 16.62°S and 167.13°W, are warmer than present day temperatures at the depths of the dredge locations. For site RD-46, depth of 1400 to 1500 m has a present water temperature of about 3°C, whereas the average isotopic temperature for that dredge site is 10.6°C. For sites RD-47 and 48 at 2400 to 2700 m and 2500 m water depth, the temperature is presently about 2°C, whereas the average isotopic temperature is 8.1°C for RD-47 and 22.9°C for RD-48. Because the isotopic temperature values are not in agreement with present day temperatures, the isotopic composition of the low-Mg calcite cements therefore is not in equilibrium with present day seawater. The author interprets this to indicate that lithification and cementation occurred in the geologic past when the deposit was at a warmer, probably shallower depth on the subsiding seamount and atoll.

The existence of low-Mg calcite syntaxial overgrowths on echinoid fragments typically has been assigned as a freshwater phreatic cement. The occurrence of syntaxial overgrowths on echinoid spines is a common feature in the Tertiary limestones of this study. A common characteristic of freshwater diagenesis and also of these Tertiary limestones is that echinoid fragments are transformed from the original biogenic composition of a high-Mg calcite to a low-Mg calcite. If this feature was subaerially formed in these Tertiary limestones, the resultant low-Mg calcite, the most stable form of calcite, would not have needed to recrystallize and re-equilibrate in the marine realm and should therefore contain a subaerial isotopic signature. An echinoid fragment, geochemically analyzed in this study (Table 1), yeilded positive carbon and oxygen isotopic signatures which therefore indicate a marine origin for this feature in these Tertiary limestones.

All of these data indicate that low-Mg calcite cements can be formed in deep-sea environments and do not require a subaerial origin. Experimental data also supports this contention. Fuchtbauer and Hardie (1976) demonstrated experimentally that the mole percent of Mg in inorganically precipitated calcite decreases with decreasing seawater temperatures.

Schlager and James (1978) noted the formation of low-Mg calcite limestones from Pleistocene peri-platform ooze on the seafloor near the Bahamas. The data from their study of Pleistocene carbonates is in agreement with the data from the Tertiary limestones from the southern Line Islands. The characteristics of seafloor diagenesis in association with an aragonite compensation depth, appear identical to freshwater phreatic diagenesis. This form of marine diagenesis may be more common than previously recognized, especially in ancient deep-water carbonates that are often associated with shallow-water platforms.

This form of marine diagenesis, as aragonite dissolution at depth and precipitation of low-Mg calcite, also requires a re-evaluation of mineralogic and petrographic data of limestones from atolls and seamounts that were interpreted as having been subaerially exposed in the geologic past. From Enewetak and Bikini atoll drill-hole borings, the mineralogic composition and petrographic characteristics indicated "solution unconformities" which Schlanger (1963) interpreted as the result of subaerial emergence of the atoll. Schlanger noted the existence of unaltered fragments of delicate branching corals and abundant gastropods and pelecypods as the first faunas to colonize the unconformity surface. Gross and Tracey (1966) analyzed the recrystallized limestones for carbon and oxygen isotopic compositions. The carbon ratios ranged from -0.2 to -10.0‰ and oxygen ratios ranged from -0.8 to -7.5‰, thereby confirming the subaerial diagenetic history of Enewetak and Bikini atolls. Studies of seamounts in the Pacific have not been nearly as thorough as the Enewetak program. Interpretations of subaerial exposure are based on mineralogic and petrographic data from dredged samples and consequently lack the additional stratigraphic data. Therefore, the recognition of terrestial fossil faunas or analysis for the stable isotopic composition of the carbonate cements would aid in discriminating between freshwater phreatic diagenesis and deep marine aragonite dissolution diagenesis--mineralogic composition and petrographic characteristics of the limestones are not sufficient.

SUMMARY OF THE GEOLOGIC HISTORY OF THE SOUTHERN LINE ISLANDS AND CORRELATION WITH THE CENTRAL PACIFIC

Reefing History

The shallow water skeletal debris recovered in the sedimentary rocks from the Southern Province of the Line Islands indicates the presence of reefs or shallow-water platforms during the geologic past. Displaced reef faunas of Campanian/Maestrichtian age were recovered from sites RD-44 and 45 as rudist fragments associated with globotruncanids. Displaced reef faunas of Campanian/Maestrichtian age were also recovered from the DSDP Sites 165, 315, and 316, along the Line Islands, as well as Site 462 in the Nauru Basin (see Figure 1.)

From site RD-44, miliolids were associated with planktonic foraminifera indicating the existence of a neritic-shelf environment during the Paleocene.

From sites RD-45, and 47, benthonic foraminifera, such as an Eocene Cibicides, and Lepidocyclina (Polylepidina) of middle to late Eocene age, and miliolids of Eocene? age from site RD-46, indicate the existence of a shallow-shelf environment in the southern Line Islands during the Eocene. A shallow-water environment also is indicated in the northern portion of the Line Islands and on the Tuamotu Ridge by the recovery of discocyclinids in the piston cores from the Line Islands (Appendix B) and at DSDP Site 318. In the Nauru Basin, at DSDP Site 462, Polylepidina and discocyclinids were recovered, also indicating the existence of shallow-water platforms.

Oligocene, Miocene, and Plio/Pleistocene redeposited reef skeletal debris was recovered in sites RD-46, 47, and 48 and indicates the existence of reefs during that time interval. Oligocene reef debris was also recovered from DSDP Site 462, Nauru Basin, and DSDP Site 318, on the Tuamotu Ridge. Reefs of Eocene age and younger are also recorded from Enewetak Atoll in the Marshall Islands (Cole, 1957).

Reefs existed during the Late Cretaceous in the southern and northern portion of the Line Islands. Shallow-water carbonate platforms and/or reefs were perhaps continuous throughout the Tertiary to the present in the southern and possibly in the northern Line Islands. The reefing history of the southern Line Islands is similar to that of the Marshall Islands area as previously noted by Schlanger and Premoli Silva (1981) for the northern portion of the Line Islands chain.

Erosional Events

The reworking of neritic fossils as indicated by their occurrence with younger planktonic foraminifera, and redeposited clasts of pre-existing rock fragments are interpreted as evidence of an erosional event. Premoli Silva and Brusa (1981) evaluated data from DSDP cores in the Central Pacific and demonstrated the occurrence of erosional events from the presence of shallow-water skeletal debris incorporated in pelagic sediment. Data from the southern Line Islands are correlated with their findings.

During Campanian time, volcanic rock fragments were eroded from the edifice at site RD-45. This correlates with data from Premoli Silva and Brusa for the northern Line Islands, the Mid-Pacific Mountains, and the Nauru Basin. The debris-flow conglomerates from site RD-45 also exhibit erosion of the edifice as well-rounded volcanic fragments are associated with planktonic foraminifera of late middle Maestrichtian age. This event in the southern Line Islands also correlates with an erosional event occurring in the northern Line Islands and in the Nauru Basin.

The erosion of Cretaceous strata and its incorporation into Paleocene sediment from site RD-44 is interpreted as a local erosional event due to slumping on the seamount. The local nature of this event is supported by the seismic reflection records displaying step-like features that are interpreted as slump blocks. No other dredge sites, with the exception of site RD-52, exhibit these step-like features and this also supports the idea of a local erosional event at site RD-44. From the work of Premoli Silva and Brusa, no Paleocene erosional event is recorded throughout the Pacific.

From site RD-46, an Eocene erosional event is recorded by the incorporation of rounded volcanic fragments into sediment with Eocene planktonic foraminifera. Site RD-51, may also contain evidence of an Eocene erosional event as the reworking of highly vesicular volcanic debris. During the Eocene, erosional events occurred on the Tuamotu Ridge, and questionably in the northern Line Islands, and the Nauru Basin (Premoli Silva and Brusa, 1981).

Oligocene erosional events occur throughout the Pacific and may coincide with a major sea level drop at approximately 28 m.y.B.P. recognized by Vail et al. (1977). At site RD-47, Eocene strata were eroded and redeposited with Oligocene skeletal debris. An Oligocene erosional event also is noted in the northern Line Islands, the Nauru Basin, and at Enewetak.

At sites RD-46 and 47, a middle Miocene erosional event is recorded from the occurrence of pre-existing limestone rock fragments deposited with planktonic foraminifera of middle Miocene age. A middle Miocene event is also recorded in the Nauru Basin, and on the Tuamotu Ridge. Once again the event appears to correlate with a sea level drop at approximately 13 m.y. on the sea level curves developed by Vail et al. (1977).

A Pleistocene erosional event is recorded at site RD-48 from the occurrence of pre-existing rock fragments that were redeposited. The Nauru Basin, DSDP Site 462, and the Tuamotu Ridge, DSDP Site 318, also contain evidence of a Pleistocene erosional event.

In the southern Line Islands, several erosional events are recorded and correlate with other known erosional events in the northern Line Islands and throughout the Pacific.

Volcanic Events

The occurrence of a volcanic episode during or prior to Late Cretaceous (Campanian/Maestrichtian) time in the Caroline Island vicinity of the Southern Province of the Line Islands is documented in rocks from sites RD-44 and 45. The oldest minimum age of volcanism that can be deciphered is from phosphatized foraminiferal limestones from site RD-45. The association of planktonic foraminifera of early Campanian age, and upper-slope benthonic foraminifera with rounded volcanic fragments indicates the existence of a volcanic edifice with a minimum age of early Campanian providing an upper slope benthonic environment.

At three of the southern dredge sites, RD-45, 46, and 51, volcanic material was incorporated in middle Eocene strata. From site RD-46, volcanic rock fragments were associated with Eocene planktonic foraminifera, and from site RD-51 the volcanic sandstone also contains middle Eocene planktonic foraminifera. These rocks indicate that a volcanic event occurred at sites RD-46, and 51 during or more likely prior to middle Eocene time. The highly vesicular nature of the volcanic debris from site RD-46 may indicate shallow water volcanism.

In dredge RD-45, a minimum and maximum age of volcanism of middle Eocene was recorded. Slightly phosphatized chalks containing altered vesicular glass and planktonic foraminifera of middle Eocene age yield a minimum age of volcanism. A peperite containing middle Eocene planktonic foraminifera yields a maximum age of volcanism. On the basis of the association of the planktonic foraminifera with the volcanic debris in the phosphatized limestone, as well as in the peperite, the age of the volcanic event is assigned as middle Eocene.

From site RD-50, highly altered glass shards in a reworked and stratified hyaloclastite are associated with planktonic foraminifera of Miocene? age deposited in burrows. The volcanic material is reworked and is interpreted as either Miocene? or, most likely, older than Miocene in age.

These events correlate with results from Schlanger and Premoli Silva (1981), and Premoli Silva and Brusa (1981) from DSDP cores in the Pacific. The association of shallow-water skeletal debris and abundant volcanic material in a stratigraphic level is interpreted as indicating that volcanic activity provided the structure upon which carbonate platforms and reefs could form.

A middle Miocene? volcanic event is noted to have occurred in the Nauru Basin and on the Tuamotu Ridge. The evidence for a Miocene volcanic event is much more tentative in the southern Line Islands.

The Southern Province of the Line Islands has strong evidence for the history of recurrent volcanism with one event during or prior to the Campanian and a second event occurring in middle Eocene time. An early?-late Campanian event is also recorded in the northern Line Islands, the Mid-Pacific Mountains, and in the Nauru Basin. An early?-middle Eocene volcanic event is interpreted as occurring on the Tuamotu Ridge, and at Enewetak in the Marshall Islands. The occurrence of both Late Cretaceous and Eocene volcanism in the southern Line Islands indicates that the history of the Line Islands is similar to that of the Marshall Islands (Haggerty et al., 1982).

Phosphatization Events

Post-depositional alteration of carbonate sediments by phosphatization is noted in sedimentary rocks recovered throughout the southern Line Islands. Cretaceous rocks recovered from site RD-45, contain evidence of three different paleoenvironments: shallow-water reef, an intermediate depth of an upper slope, and a deeper water pelagic environment. All of these Cretaceous rocks have volcanic rock fragments incorporated in the sediment which were deposited on the fore-reef slope and on the upper flank of the seamount. Of these Cretaceous rocks, only the rudist coquina composed of shallow-water debris deposited in a fore-reef slope environment is not phosphatized. The phosphatization event therefore does not appear to be due to guano deposits, nor does it appear to be the result of leaching or the alteration of volcanics. Site RD-45, also recovered Eocene pelagic deposits composed of planktonic foraminifera which are phosphatized and are part of a hardground.

Due to the depositional environments associated with the phosphatized sediment, the phosphatization event(s) may be correlated with anoxic event(s) and/or oxygen minima in the geologic past. Burnett et al. (1980) have shown that Recent marine phosphorites, off the west coast of South America occur only where the dissolved oxygen content of the water is extremely low. Sheldon (1980) correlated major phosphogenic epochs (Cook and McElhinny, 1979) with sea-level maxima. Arthur and Jenkyns (1981) list several additional variables which are involved in the formation of marine phosphate deposits. Elevated sea level, such as a transgression, with associated warm climates correlate with the development of major marine phosphorites. Arthur and Jenkyns point out that world-wide oceanic anoxic events generally do not correlate with major phosphatization events, but that phosphatized limestones from seamounts and phosphatic hardgrounds in shelf-sea chalks may be formed during oceanic anoxic events.

Jarvis (1980) in his analysis of phosphatic chalk sedimentation in the Senonian of the Anglo-Paris Basin noted the presence of *Thalassinoides*, which would have required at least slightly oxic conditions. However, Jarvis also noted the presence of organic matter and reduced iron and pyrite which would have required anaerobic conditions in these phosphatic chalks. Anoxic periods may have been very short lived or intermittent. Baturin and Dubinchuk (1981) also discovered pyrite and galena in phosphorites recovered from the Mid-Pacific Mountains and the Emperor Seamounts. They attribute the formation of these sulfides to reducing conditions occurring during the shallow-water history of these seamounts. The similarity of the phosphatized pelagic deposits from site RD-45, to shelf-sea chalks also containing *Thalassinoides*, indicates that if anoxic conditions existed during the phosphatization event, the periods would have been intermittent. The other alternative, considering the governing variables presented, is that the phosphatization and the occurrence of *Thalassinoides* took place in an oxygen minimum zone.

According to Jarvis (1980), the oxygen minimum layer is usually between 100 and 500 m in the present oceans, but may expand into shallow water during periods of slowed oceanic circulation. Today at about 500 m water depth in the region of the southern Line Islands, the dissolved oxygen content drops to 2 ml/l or less and then increases at greater depths (Barkley, 1968). During the months of October through December, a tongue of 1 ml/l dissolved oxygen stretches from the eastern Pacific to the Marshall Islands, impinging upon the islands at 500 m water depth. If the phosphatized sediments from the southern Line Islands were formed in an anoxic or oxygen minimum zone, the event must have occurred during the geologic past because the rocks were recovered from well below the oxygen minimum zone of today.

Subsidence History

A merging of data presented in earlier chapters with the normal subsidence curve of oceanic crust from Parsons and Sclater (1977), the island subsidence curve from Detrick and Crough (1978), and the sea level curve from Vail et al. (1977), enables one to construct a predictive paleoenvironmental model and subsidence history for the southern Line Islands. According to Detrick and Crough, if the crustal age is older than 25 m.y. and lithospheric thinning occurs, the thermal age of the crust will reset to about 25 m.y. Their lithospheric thinning model also demonstrates that lithospheric thinning and a reset of the thermal age will not occur near a ridge crest (i.e. in crust 25 m.y. old or less), but instead will continue to have normal oceanic crust subsidence. The age and habitat depth range of recovered benthonic organisms define the observed paleoenvironments. The following underlying assumptions about benthonic organisms are used in the interpretation of the paleoenvironments and subsidence history.

Most paleoecological studies focus on species or genera that may serve as environmental indices. The majority of the Recent foraminiferal genera evolved in Late Cretaceous and early Tertiary time, and therefore their paleoecology can be extrapolated back into early Tertiary or Cretaceous time (Douglas, 1979). The paleodepth interpretations follow Sliter and Baker (1972) who combine modern faunal distributions with homeomorphic comparisons of Cretaceous and modern foraminiferal species and genera; and Saidova (1966), who compiled distributions of common modern Pacific genera according to depth and latitude.

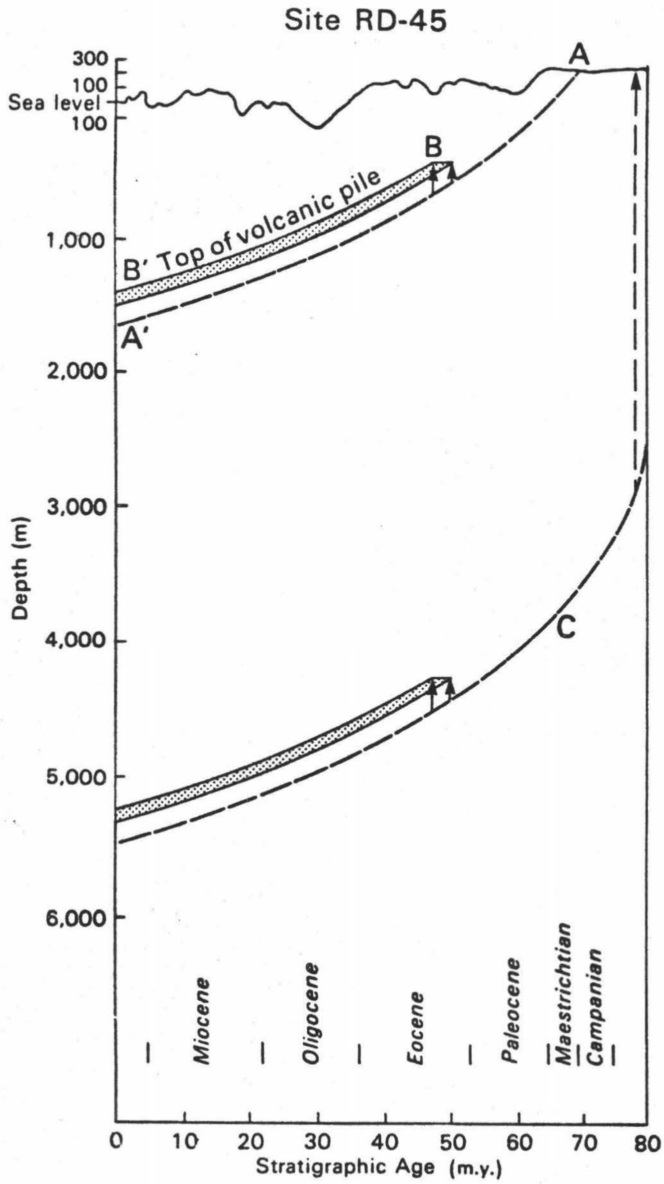
An assumption is also be made that trace fossils are evidence for the existence of a particular benthonic organism associated with a particular environment. In the interpretation section of dredge RD-45 results, the available evidence on the paleoecology of *Thalassinoides* was discussed and it was concluded that the site RD-45 deposit more closely fits with shelf-sea chalks which occur in less than 500 m water depth.

From the data and discussions in previous chapters, the following geologic history of the southern Line Islands is presented.

The crust upon which the southern Line Islands was formed is about 80 m.y. old (Watts et al., 1980). Evidence from site RD-45, demonstrates that a volcanic edifice with an upper-slope benthonic environment existed by early Campanian time (78-74 m.y.B.P.). Cretaceous rudist reefs existed in the southern Line Islands as documented at sites RD-44 and 45, and were eroded during Campanian/Maestrichtian time. The seamount at site RD-45 existed at or very near sealevel in the photic zone during the Late Cretaceous, supporting these rudist reefs. By late middle Maestrichtian time (67-68 m.y.B.P.), major erosion of the edifice was occurring as documented in site RD-45 by debris flow conglomerates with well-rounded volcanic pebbles. The edifice at site RD-45 therefore is interpreted as having subsided below sealevel by 68 m.y.B.P. (Figure 19, Point A).

The subsidence of this edifice follows that of normal subsidence of the oceanic crust because it formed near the ridge crest on very young crust. The isostatic load of the volcanic pile forming the seamount is not included. The depth to the top of the volcanic pile forming the seamount may eventually be deeper than the curve from A to A′ if the isostatic loading is included. The path from A to A′ is intended to show the shallowest possible paleoenvironments expected with normal subsidence curves. Sediment accumulation (assuming rates of 1-4 m/m.y.) is negligible in this discussion.

Figure 19. Subsidence history diagram of site RD-45. Tertiary sealevel curves (Vail et al., 1977), normal oceanic crust subsidence curve (Parsons and Sclater, 1977), and seamount uplift model from Detrick and Crough (1978) are used. No correction is made for the isostatic loading, and subsequent sedimentation.



A-A': Normal subsidence from sealevel at 68-70 m.y.
(No isostatic compensation)
B-B': Subsidence of crust after thermal reset to 25 m.y. old crust
C: Normal subsidence curve of 80 m.y. plate

There is no evidence for reefs occurring during the Paleocene in the southern Line Islands, nor, to the best of the author's knowledge, on any other seamounts in the Pacific. A shallow-water carbonate platform as a neritic-shelf environment is recorded at site RD-44. These data, and lack of data, support the idea that the seamounts were subsiding during the Paleocene in the southern Line Islands. By the end of the Paleocene, site RD-45 seamount had subsided a minimum of 590 m, but with a 100 m drop in sealevel the shallowest possible depth to the top of the seamount would be 490 m.

During middle to late Eocene time, sites RD-45 and 47 recorded the existence of Cibicides, and Lepidocyclina (Polylepidina), and miliolids of Eocene? age from site RD-46. These foraminifera indicate the existence of shallow-shelf environments during the Eocene in the southern Line Islands. By the beginning of middle Eocene time (the base of Zone P10, 49 m.y.), the shallowest depth to the top of the seamount on a normal subsidence curve adjusted for sealevel changes is 637 m. By 45 m.y. ago (into Zone P12), with the same constraints, the top of the seamount would be at 709 m water depth. Note that these values also exclude the additional subsidence from isostatic loading. These depths would not be conducive for the growth of organisms from a shallow-shelf environment.

Additional evidence from site RD-45, also points to the existence of shallower paleoenvironments than expected from the normal subsidence curve (A to A') during or after middle Eocene time. A specimen of Planulina was found on the exterior of the Middle Eocene peperite, this benthonic foraminifer inhabits middle to outer shelf environments. The occurrence of Thalassinoides and the phosphatic foraminiferal limestone hardgrounds also testify to the existence of paleoenvironments shallower than 500 m water depth. The small sealevel drop during the Eocene, or the major sealevel drop during the Oligocene are insufficient to create these shallow water environments along the normal subsidence curve.

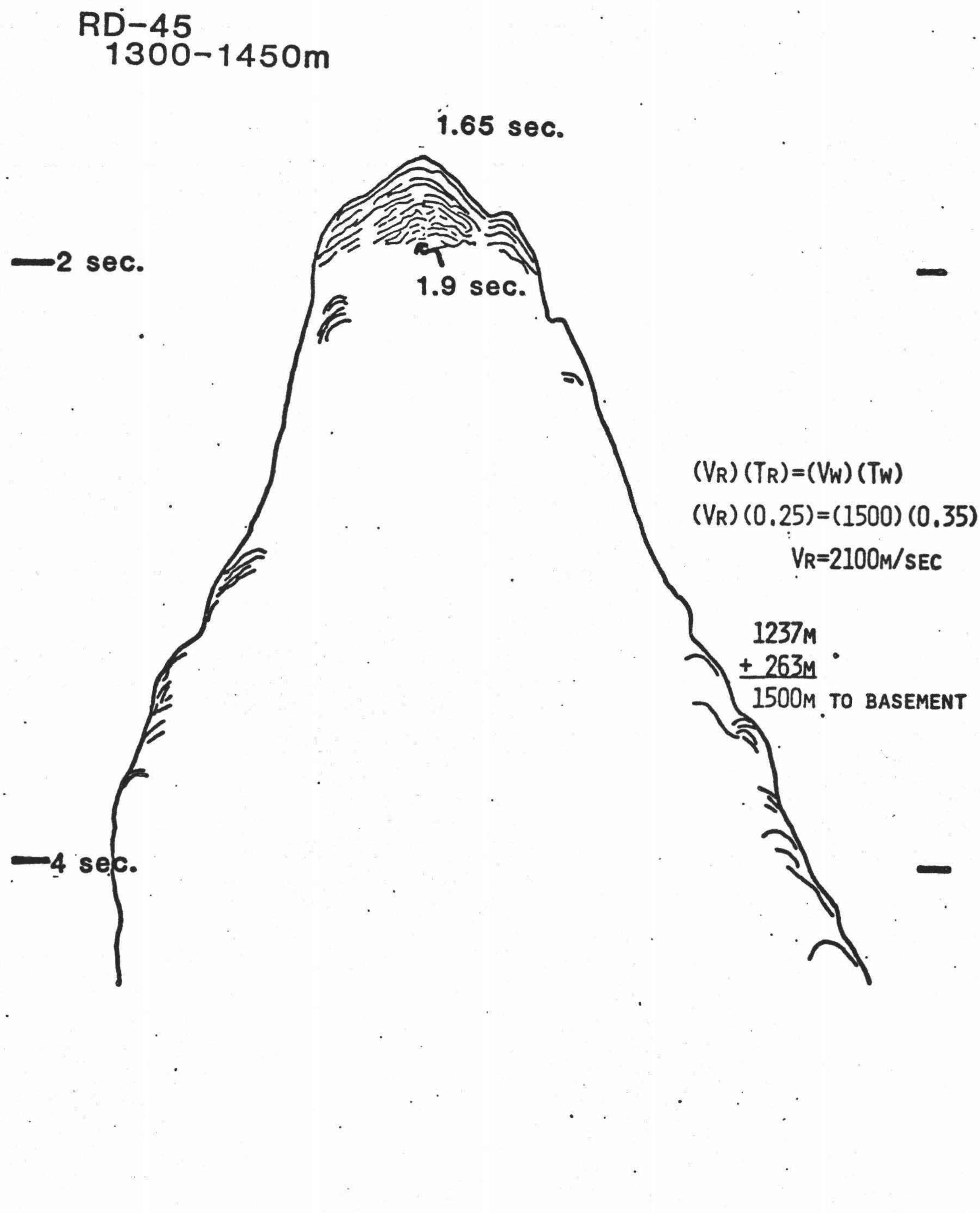
From the observed paleoenvironments and documentation of a volcanic event during middle Eocene time at site RD-45, tectonic uplift and possibly lithospheric thinning occurred in middle Eocene time. With the thermal reset to a 25 m.y. old crust, a minimum of 199 m to 321 m of uplift would have occurred at 49 to 45 m.y. ago, respectively (Figure 19, Point B). This uplift places the edifice to within 438 m of sealevel at 49 m.y. ago or 388 m of sealevel at 45 m.y. ago, and does not account for the addition of volcanic material which may place the top of the seamount at an even shallower depth.

After this uplift event, reefs again flourished in the southern Line Islands and growth was perhaps continuous throughout the remainder of the Tertiary to the present. From the stable isotope geochemistry of the carbonate cements developed in these Tertiary reef limestones, no evidence for subaerial exposure of these limestones is noted. This is in agreement with the subsidence curve from B to B′.

From an interpretation of a line drawing (Figure 20) of the seismic reflection record from site RD-45, 263 m of sediment are observed as having accumulated on the seamount. This places the depth to the volcanic basement on the seamount at 1500 m, or in other words, that a minimum of 1500 m of subsidence has occurred on this seamount. Calculated present depth to the top of the volcanic pile, including sea level changes, and using the subsidence curves with a 25 m.y. thermal reset at 49 m.y. ago and 45 m.y. ago, are 1478 m and 1363 m, respectively. These values would be to the top of the Cretaceous volcanic pile and do not include isostatic loading which would cause additional subsidence. Taking this into consideration, the calculated and observed depths to the top of the Cretaceous volcanic pile are in agreement.

The southern Line Islands therefore had uplift and possible lithospheric thinning during the middle Eocene, and subsidence after middle Eocene time.

Figure 20. Line drawing of seismic reflection profile of site RD-45. Calculation to depth of volcanic pile, or subsidence is shown.


RD-45
1300-1450m
1.65 sec.
2 sec.
1.9 sec.
(VR)(TR)=(VW)(TW)
(VR)(0.25)=(1500)(0.35)
VR=2100M/SEC
1237M
+ 263M
1500M TO BASEMENT
4 sec.

REGIONAL IMPLICATIONS

The evidence for the existence and erosion of volcanic edifices during the Late Cretaceous in the southern Line Islands, in conjunction with DSDP data from the northern and central Line Islands, indicates that synchronous Cretaceous volcanism followed by Late Cretaceous reef development occurred over a distance of 2500 km from Kingman Reef to Caroline Island in the Line Islands (Figure 21). If the Line Islands were equivalent to the Emperor Seamount chain as postulated by Morgan (1972), the chain should show an age difference of at least 27 m.y. along the length. The 27 m.y. is derived from the difference between 43 m.y., the age of the Hawaiian-Emperor elbow, and 70 m.y., the age of Meiji Seamount, the oldest in the Emperor chain (Creager et al., 1973). The lack of an apparent age progression in the Late Cretaceous volcanism along the Line Island chain demonstrates that a single, simple hotspot model is an unlikely explanation for the origin of the Line Islands chain. Further, the minimum age of early Campanian (about 74-78 m.y.) for the southern Line Islands is older than the oldest Emperor Seamount, Meiji. This age relationship contradicts the Morgan (1972) argument that the Emperor Chain is the temporal equivalent of the Line Islands chain. The recurrence of volcanism in the Southern Province of the Line Islands during Eocene time also argues against a single hotspot being responsible for the formation of the Line Islands.

Figure 21. Location and extent of reefs of Late Cretaceous age along the Line Islands.

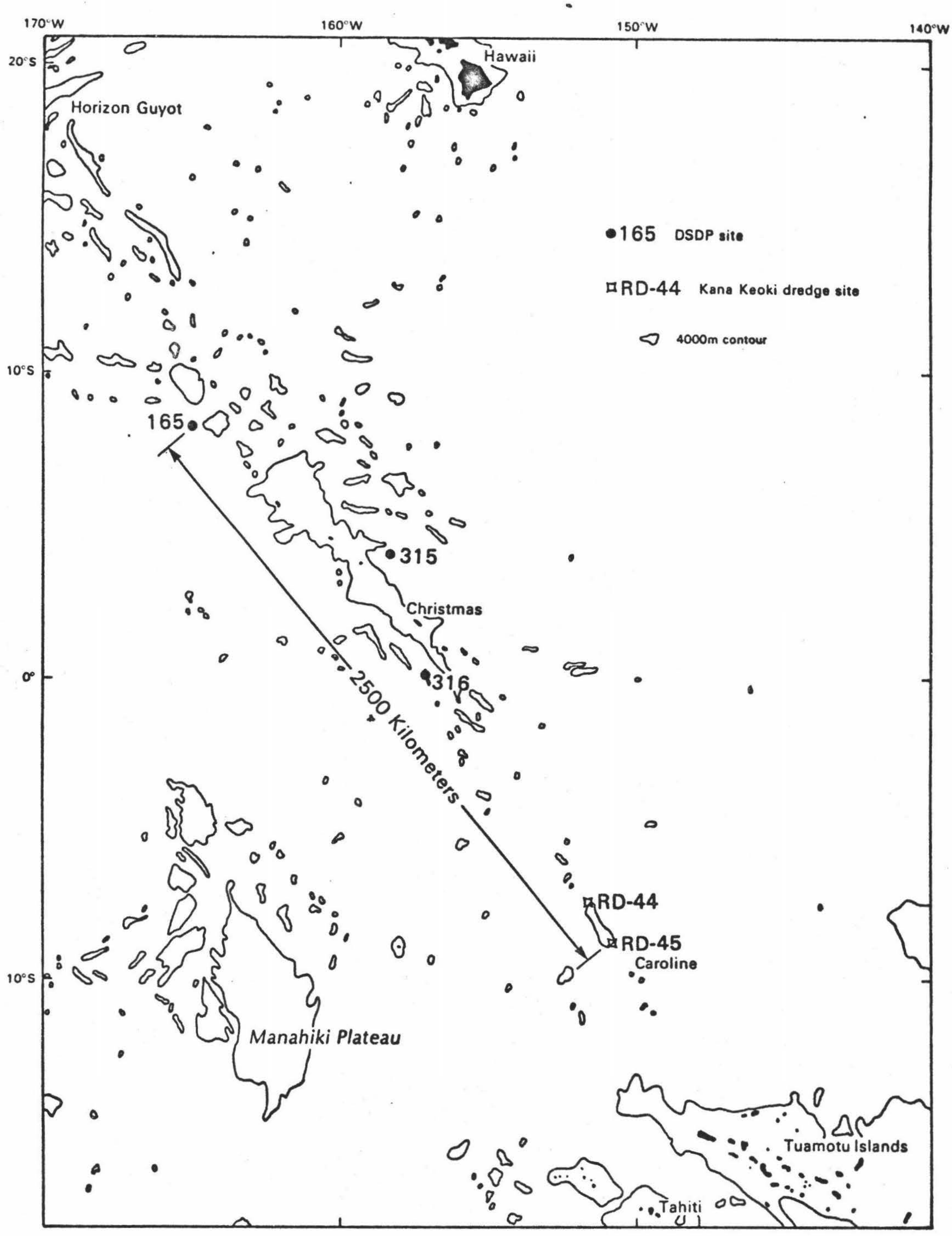

170°W
160°W
150°W
140°W
20°S
10°S
0°
10°S
Hawaii
Horizon Guyot
●165 DSDP site
⌑RD-44 Kana Keoki dredge site
4000m contour
165
315
Christmas
316
2500 Kilometers
RD-44
RD-45
Caroline
Manahiki Plateau
Tuamotu Islands
Tahiti

Plate boundary volcanism either associated with a transform fault or a ridge crest has been called upon by several authors to explain the origin of the chain. The data derived from this study does not prove or disprove these theories. The idea of a leaky transform fault as the origin of the Line Islands is not especially appealing to the author. The length of the Line Islands, 4200 km, or more, is exceptionally long for a transform fault, and requiring simultaneous leakage over 2500 km is improbable.

The idea that the Line Islands are associated with or are an abandoned ridge appears to be more likely. If the underlying structure of the Line Islands was a fossil ridge, which was unstably developed and quickly abandoned, it is unlikely that magnetic stripes would be well-developed. Free-air gravity anomaly data supports the idea that the Line Islands formed very near a ridge crest, as had been suggested by Watts et al. (1980). The observed ages of the Cretaceous seamounts in the southern Line Islands, are close to the plate age suggested by Watts et al.

Tamaki et al. (1979) identified what are believed to be remnants of an unstable spreading system, called the Magellan spreading system, that may have been developed to buffer the change in movements of the Phoenix, Farallon, and Pacific plates.The Line Islands may be associated with this ancient spreading center, but the lack of magnetic data does not permit a clear association.

New data from the Mathematicians Seamounts (Vanko and Batiza, 1982; Watkins et al., 1982) have been interpreted as evidence of alkalic lavas erupted along a fossil ridge which may have been reactivated due to intraplate stresses. The recurrence of volcanism as alkalic basalts during the middle Eocene in the Line Islands also may be due to intraplate stresses as the plate motion began to change direction before its last orientation 43 m.y. ago.

The Line Islands chain appears to have had a history similar to that of the central Marshall Islands. In the Marshall Islands, Enewetak Atoll is known to have developed on a middle to early Eocene volcanic edifice (Ladd et al.,1953; Cole, 1957; Kulp, 1963), and Cretaceous sill and edifice-bulding volcanism in Cretaceous time has affected the Nauru Basin (Larson et al., 1981) and surroundings areas (Figure 22). Von Valtier Seamount which lies in the Marshall-Gilbert-Tuvalu chain, 30 miles NE of Arno Atoll, is an edifice with a minimum age, based on fossils, of middle to Late Cretaceous (Schlanger et al., 1981a).

The presence of Cretaceous edifices in the Southern Province of the Line Islands significantly enlarges the known geographical area over which Cretaceous seamounts and guyots are distributed on the Pacific plate (Figure 23).

A number of authors have summarized data that indicate the widespread nature of mid-plate volcanism on the Pacific Plate within the time envelope of 115-70 m.y. (Schlanger and Premoli Silva, 1981; Schlanger et al., 1981b; Rea and Thiede, 1981), a volcanic history

Figure 22. Map of the western Pacific showing the extent and type of Cretaceous volcanism. Modified from Schlanger et al., 1981b.

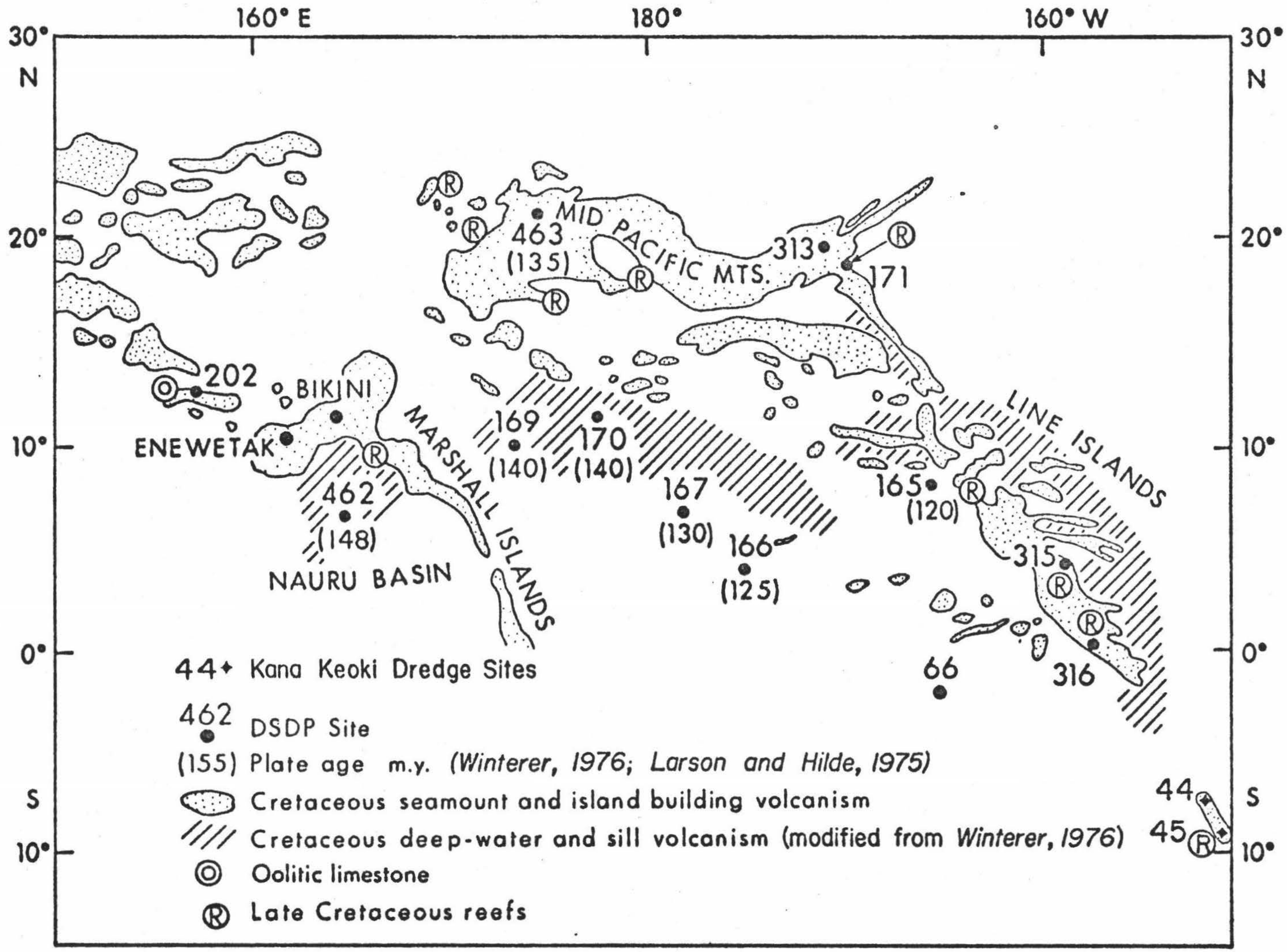
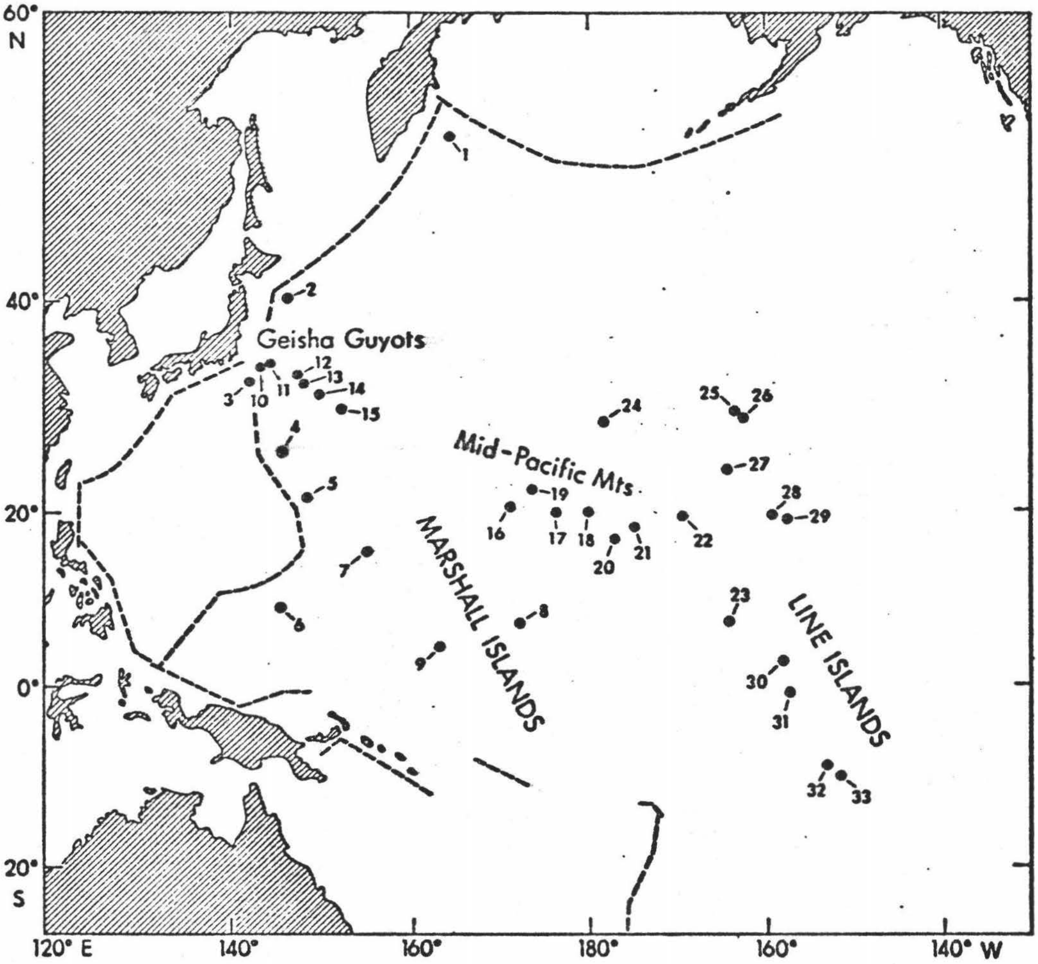

160° E
180°
160° W
30° N
20°
10°
0°
S
10°
MID PACIFIC MTS.
463
(135)
313
171
202
BIKINI
ENEWETAK
MARSHALL ISLANDS
462
(148)
NAURU BASIN
169
(140)
170
(140)
167
(130)
166
(125)
LINE ISLANDS
165
(120)
315
316
66
44
45
44+ Kana Keoki Dredge Sites
462 DSDP Site
(155) Plate age m.y. (Winterer, 1976; Larson and Hilde, 1975)
Cretaceous seamount and island building volcanism
Cretaceous deep-water and sill volcanism (modified from Winterer, 1976)
Oolitic limestone
Late Cretaceous reefs

Figure 23. Map showing locations of seamounts and guyots of Cretaceous age on the Pacific Plate. 1. Meiji Seamount (Creager et al., 1973); 2. Erimo Seamount (Tsuchi and Kagami, 1967); 3. Daiichi-Kashima Seamount (Daiichi-Kashima Research Group, 1976); 4. Yabe Guyot (Shiba, 1979); 5. Syunsetsu Seamount (Konishi, 1973); 6. Seamount 853, 7. Ita Maitai Guyot (Haggerty et al., 1982); 8. von Valtier Seamount (Schlanger et al., 1981b); 9. Nauru Basin (Larson et al., 1981); 10. Seiko Seamount. 11. Eiko Seamount. 12. Winterer Guyot, 13. Thomas Washington Guyot, 14. Isakov Guyot, 15. Makarov Guyot, 16. Menard Guyot, 17. Jacqueline Guyot, 18. Shepard Guyot (Heezen et al., 1973); 19. Darwin Guyot (Ladd et al., 1974); 20. Cape Johnson Guyot, 21. Hess Guyot (Hamilton, 1956); 22. Horizon Guyot, 23. DSDP Site 165 (Winterer et al., 1973); 24. Wentworth Seamount, 25. Rachmaninoff Seamount, 26. Khachaturian Seamount, 27. Necker Island (Clague and Dalrymple, 1975); 28. Seamount 9, 29. Seamount 7 (Dymond and Windom, 1968); 30. DSDP Site 315, 31. DSDP Site 316 (Schlanger et al., 1976); 32. RD-44, 33. RD-45 (Haggerty et al., 1982).



60° N
40°
20°
0°
20° S
120° E
140°
160°
180°
160°
140° W
Geisha Guyots
Mid-Pacific Mts.
MARSHALL ISLANDS
LINE ISLANDS
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
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18
19
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32
33

similar to that proposed by Menard (1964) for the Darwin Rise. A relatively new development has been the realization that areas have undergone multiple episodes of recurrent volcanism. If the Nauru Basin-Enewetak area is considered as a single unit, there are three distinct volcanic episodes of middle to Late Cretaceous age and one of early Eocene age. In the southern Line Islands, two events of volcanism are documented. This widespread distribution of mid-plate volcanism and its recurrent aspect makes it difficult to reconcile this volcanic activity with a hotspot model. Further, this intense Cretaceous volcanic activity is not restricted to the Pacific Plate. Cretaceous volcanic activity is recorded from remnants of the Farallon Plate (Schlanger et al., 1981b) such as the present Caribbean basin and the Nicoya Complex, an allochthonous terrane along the west coast of Central America (Schmidt-Effing, 1979). Kumar (1979) documented Cretaceous volcanism in the Ceara, Sierra Leone, and the Rio Grande Rises and the Walvis Ridge from 100-80 m.y. Kelts and Arthur (1981) in a review of volcanogenic turbidites from the DSDP sites, point to evidence of Late Cretaceous volcanism in the Caribbean, on Nashville and Vogel seamounts in the Atlantic, on the Naturaliste Plateau, and at several sites in the Indian Ocean. The construction of large plateaus and rises in the Pacific Basin such as the Ontong Java, Magellan, Manihiki, Hess, and Shatsky was largely determined by Cretaceous volcanism, although these may be related to ridge crest rather than strictly mid-plate volcanism.

The complex origin of the Line Islands can not be resolved with the data derived in this study. However, the Late Cretaceous volcanic event in the Line Islands does coincide with the Cretaceous mid-plate volcanic events in other areas of the Pacific. Further, the Line Islands appear to be an eastern boundary for this volcanism as well as a major division between the seamount provinces to the west and the lack of high bathymetric features to the east in the Pacific. This association with the intense period of volcanism and this division between geomorphic expressions on the seafloor, may indicate that the Line Islands are a remnant of an old plate boundary.

PLATE I

PHOTOMICROGRAPHS OF ROCKS FROM SITE RD-44

A. Sample KK79-44-01. Manganese-coated phosphatized volcanic conglomerate from RD-44. Subrounded, poorly-sorted volcanic and sedimentary pebbles floating in a phosphatized, Paleocene foraminiferal micritic matrix. Note infiltration of manganese and infill of middle Eocene foraminiferal limestone. Transmitted light. Bar scale equals 5 mm.

B. Sample KK79-44-01. Bioclast interpreted as a rudist fragment in manganese rind of sample described above. Microstructure composed of infilled chambers and/or canals. Transmitted light. Bar scale equals 1 mm.

C. Sample KK79-44-02. Volcanic breccia with zeolitic rims infilled with phosphatized micritic matrix. Note molds of globotruncanid and rugoglobigerinid. Transmitted light. Bar scale equals 0.5 mm.

D. Sample KK79-44-03. Volcanic breccia with zeolitic rims, sparsely infilled with a phosphatized micritic matrix. Transmitted light. Bar scale equals 2 mm.

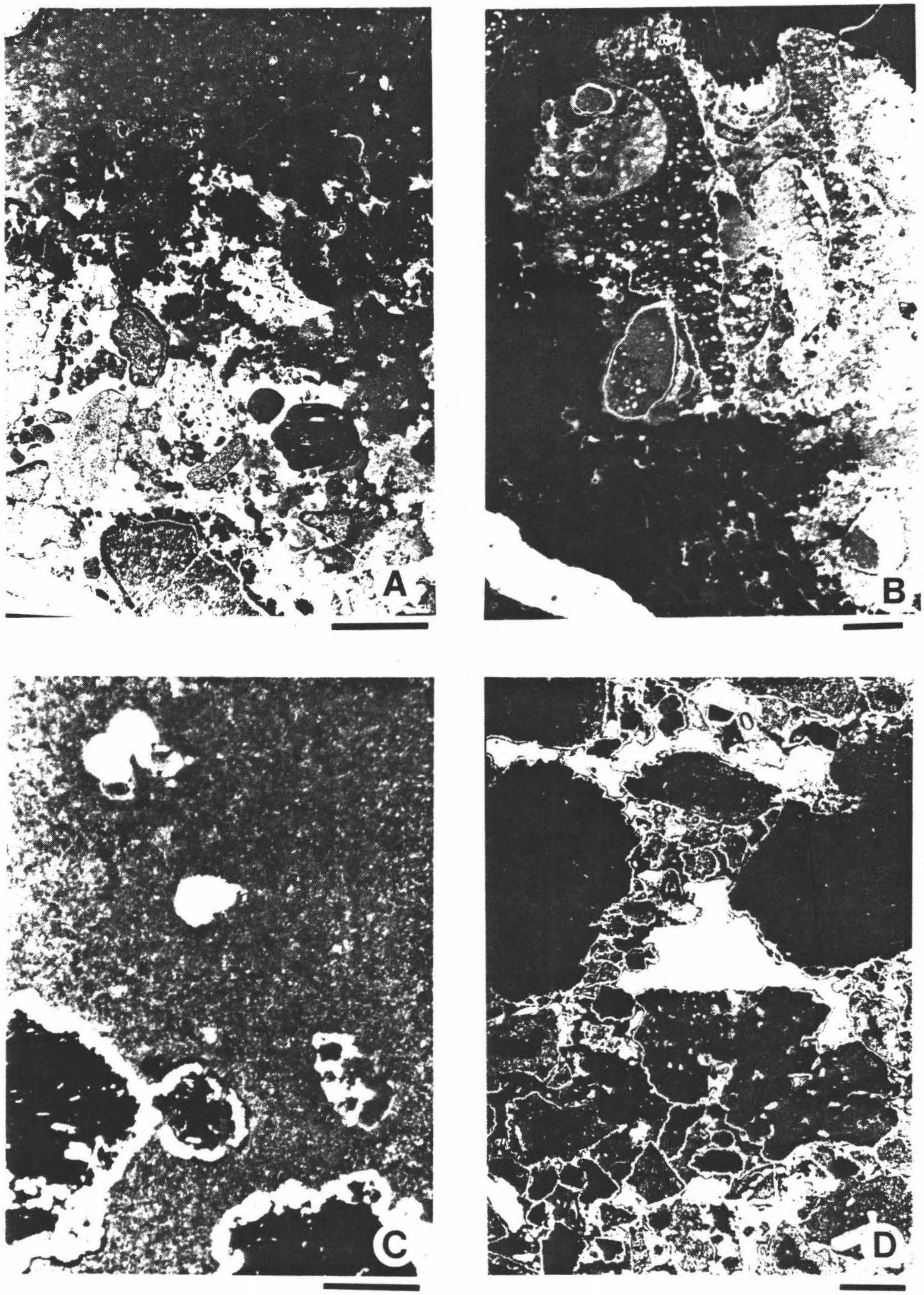

A
B
C
D

PLATE II

PHOTOMICROGRAPHS OF CRETACEOUS ROCKS FROM SITE RD-45

A. Sample KK79-45-24. Slightly phosphatized limestone containing volcanic fragments among planktonic and benthonic foraminifera of late Campanian age in contact with a palagonitized volcanic rock. Plane-polarized light. Bar scale equals 0.5 mm.

B. Sample KK79-45-06. Stensioina, an upper-slope benthonic foraminifera, that became extinct at the end of the Cretaceous. Plane-polarized light. Bar scale equals 0.5 mm.

C. Sample KK79-45-06. Spiroplectammina, an upper-slope benthonic foraminifer associated with volcanic fragments in sediment of Campanian age. Plane-polarized light. Bar scale equals 0.5 mm.

D. Sample KK79-45-13. Rounded volcanic pebbles, some with manganese rims, deposited with phosphatized foraminiferal limestone (G. contusa Zone, late middle Maestrichtian) in a debris flow conglomerate. Transmitted light. Bar scale equals 1 mm.

E. Sample KK79-45-02. Molds of Cretaceous planktonic foraminifera in a matrix of porous, fine-grained aggretates of apatite crystals. Note detail in center mold from the ornamentation of a heterohelicid test. SEM photo. Bar scale equals 0.1 mm.

PLATE VI

LOW-MAGNESIUM LIMESTONES FROM SITE RD-46 AND SITE RD-47

A. Sample KK79-46-03. Miocene limestone breccia, very dense. Contains clasts of recrystallized corals and other shallow-water debris deposited in a deep fore-reef slope environment. Diameter of coin equals 17 mm.

B. Sample KK79-47-08. Miocene foraminiferal microbreccia. Note molds of corals and flowstone-like deposits on exterior of rock. Diameter of coin equals 17 mm.

C. Sample KK79-47-08. Interior of rock in Figure B. Note large mold from coral in upper left of photo. Diameter of coin equals 17 mm.

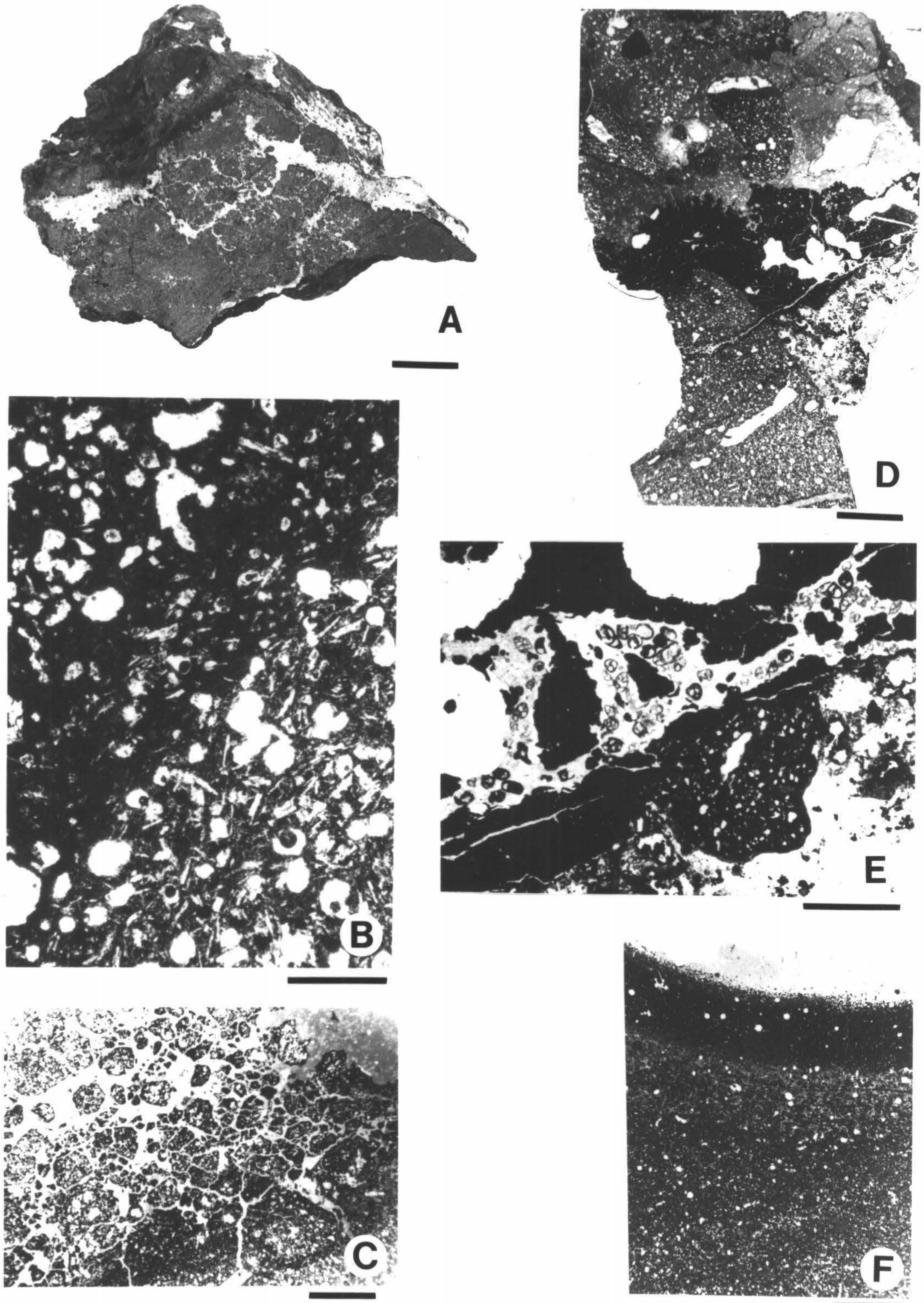

A
B
C
D
E
F

PLATE V

VOLCANIC ROCKS ASSOCIATED WITH EOCENE SEDIMENT FROM SITES RD-45 AND RD-46

A. Sample KK79-45-26. Peperite composed of alkalic basalt with anastomosing fractures filled with phosphatized foraminiferal limestone. Bar scale equals 20 mm.

B. Sample KK79-45-26. Opague, basaltic glass (tachylite) progressively becomes more crystalline to the lower right of the photo, trending away from the sediment in the peperite. Plane-polarized light. Bar scale equals 0.5 mm.

C. Sample KK79-45-26. Fragments of tachylite form a disjointed rim that has brecciated in place upon intrusion into the sediment. Compare with the pillow basalt in Figure F. Transmitted light. Bar scale equals 5 mm.

D. Sample KK79-46-17. Phosphatized foraminiferal limestone containing volcanic fragments. Transmitted light. Bar scale equals 5 mm.

E. Sample KK79-46-17. Close up of Figure D; miliolids concentrated in the fracture near the manganese rim coating the volcanic pebble. Plane-polarized light. Bar scale equals 0.5 mm.

F. Pillow basalt rim; grades from sideromelane, on the exterior, to tachylite to crystalline basalt. The presence of sideromelane is evidence of rapid quenching in water. Sample from the Galapagos spreading ridge at 2440 m water depth recovered by R/V Kana Keoki cruise KK78-12.

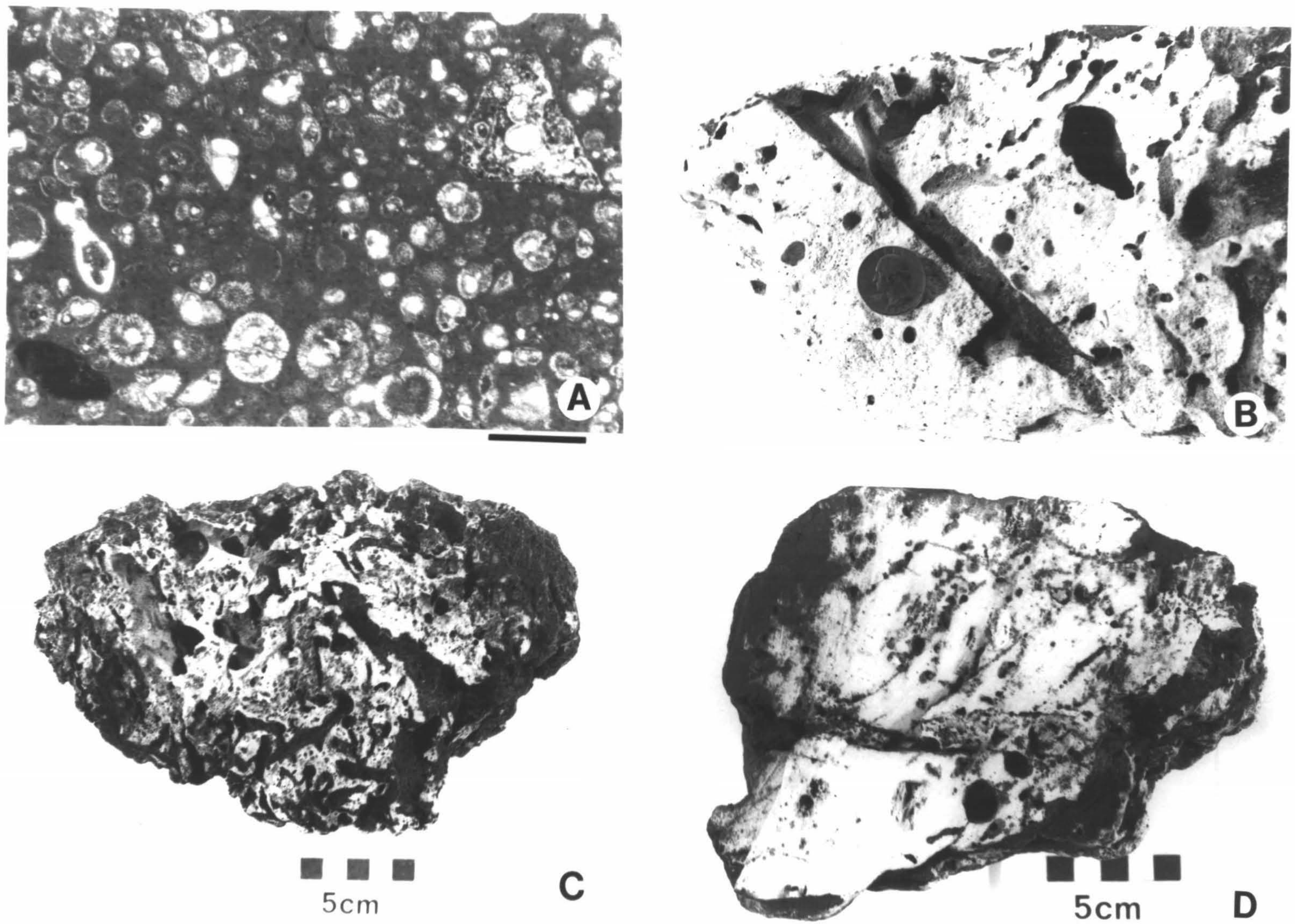

A
B
5cm
C
5cm
D

PLATE IV

PHOSPHATIZED AND BURROWED FORAMINIFERAL LIMESTONES FROM SITE RD-45

A. Sample KK79-45-10. Planktonic foraminifera of middle Eocene age associated with altered vesicular glass in a phosphatized micritic matrix. Photomicrograph of rock in Figure B. Plane-plarized light. Bar scale equals 0.5 mm.

B. Sample KK79-45-10. Trace fossil Thalassinoides appearing as long shafts or tunnels with Y-shaped branching patterns. These burrows are interpreted as being formed during early lithification of a hardground. Diameter of coin equale 25 mm.

C. Sample KK79-45-28. Trace fossil Thalassinoides appearing as an irregular network of contorted shafts and tunnels. These burrows are interpreted as being formed during a later stage of lithification of a hardground than those in Figure B. Bar scale equals 5 cm.

D. Sample KK79-45-01. Burrowed and fractured foraminiferal limestone with manganese rim. Bar scale equals 5 cm.

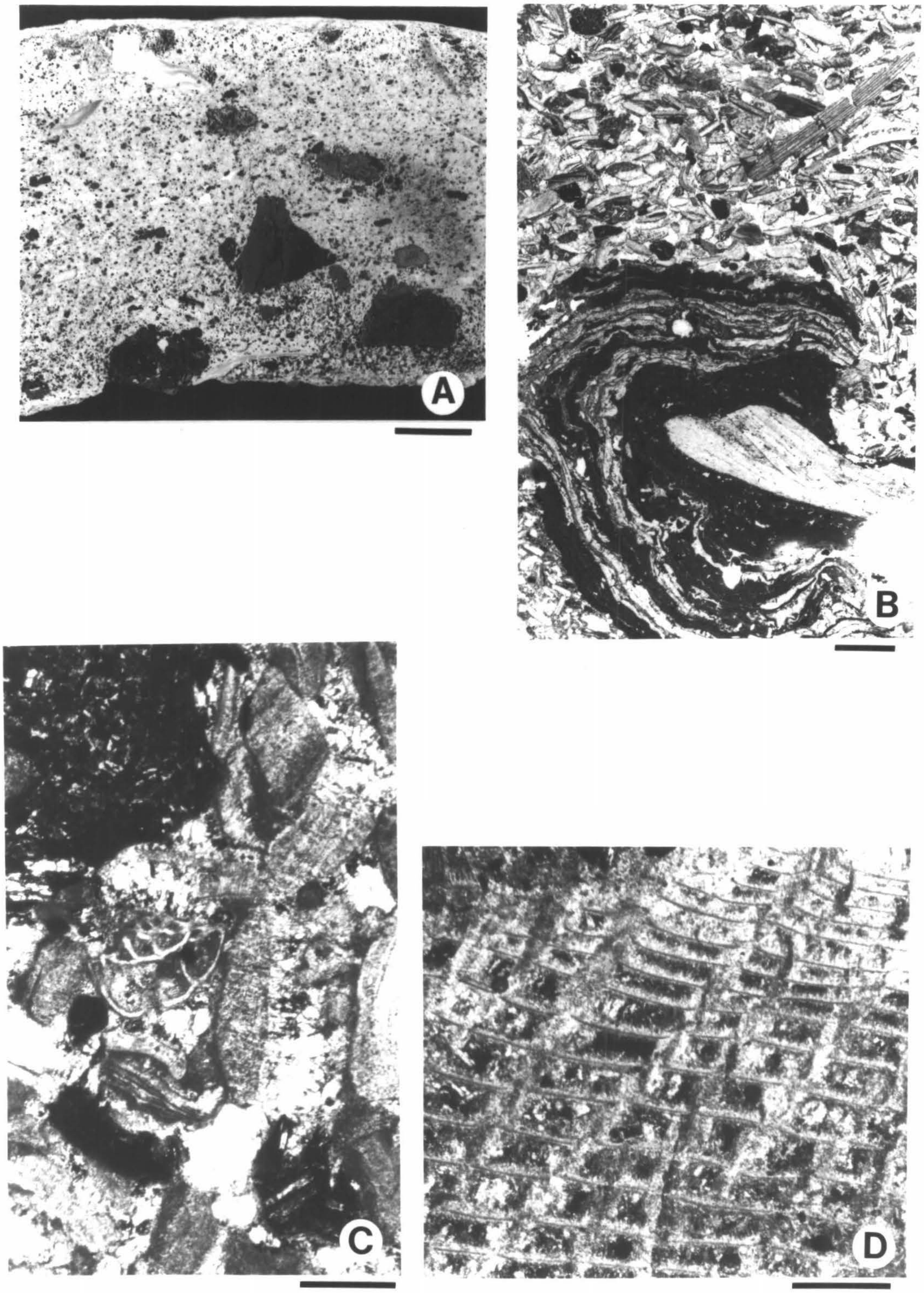

A
B
C
D

PLATE III

CRETACEOUS COQUINA FROM SITE RD-45

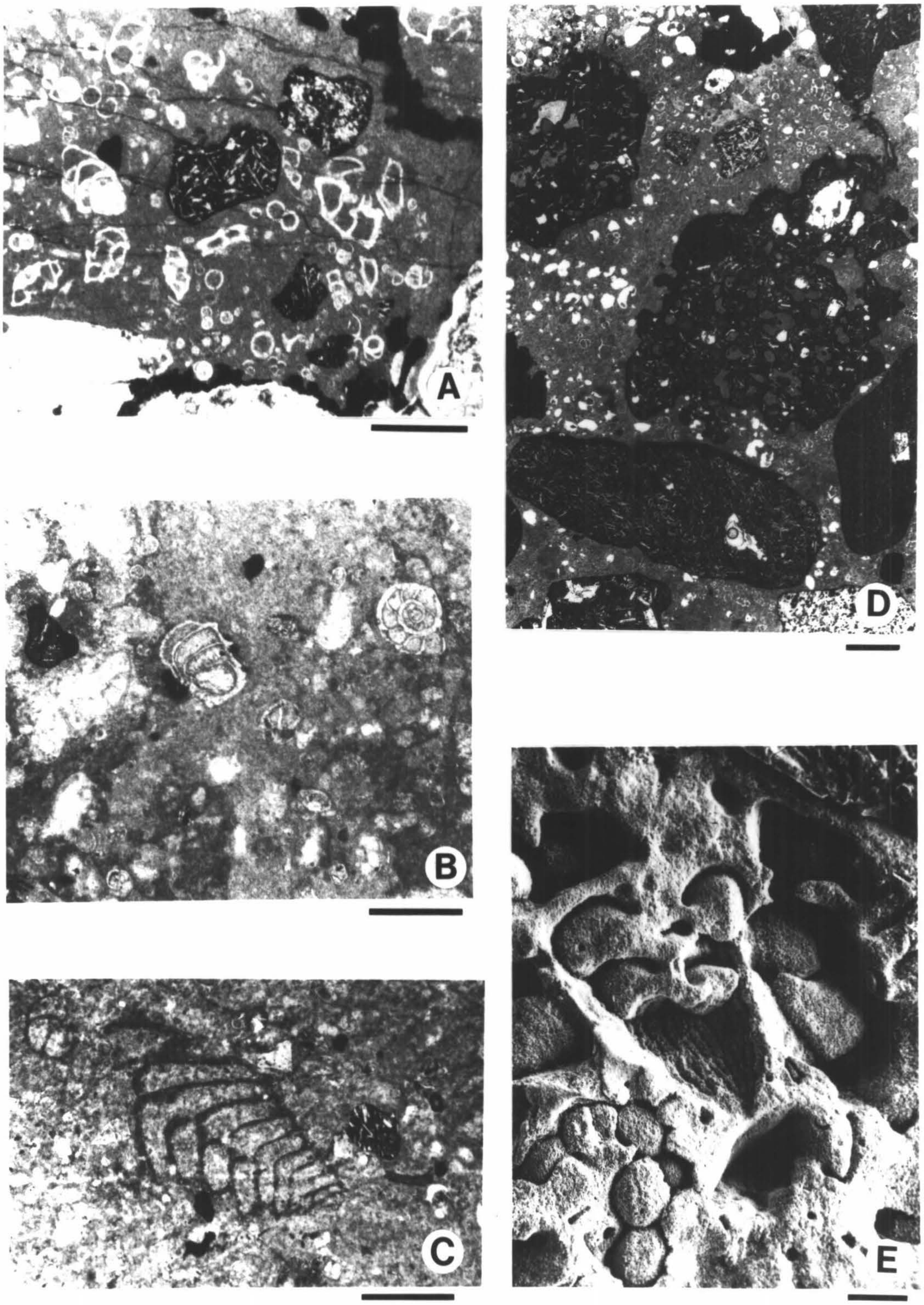
Sample KK79-45-08.

A. Coquina containing abundant shell debris and large volcanic cobbles. Bar scale equals 15 mm.

B. Well-sorted and abraded molluscan debris. Note algal ball incorporating a mollusk fragment. Transmitted light. Bar scale equals 2 mm.

C. Globotruncanid of Campanian/Maestrichtrian age among shell debris and volcanic fragments. The presence of planktonic foraminifera mixed with shallow-water skeletal debris suggests deposition in a fore-reef slope environment. Plane-polarized light. Bar scale equals 0.5 mm.

D. Fragment of a rudist of the Family Radiolitidae. The presence of these mollusks indicate that Cretaceous reefs or banks existed at site RD-45. Under crossed nicols. Bar scale equals 0.5 mm.


A
B
C
D
E

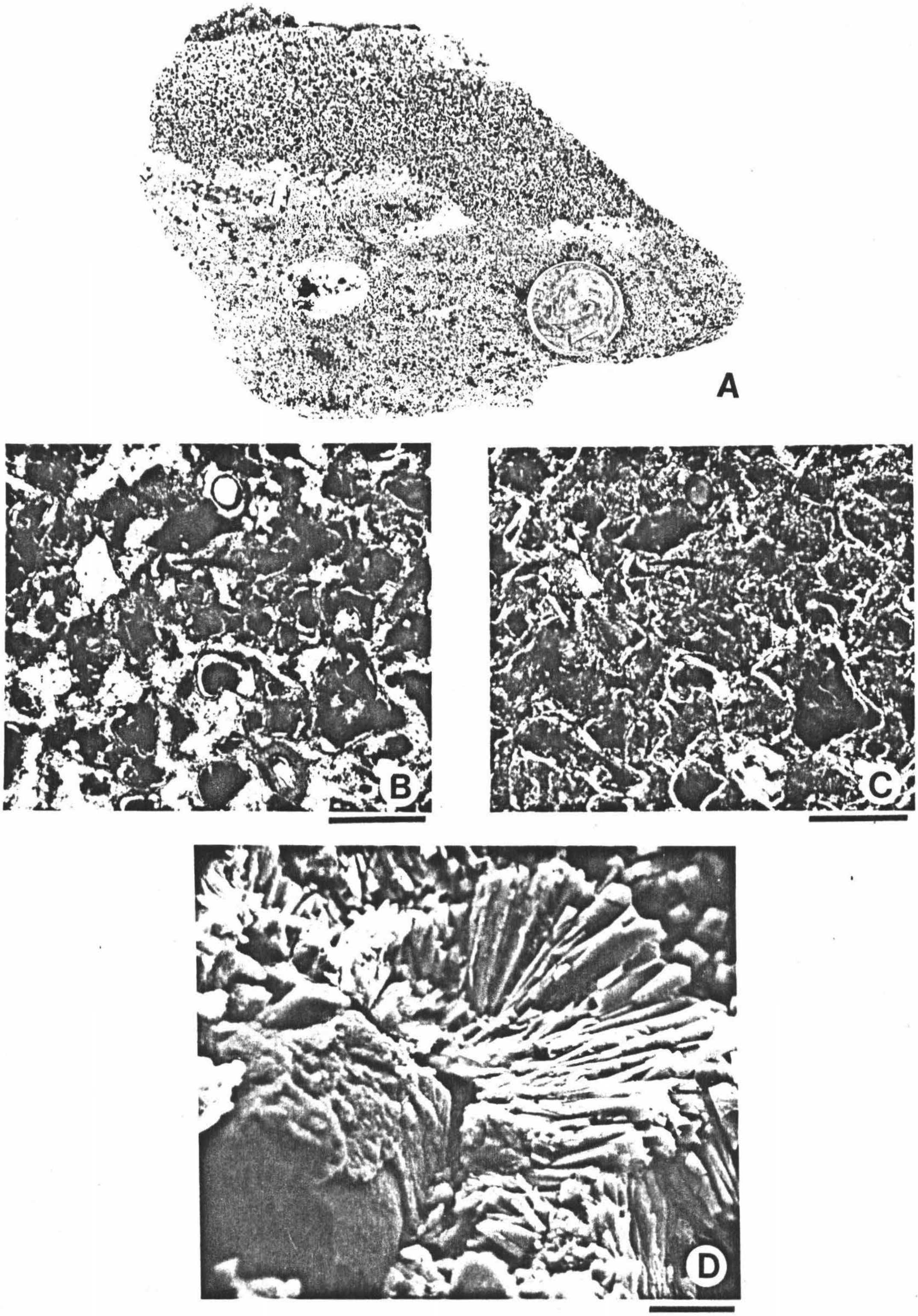

A
B
C
D

PLATE XII

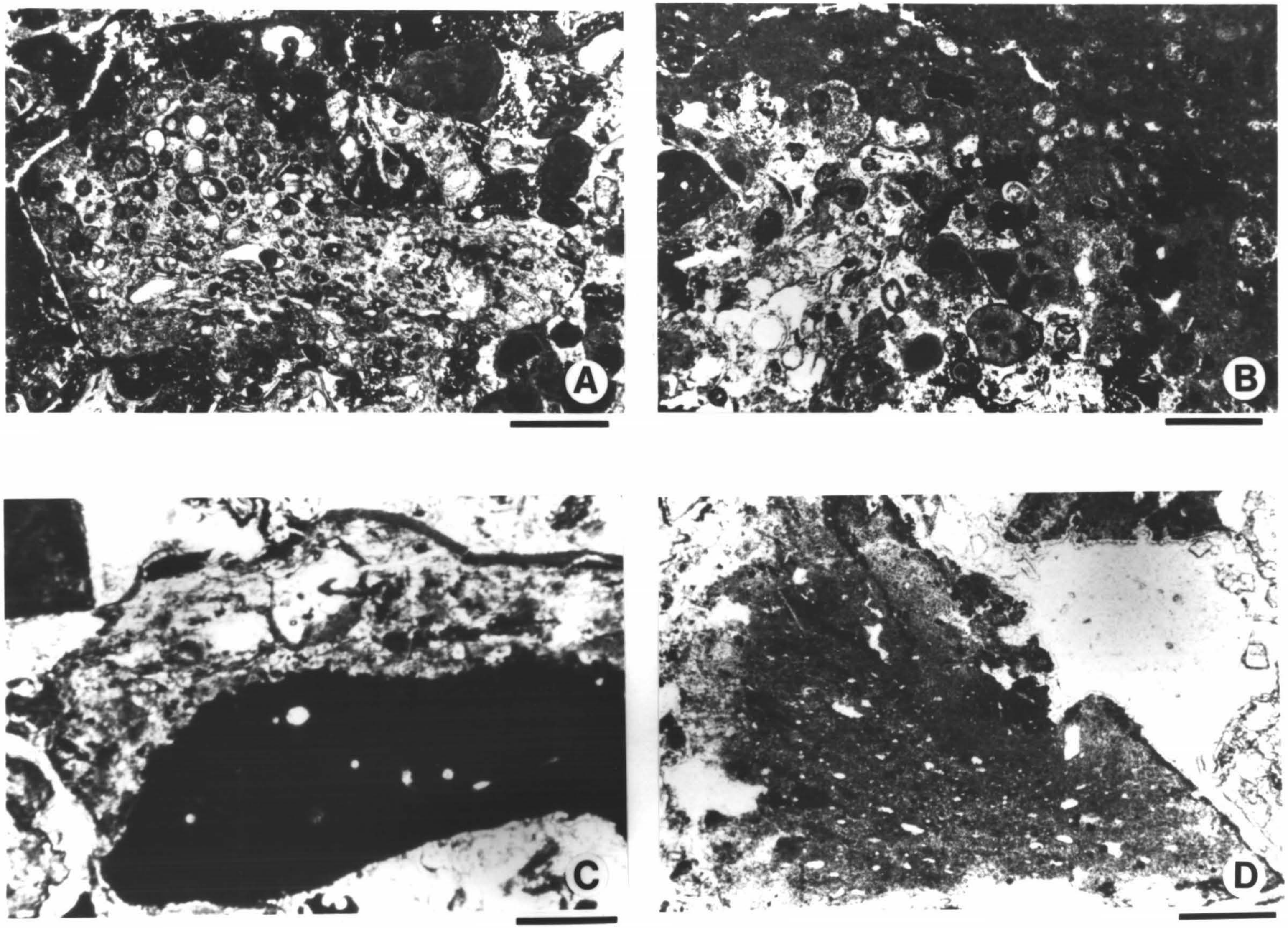
PHOTOMICROGRAPHS OF VOLCANIC SANDSTONES FROM SITE RD-51 AND SITE RD-52

A. Sample KK79-51-01. Highly-altered vesicular glass fragments deposited with Eocene planktonic foraminifera. Plane-polarized light. Bar scale equals 0.5 mm.

B. Sample KK79-51-01. Phosphatized foraminiferal and radiolarian sediment on the right side of the photo overlay the volcanic sandstone on the left. Plane-polarized light. Bar scale equals 0.5 mm.

C. Sample KK79-52-01. Probable pillow basalt rim composed of palagonite and tachylite. Compare with fresh Galapagos pillow rim in Plate V, Figure F. Plane-polarized light. Bar scale equals 0.5 mm.

D. Sample KK79-52-01. Highly-altered aphyric vesicular basalt displaying flow texture. Plane-polarized light. Bar scale equals 0.5 mm.


A
B
C
D

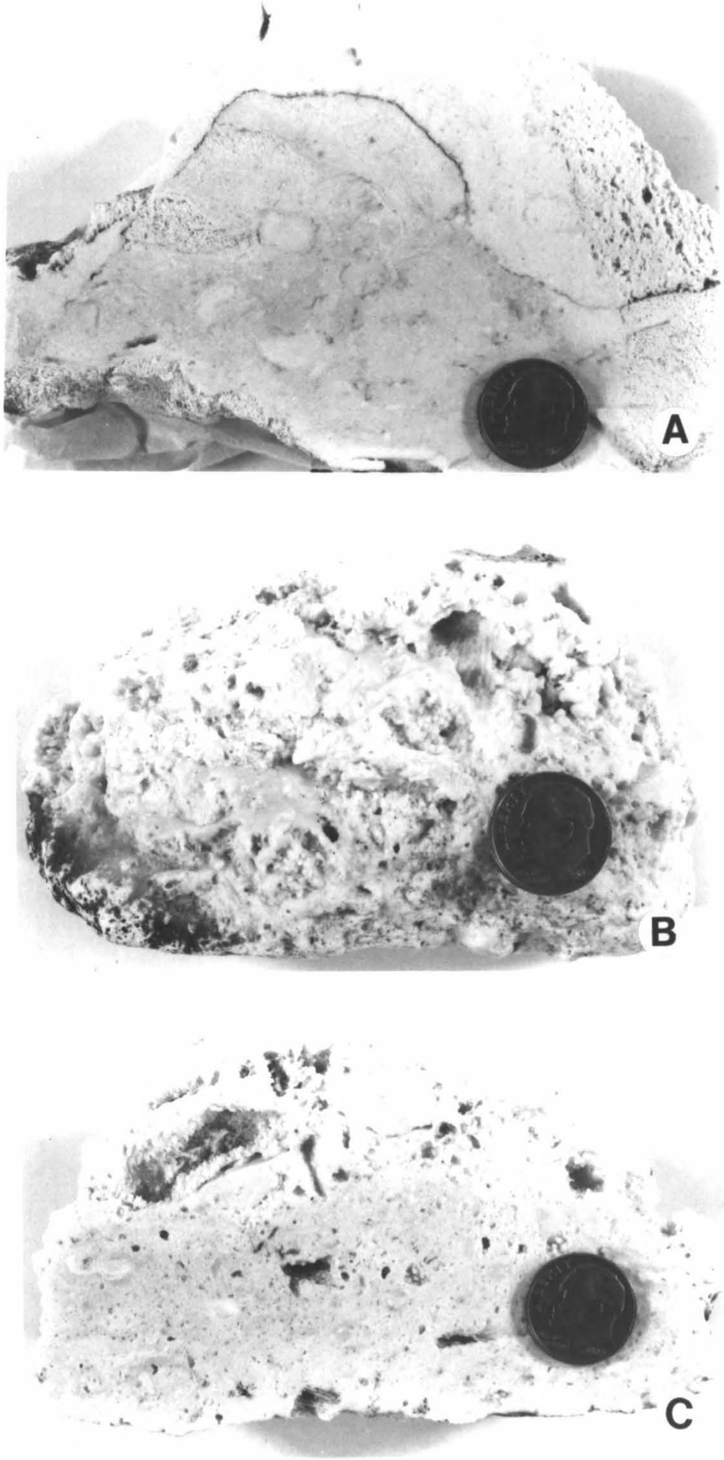

A
B
C

PLATE VII

ARAGONITE DISSOLUTION FEATURES IN ROCKS FROM SITE RD-47

A. Sample KK79-47-10. Fore-reef slope deposit exhibiting abundant molds from corals. Bar scale equals 5 cm.

B. Sample KK79-47-10. Close up of Figure A. Note detail in mold of coral calices, probably from Porites. Diameter of coin equals 17 mm.

c. Sample KK79-47-05. Fore-reef slope deposit exhibiting relatively flat surface with holes as molds from corals. Bar scale equals 5 cm.

D. Sample KK79-47-05. Close up of Figure C. Patchy, thin coatings of manganese, molds of corals and gastropod are present. Diameter of coin equals 17 mm.

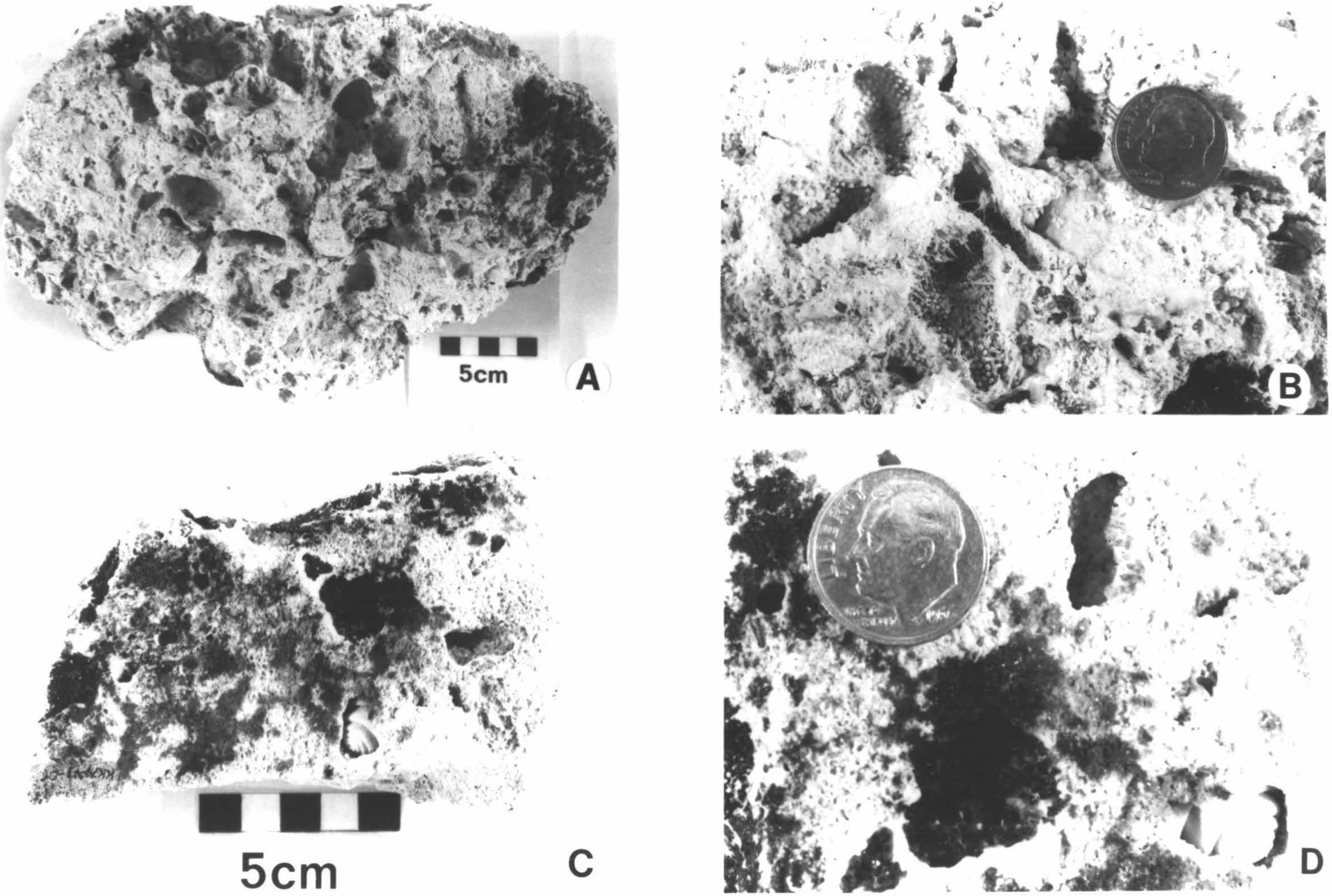

5cm
A
B
5cm
C
D

PLATE VIII

PHOTOMICROGRAPHS OF ROCKS FROM SITE RD-46 AND SITE RD-47

A. Sample KK79-46-03. Miocene paracoquinite composed of shallow-water debris; reversed coral on the right side of photo. Note echinoid spine with syntaxial overgrowth, and abundant micritic envelopes from which sand-size grains have been dissolved. Transmitted light. Bar scale equals 2 mm.

B. Sample KK79-46-03. Pebble of Miocene foraminiferal microbreccia. These pebbles are scattered throughout the paracoquinite in Figure A. Plane-polarized light. Bar scale equals 0.5 mm.

C. Sample KK79-47-11. Oligocene foraminiferal microbreccia with micritic rim. Transmitted light. Bar scale equals 3 mm.

D. Sample KK79-47-01. Miocene foraminiferal microbreccia with pre-existing rock fragments. Note echinoid spine with syntaxial overgrowth. Transmitted light. Bar scale equals 1.5 mm.

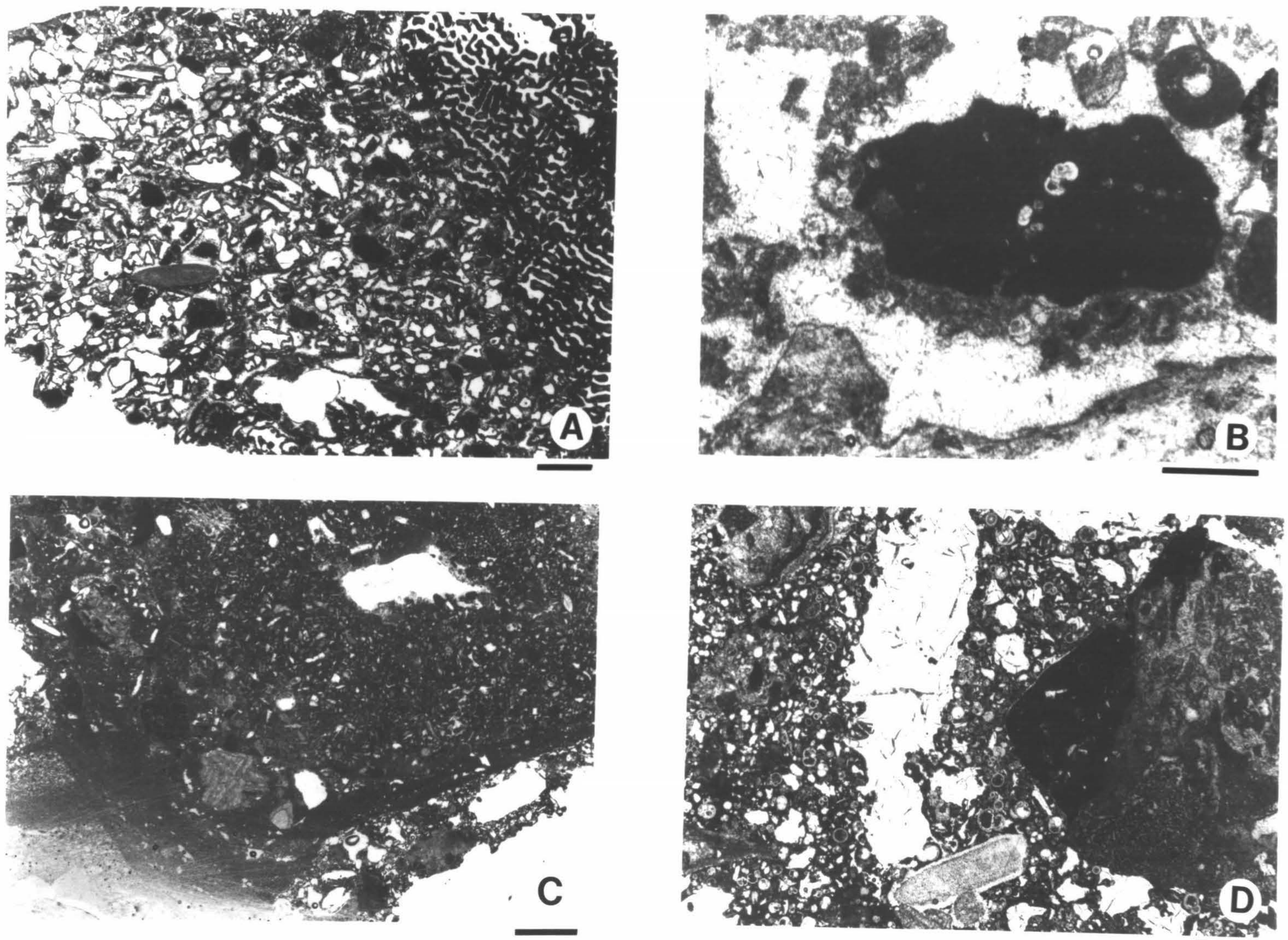

A
B
C
D

PLATE IX

PHOTOMICROGRAPHS FROM ROCKS FROM SITE RD-47 AND SITE RD-48

A. Sample KK79-47-09. Cobble of paracoquinite within a Miocene foraminiferal microbreccia. Note layer of micritic cement. Transmitted light. Bar scale equals 3 mm.

B. Sample KK79-47-22. Miocene foraminiferal microbreccia with coral cobbles. Transmitted light. Bar scale equals 3 mm.

C. Sample KK79-48-01. Plio/Pleistocene coral breccia; stratification of sand-size skeletal debris among rounded fragments of recrystallized coral. Transmitted light. Bar scale equals 3 mm.

D. Sample KK79-48-02. Pliocene foraminiferal paracoquinite. Tests of *Heterostegina*, *Operculina*, and *Amphistegina* are present. Transmitted light. Bar scale equals 2 mm.

PLATE IX

PHOTOMICROGRAPHS FROM ROCKS FROM SITE RD-47 AND SITE RD-48

A. Sample KK79-47-09. Cobble of paracoquinite within a Miocene foraminiferal microbreccia. Note layer of micritic cement. Transmitted light. Bar scale equals 3 mm.

B. Sample KK79-47-22. Miocene foraminiferal microbreccia with coral cobbles. Transmitted light. Bar scale equals 3 mm.

C. Sample KK79-48-01. Plio/Pleistocene coral breccia; stratification of sand-size skeletal debris among rounded fragments of recrystallized coral. Transmitted light. Bar scale equals 3 mm.

D. Sample KK79-48-02. Pliocene foraminiferal paracoquinite. Tests of _Heterostegina_, _Operculina_, and _Amphistegina_ are present. Transmitted light. Bar scale equals 2 mm.

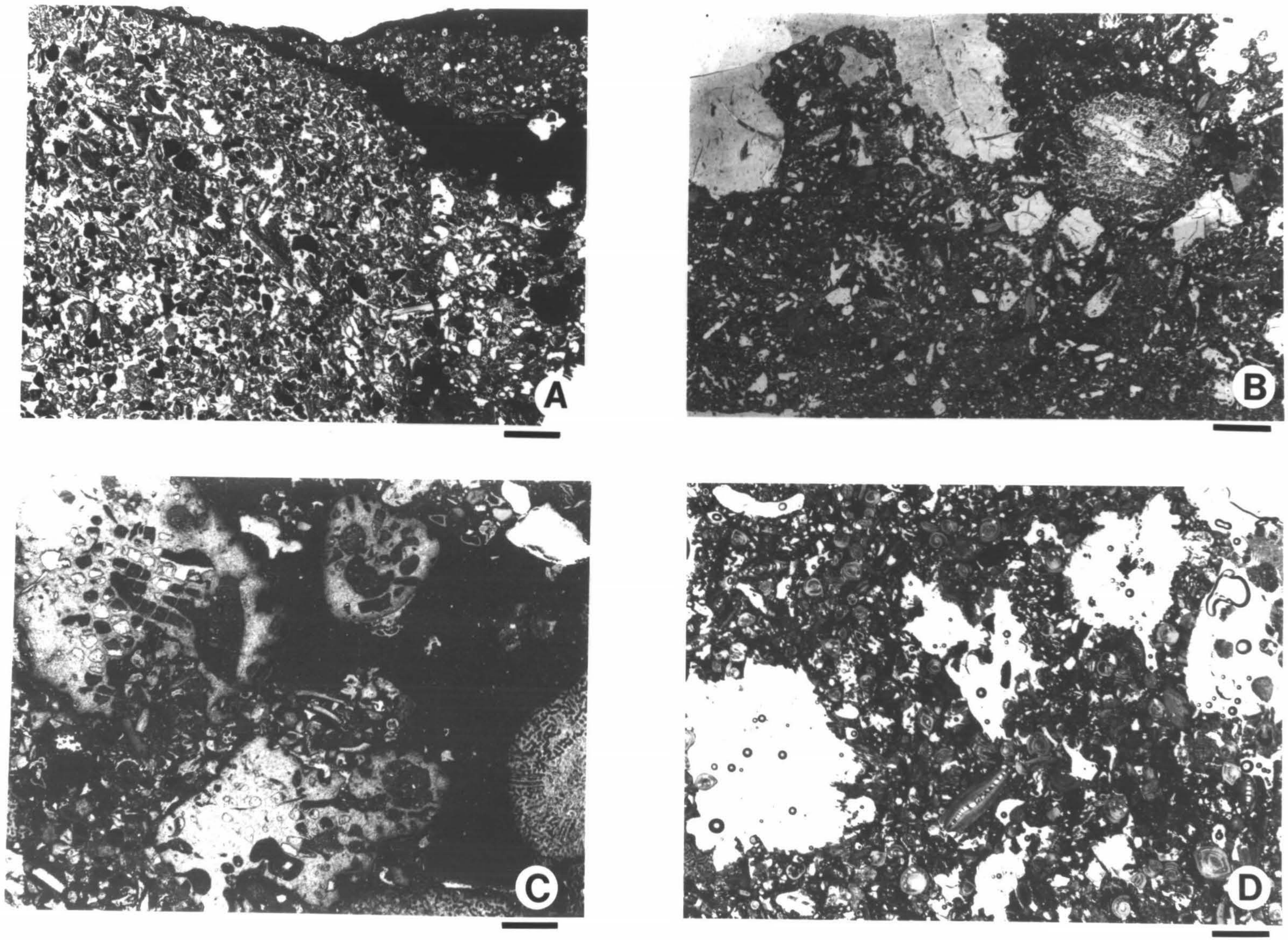

A
B
C
D

PLATE XI

REWORKED HYALOCLASTITE FROM SITE RD-50

Sample KK79-50-01.

A. Stratified hyaloclastite containing infilled burrows. Diameter of coin equals 17 mm.

B. Shards of altered glass rimmed with zeolites. Plane-polarized light. Bar scale equals 0.5 mm.

C. Same as Figure B. Under crossed nicols. Bar scale equals 0.5 mm.

D. SEM photo of altered glass shard with fiberous zeolitic rim. Bar scale equals 0.2 mm.

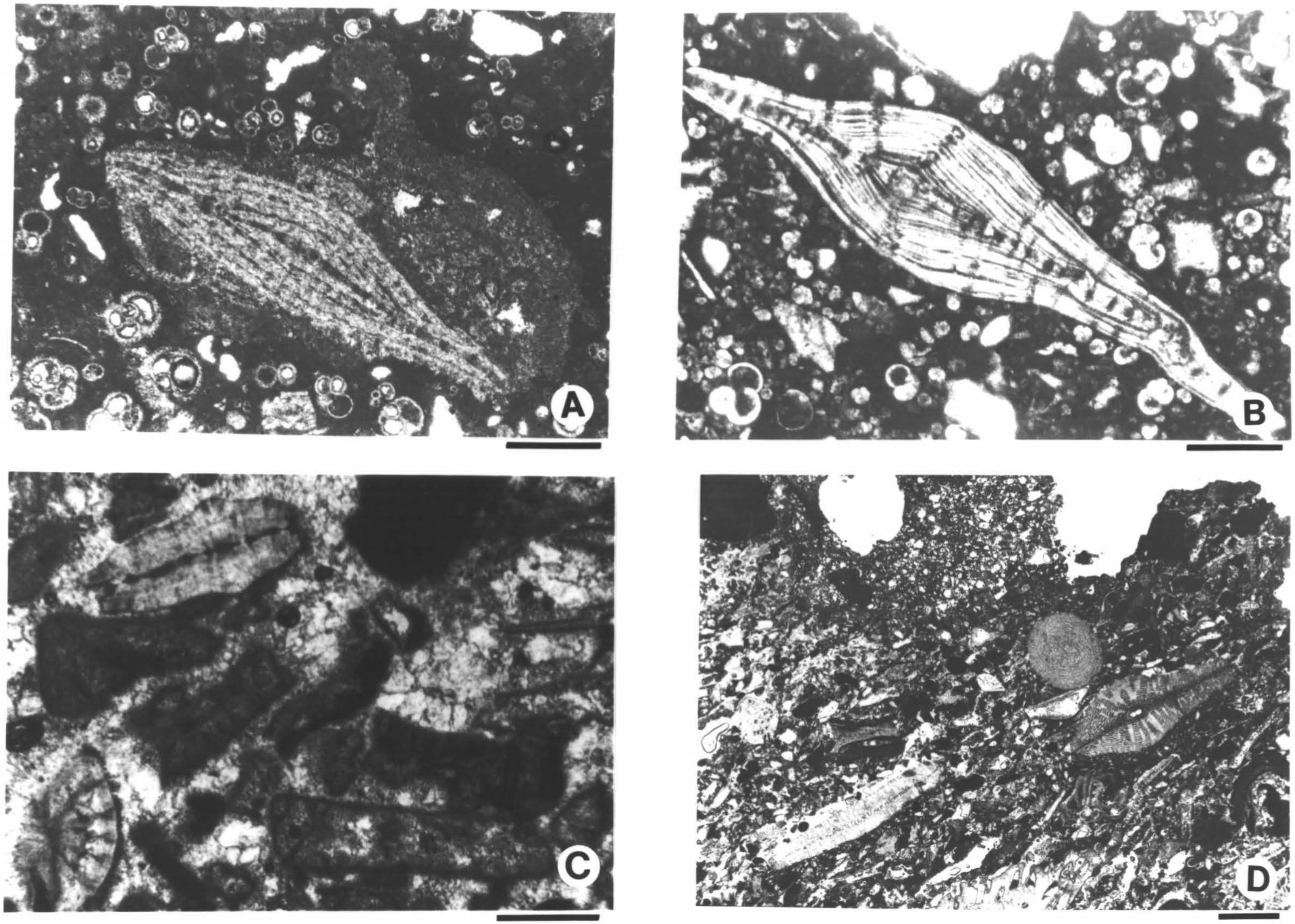

A
B
C
D

PLATE X

LARGER FORAMINIFERA IN ROCKS FROM SITE RD-47

A. Sample KK79-47-01. *Spiroclypeus* in a pre-existing rock fragment that has been redeposited downslope. Plane-polarized light. Bar scale equals 0.5 mm.

B. Sample KK79-47-08. *Cycloclypeus*. Plane-polarized light. Bar scale equals 0.5 mm.

C. Sample KK79-47-07. Broken and abraded tests of *Operculina* deposited in a Miocene paracoquinite. Also note coarsening of calcite crystals toward the center of pores and micritic envelopes on skeletal debris. Plane-polarized light. Bar scale equals 0.5 mm.

D. Sample KK79-47-07. Large fragments of *Lepidocyclina* in a Miocene paracoquinite. Transmitted light. Bar scale equals 3 mm.

APPENDIX A

A REVIEW OF THE STABLE ISOTOPE GEOCHEMISTRY OF CARBONATE CEMENTS

PRINCIPLES OF CARBON AND OXYGEN STABLE ISOTOPE VARIATION DURING CARBONATE DIAGENESIS

The oxygen isotopic composition of a precipitating carbonate is a function of the isotopic composition of the surrounding medium and temperature. The mean $\delta^{18}O$ of today's oceans is about -0.08‰. Meteoric water is depleted in ^{18}O and has a larger range relative to sea water; the variation is a function of latitude and elevation. The oxygen isotopic composition of groundwater is a function of the isotopic composition of meteoric waters as well as contributions from the rock-water interactions and increasing temperature with increasing depth of burial. If carbonate dissolves, the oxygen rapidly equilibrates with the surrounding water. When reprecipitation occurs, the carbonate will not always have the same oxygen isotopic composition of the original carbonate. The new oxygen isotopic composition will be a function of the factors listed above. In a solid-solid solution, the original isotopic composition may be maintained.

The carbon isotopic composition of carbonates appears to be directly or indirectly related to photosynthesis (Garrels and Perry, 1974). According to Degens (1965) organic matter (about -25‰ PDB) is about 30% enriched in ^{12}C relative to atmospheric carbon dioxide (about -7‰ PDB). Marine carbonate in isotopic equilibrium with sea water is about 0‰ PDB. Aerobic oxidation of organic matter by micro-organisms yields soil CO_2 having a light carbon isotopic composition similar to the organic material; this CO_2 may in turn be picked up by meteoric waters and enter the groundwater system.

The total dissolved bicarbonate in the pore water is comprised of $MgHCO_3^+$, $H_2C_2O_3$, $CO_2(aq)$, HCO_3^-, CO_3^{2-}, $CaHCO_3^+$ and other minor species as the result of the solution of carbon dioxide and also possibly dissolution of carbonate minerals. The $\delta^{13}C$ value of the total bicarbonate is dependent on the isotopic composition of the CO_2 and/or the carbonate minerals with some changes due to the interaction of the water with the sediments over time (Carothers and Yousif, 1980).

Primary sources of CO_2 are the atmosphere, organic matter, and carbonate deposits. The modification of organic matter during diagenesis and its effect on pore water and precipitation of carbonate cement has been derived for essentially a closed system (Curtis, 1978; Irwin et al., 1977). The model contains depth related zones that are a function of the rate of burial, which in turn determines the extent and type of diagenetic modification. Bacterial processes compose the upper three zones, and thermal decarboxylation and ferric oxidation dominate as the abiotic reactions occurring in a fourth zone. All the reactions generate carbon dioxide which enters the pore water and increases the bicarbonate concentration.

The overall variation in the $\delta^{13}C$ of the pore water CO_2 generated from the organic matter is a function of the depth and affects the precipitating carbonate in a closed system. Curtis (1978) has successfully demonstrated that diagenetic reactions can modify organic matter and produce massive amounts of carbonate cement. The isotopic composition of the cement can indicate what the main source of the CO_2 is within a closed system. Friedman and Murata (1979) have shown that in sedimentary sections with more than one zone of microbial diagenesis, the precipitated carbonate (in this case dolomite, which has a greater stability than other carbonates) did not reflect the isotopic composition of the dissolved CO_2 in the zone from which it was sampled. Instead, the isotopic composition of dolomite indicated precipitation from an organic source in an overlying microbial diagenetic zone and continuation of burial.

Variations of the above mechanisms as well as those for pore water isotopic composition in diagenetic environments at greater burial depths have been described in the literature (Presley and Kaplan, 1968 and 1972; Hathaway and Degens, 1969; Nissenbaum et al., 1972; Claypool et al., 1973; Friedman and Murata, 1979; Carothers and Yousif, 1980). Isotopically light bicarbonate in pore water is generated by metabolism of organic matter (Presley and Kaplan, 1968) or possibly by oxidation of methane (Hathaway and Degens, 1969). Isotopically heavy bicarbonate values in pore water may also be due to the presence of methane whereby there is an isotopic exchange to equilibration with the dissolved CO_2 (Nissenbaum et al., 1972). Another two methods for producing heavy carbon is the previously displayed fermentation of organic acids or acetate dissimilation yielding methane (Nissenbaum et al., 1972; Friedman and Murata, 1979; Irwin et al., 1977; and Curtis, 1978), and methane produced from reduction of preformed CO_2 by methane-producing bacteria using the molecular or organic hydrogen that is available (Nissenbaum et al., 1972; Friedman and Murata, 1979). According to Cappenberg (1974, in Friedman and Murata, 1979), 60-100%

methane is produced by acetate fermentation in sediments where both CO_2-reduction and acetate fermentation could occur. ^{14}C tracer studies of lake sediments, sewage sludges, and paddy soils (cited in Games et al., 1978) confirm that 70% of produced methane is formed by acetate dissimilation whereby only 30% is formed by reduction of carbon dioxide. Laboratory cultured methane producing bacteria yielded bacterial fractionation factors that are in general agreement with the fractionation observed by Nissenbaum et al. (1972) in their study of a natural environment, a reducing fjord. With increasing burial the organic material gradually changes to the diagenetic product of a kerogen. As the kerogen matures, it isotopically fractionates favoring heavy carbon because of binding energy differences within the carbon complex (Stahl et al., 1978). Therefore gaseous hydrocarbons given off during the maturation process become isotopically heavier relative to those given off at an earlier stage of maturation.

In general, the $\delta^{13}C$ of the dissolved CO_2 is a function of the initial ^{13}C content, and the method of carbon bonding involved in organic degradation producing the CO_2.

OBSERVED ISOTOPIC COMPOSITION OF CARBONATES FROM VARIOUS DIAGENETIC ENVIRONMENTS

Diagenesis involves all processes, physical and chemical, that change the sediment after deposition and cause it to lithify. With respect to changes in the isotopic composition, diagenesis begins with the decomposition of organic matter and continues as isotopic exchange with pore water changes with time and depth due to the rate of sedimentation, oxidation potential, and amount of organic matter (Brownlow, 1979).

The solubility and stability of carbonate mineral species in various diagenetic environments has a direct consequence on the isotopic composition of the rock due to the processes of solution and reprecipitation. High-Mg calcite, aragonite, and low-Mg calcite are in order of increasing stability. Thermodynamically, dolomite is the most stable carbonate but rarely occurs in modern sedimentary environments (Brownlow, 1979). The order of abundance of these carbonate species in today's carbonate sediments is the reverse of their order of thermodynamic stability. In other words the least stable calcite, high-Mg calcite, is precipitated more abundantly as a primary mineral in the marine environments than the more stable form of low-Mg calcite. Apparently the concentration of Mg^{2+} has an inhibiting effect on the nucleation and growth of low-Mg calcite. According to Brownlow (1979), dolomite does not readily form as a primary mineral in modern sediments of normal marine salinity because the kinetics of ordering the cations

(Ca^{2+} and Mg^{2+} in alternating crystallographic planes) requires a high temperature for rapid formation (Matthews and Katz, 1977). Dolomite may form secondarily through oxidation of organic carbon as documented on the continental margin of Peru (Kulm et al., 1981). Once dolomite has formed, it is believed to be more resistant to solution and equilibration (Degens and Epstein, 1963; Weber, 1965).

The process of solution and reprecipitation of a carbonate can significantly alter the isotopic composition. This is drastically apparent in the oxygen isotope composition because the relatively small proportion of oxygen from the carbonate is overwhelmed and equilibrates rapidly with the large amount of oxygen in the water. The oxygen isotopic composition of the reprecipitated carbonate will once again be a function of the isotopic composition of the water, and temperature. The change in the carbon isotopic composition of the carbonate in a closed system will not be as drastic because of the small amount of carbon available for exchange. When there is a large amount of pore water available and migrating, the change in the carbon and oxygen isotopic composition of the reprecipitated carbonate can be significant. Most transformations from one carbonate polymorph to another involve solution and reprecipitation and thereby usually alter the isotopic composition.

Submarine Lithification

Sediments are cemented by aragonite at shallow sub-tidal depths, or by calcite down to abyssal depths (Folk, 1974; Ginsburg and James, 1976; Schlanger and James, 1978; Magaritz et al., 1979). This initial stage of cementation has a carbon isotopic composition similar to modern marine sediments (0‰ PDB) as demonstrated in the studies of Holocene reef limestone in Belize (Ginsburg and James, 1976), Holocene beachrock in Israel (Magaritz et al., 1979), and Pleistocene limestones formed in the deep sea off the Bahamas (Schlager and James, 1978). Mississippian shallow marine lime muds were also diagnosed as having undergone submarine cementation by petrographic and isotopic analysis (Choquette, 1968). Apparently, it is possible to decipher burial lithification from submarine lithification on the deep sea floor. Calcite from dissolving planktonic foraminifera forms overgrowths on nannofossils and the ^{18}O value decreases--most likely due to the increase in temperature with burial that accompanies reprecipitation (Hudson, 1977).

Subaerial Diagenesis

Diagenesis produced by near-surface freshwater may occur in a few thousand years, but can result in lithified sediments having an average of up to 20% porosity due to freshwater leaching (Hudson, 1975). The lithification involves the reactions of the carbonate sediments (aragonite or high-Mg calcite) with groundwater composed of meteoric water and dissolved CO_2 from soil gases. The $\delta^{13}C$ value of the limestone may decrease as much as 8‰ in comparison to the original sediment due to the light carbon CO_2 originally derived from oxidized organic matter. A study conducted on Barbados limestones by Allan and Matthews (1977), documented a distinct $\delta^{13}C$ versus depth pattern downhole for vadose and phreatic environments. An abrupt shift of the ^{13}C values could be seen at the transition of the vadose to the phreatic zone and a gradual enrichment in $\delta^{13}C$ with increasing depth in the phreatic zone, thereby enabling one to use isotopic data as diagenetic and stratigraphic tools.

Late Cementation

Sparry calcite infills the pore space remaining after initial diagenesis (Folk, 1974). According to studies cited by Hudson (1975), late cementation appears to occur under reducing conditions and below the permanent water table. These calcite cements have a $\delta^{13}C$ near zero.

APPENDIX B

DESCRIPTION OF DREDGE HAULS AND PISTON CORES

TABLE 2. DESCRIPTIONS OF ROCKS DREDGED DURING LEGS 1 AND 2 OF THE R/V KANA KEOKI CRUISE KK79-08-08

Dredge #	Latitude Longitude	Water Depth	Rock Characteristics
33	08°10.9'N 161°55.1'W	3900m	Basalt-Plagioclase, olivine phyric; massive and pillow lava fragments; moderately altered with thin Mn-coating (1-5mm thick); 10 rocks total; some soft sediment in fractures; rock types--tholeiitic to alkalic olivine basalt.
34	07°08.2'N 160°38.7'W	1900m	Lost dredge and weight
35	03°31.9'N 160°14.6'W	2150m	Basalt-Plagioclase phyric fragments embedded in dredge weight
36	03°32.7'N 160°04.7'W	2010m	Lost dredge and weight
37,38,39	03°48.1'N 159°24.8'W	1000- 2250m	Mixture of coralline fragments, reef rock, shells, volcanic breccia and sandstone, and basalt. Basalt-dense, reddish, altered olivine-phyric basalt fragment moderately altered with thin Mn-crust (1-3 mm thick). Breccia- contains clasts of basalt in fine-grained dark green matrix. Sandstone- graded, medium grain-sized rocks containing feldspar, calcite volcanic fragments, biotite flakes, and calcareous shallow water debris.
40	02°01.5'N 157°16.4'W	2250m	Dredge bag empty.
41	02°05.5'N 157°20.6'W	1350- 1550m	Volcanic brecca fragments (6) - enclosed basalt fragments are clinopyroxene-plagioclase-altered olivine phyric set in glassy to holocrystalline matrix with thin (1-3 mm) Mn crust. Rock type: alkali olivine basalt.
42	00°32.7'N 157°53.9'W	1750- 1900m	Basalt-altered olivine & clinopyroxene phyric vesicular (20-30%) thickly (4-10cm) Mn crusted basalt. Rock type: alkali olivine basalt.

TABLE 2. (Continued) DESCRIPTIONS OF ROCKS DREDGED DURING LEGS 1 AND 2 OF THE R/V KANA KEOKI CRUISE KK79-08-08

Dredge #	Latitude Longitude	Water Depth	Rock Characteristics
43	00°42.4'S 155°17.2'W	2300-3000m	Basalt- Massive basalt thickly (4-5cm) Mn crusted. Vesicular (25-30%), Aphanitic. Rock type: alkali olivine basalt.
44	07°35.3'S 151°32.6'W	1800-2100m	Basalt- Massive, non-vesicular brownish grey basalt with patches of platioclase and pyroxene, 25 Kg. Breccia- reddish-brown angularclasts of basalt in a sandy matrix with very thin, patchy Mn crust. 25 KG. Mn-encrusted breccia- Mn crust 4 cm thick on a fine-grained yellow to reddish brown breccia; some soft calcareous sediment infilling fractures.
45	09°03.8'S 150°41.6'W	1300-1450m	Mixture of phosphatized limestone and limestone breccia, biogenic volcanic sandstone, volcanic breccia, and basalt. Basalt- massive non-vesicular, olivine phyric altered basalt fragments. Volcanic breccia - basalt clasts (10 cm long) set in altered glass matrix; Mn crusted (1-5 cm). Limestone & Limestone breccia - major rock recovered. Biogenic volcanic sandstone - foraminiferal, volcanic debris rich, chalky angular fragments containing mollusk, echinoid, and algae fragments.
46	09°53.1'S 150°12.1'W	1400-1500m	Basalt - vesicular (15%), Aphanitic basalt with calcite infilling of vugs. Volcanic breccia & Sandstone- reddish oxized surface. Limestone & Limestone breccia - major rock recovered contains shallow water material and pelagic sediment.
47	09°53.3'S 150°09.1'W	2400-2750m	Basalt - vesicular (20%), olivine and plagioclase phyric rock with with no Mn crust. Rock type: alkali olivine basalt. Limestone - coarse grained; planktonic rich.
48	10°01.8'S 152°21.7'W	2500m	Limestone contains coralline fragments, red algae and foraminiferal debris.
49	09°55'S 151°25'W	4700-4900m	Dredge bag torn. Approx. 1g of sand and mud recovered from dredge yoke containing recrystallized corals and volcanic rock fragments.

TABLE 2. (Continued) DESCRIPTIONS OF ROCKS DREDGED DURING LEGS 1 AND 2 OF THE R/V KANA KEOKI CRUISE KK79-08-08

Dredge #	Latitude Longitude	Water Depth	Rock Characteristics
50	11°03.1'S 152°05.8'W	4250-4400m	Volcanoclastic sandstone - several angular, Mn-crusted (1mm-1cm), graded sandstones containing bands of opaques, altered glass shards, olivine, and plagioclase grains and some poorly preserved radiolarians and planktonic foraminifera.
51	12°52.5'S 150°45.8'W	3000-3200m	Volcanic breccia - basalt clasts (20cm long) in clay-carbonate matrix; contains abundant plantonic foraminifera.
52	15°00.8'S 149°02.3'W	3400m	Basalt- Angular to subangular, vesicular (15%), pillow fragments with glassy chill margin on a few pieces; 115 Kg Volcanic sandstone--graded tuff boulder with interstitial clay; 45 Kg.
53	13°01.5'S 147°55.7'W	4700m	Mn-crusts - 1-20cm long, tabular shaped with pockets infilled with dark brown radiolarian clay yielding a middle Pliocene to Recent age.
54	03°38.4'N 159°31.4'W	2800m	Basalts and volcanic breccias - mixture of massive, non-vesicular basalts and vesicular (30-40%) lavas, angular, thing (< 1cm) and patchy Mn-crust.
55	04°22.3'N 159°05.3'W	2150-2650m	Mixture of large chalky limestone boulders, and fine-grained volcanic sandstone fragment with burrows, and a small amount of grey mud lumps.

Piston Core Results.

From the six attempted piston cores, five were successfully recovered and collected approximately 61 m of sediments. An orientation device was attached to the coring apparatus permitting the azimuthal orientation of the sediments during coring to be recorded for future paleomagnetic work.

The main lithologic type of sediment recovered in the cores is a 0.4 to 1.0 m thick sequence of weakly graded, pelagic turbidites. These turbidites range in size from very fine-grained (composed mainly of calcareous nannoplankton and foraminiferal (fragments) to coarse-grained. Some layers contain 3 to 4 mm pebbles of volcanic rocks and/or large benthic foraminifera that are imbedded in a planktonic-foraminiferal matrix (see Table 2).

On the basis of the smaller benthic foraminiferal faunas associated with the planktonic foraminifera, the turbidites originated mostly from medium to lower bathyal slopes. Shallow-water material (such as the larger foraminifera) is thought to be re-reworked from those areas where they were formerly redeposited. This interpretation may account for the scantiness of the shallow-water debris.

Indigenous sediments, represented in the area by light brown radiolarian-clay, were recovered in only two piston cores. Deep water agglutinated benthic foraminifera are recorded in these layers and are associated with fish debris.

Planktonic foraminifera display a range in age from Late Cretaceous through the Recent. However, the most frequent assemblages belong to the early Pleistocene and the late Pliocene. The radiolarians show that reworking involved middle Miocene, late Oligocene and Eocene layers along with Pleistocene sediments.

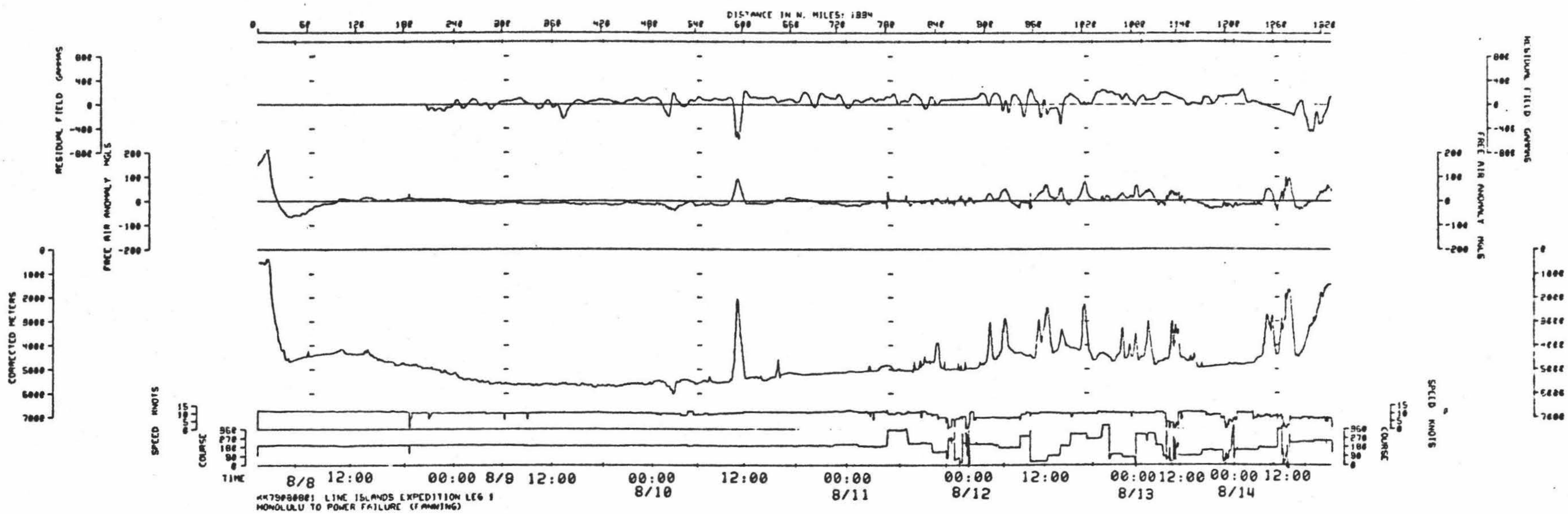
TABLE 3. DESCRIPTIONS OF PISTON CORES RECOVERED DURING LEG 1 OF THE R/V KANA KEOKI CRUISE KK79-08-08

PISTON CORE	COORDINATES	UNCORRECTED WATER DEPTH (m)	LENGTH RECOVERED (cm)	DESCRIPTION AND AGES*
PCOD-02	08°26.5'N 161°40.2'W	5015	NO CORE	Unsuccessful attempt due to piston failure. Trace sample recovered from piston head is rich in planktonic foraminifera and volcanic debris; radiolarians were rare. Ages: Pleistocene, late Pliocene, middle Miocene, late Oligocene, early Eocene, and Late Cretaceous.
PCOD-03	08°31.6'N 161°43.9'W	4934	884	White to tan sandy foraminiferal oozes, very weak grading upwards. Coarse fraction (.15 to 2.0 mm average) contains volcanic material, shallow-water debris, rare Asterocyclina. Radiolarians are absent throughout. Ages: Recent, early Pleistocene, middle Pliocene, late Pliocene, middle Miocene, late Oligocene, and Eocene.
PCOD-04	07°49.1'N 161°08.1'W	4840	1079.5	White to light brown. Radiolarian clay with fine to medium coarse grained sandy planktonic foraminiferal oozes as turbidites. Mottling is very evident close to the boundary between the two lithologies. Ages: Pleistocene, late Pliocene, middle Miocene, and late Oligocene.
PCOD-05	04°20.4'N 160°19.1'W	4160	1020	White to tan turbidites. Fine to medium coarse grained sandy foraminiferal oozes. Pyrite filled planktonic foraminifera and abundant volcanic material at 788 cm. Volcanic sandstone fragments associated with Late Cretaceous Globotruncanids at 592 cm. Ages: Pleistocene, late Pliocene, middle Miocene, and Late Cretaceous.
PCOD-06	02°34.6'N 158°30.1'W	2930	1425	White to tan turbidites. Fine to medium coarse sandy foraminiferal oozes. Radiolarians and fish debris present. Volcanic sandstone containing Discocyclinids, and chert pebbles at 362-382 cm. Ages: Recent, Pleistocene, late Pliocene, Eocene and Late Cretaceous.
PCOD-07	01°04.9'S 155°20.6'W	4760	1630	White to tan relatively coarse graded foraminiferal sandy layers changing into very fine distal turbidites with radiolarian clay layers. Mottled clay-turbidite interface. Ages: early Pleistocene, middle Pliocene, early Eocene, and Late Cretaceous.

*Ages are determined from the planktonic foraminiferal indices found throughout the core.

APPENDIX C

UNDERWAY GEOPHYSICAL DATA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CORRECTED METERS
SPEED KNOTS
COURSE
TIME
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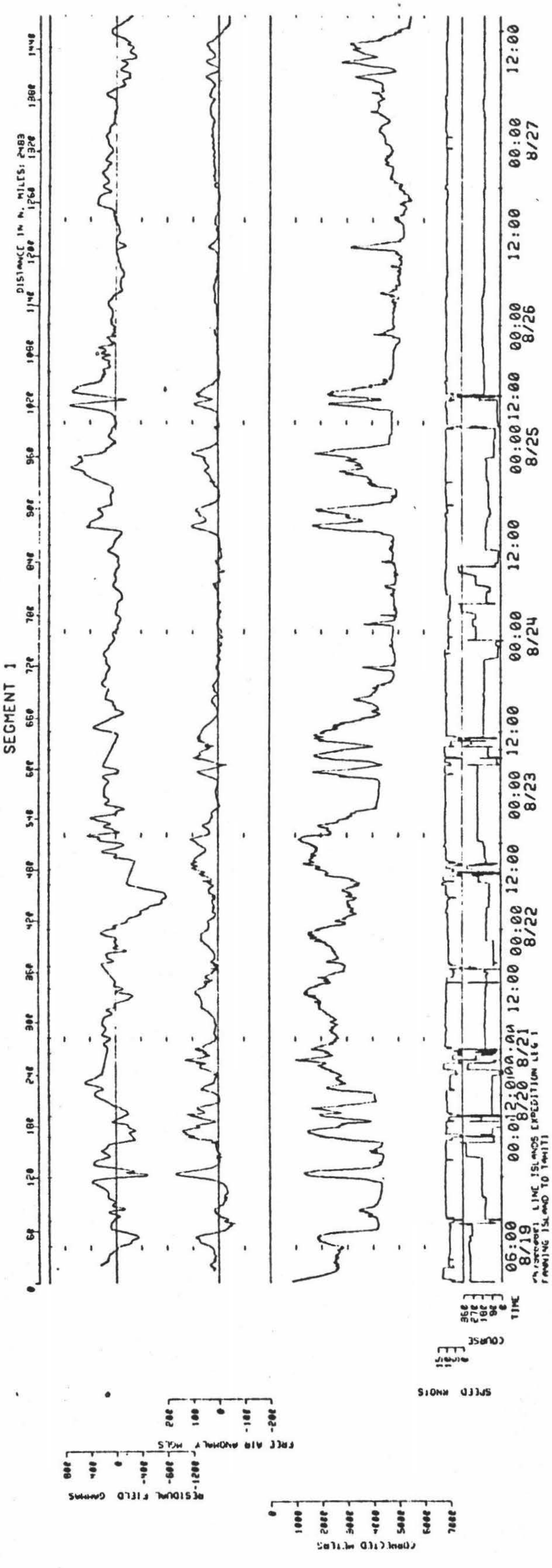
KK790801 LINE ISLANDS EXPEDITION LEG 1
HONOLULU TO POWER FAILURE (FANNING)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00:00 8/24
00:00 8/25
00:00 8/26
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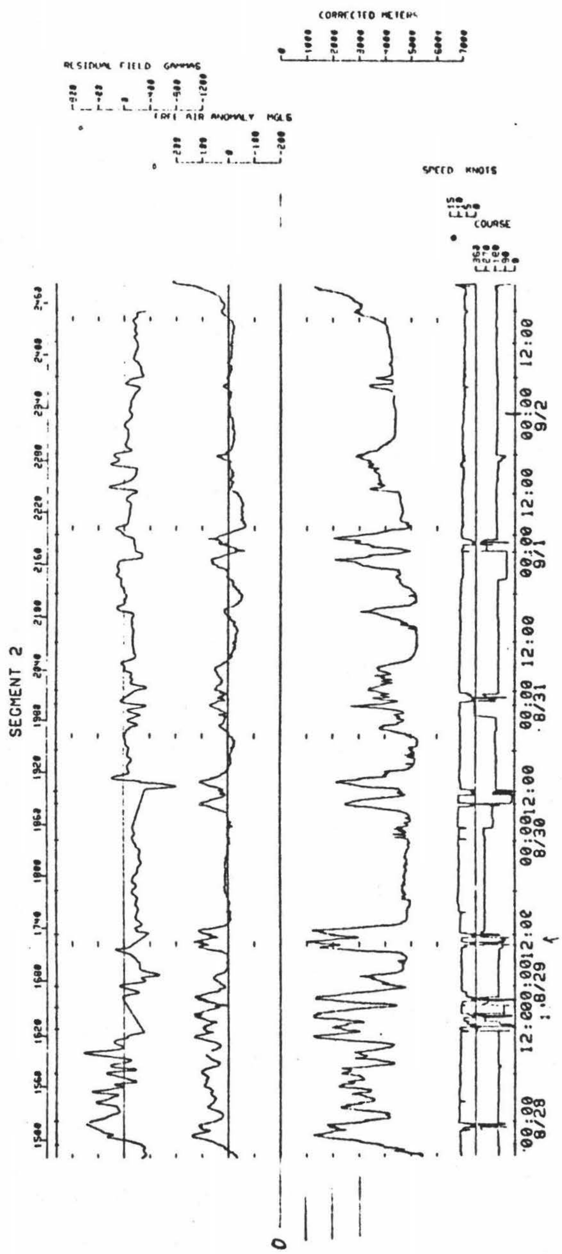
TIME
COURSE
SPEED KNOTS
FREE AIR ANOMALY MGLS
RESIDUAL FIELD GAMMAS
CORRECTED METERS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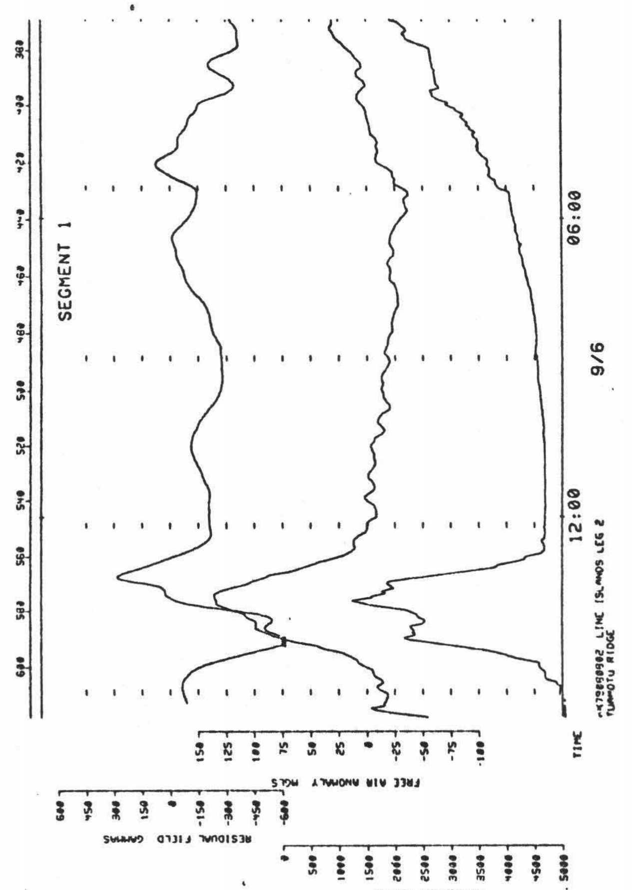
00:00 9/2
12:00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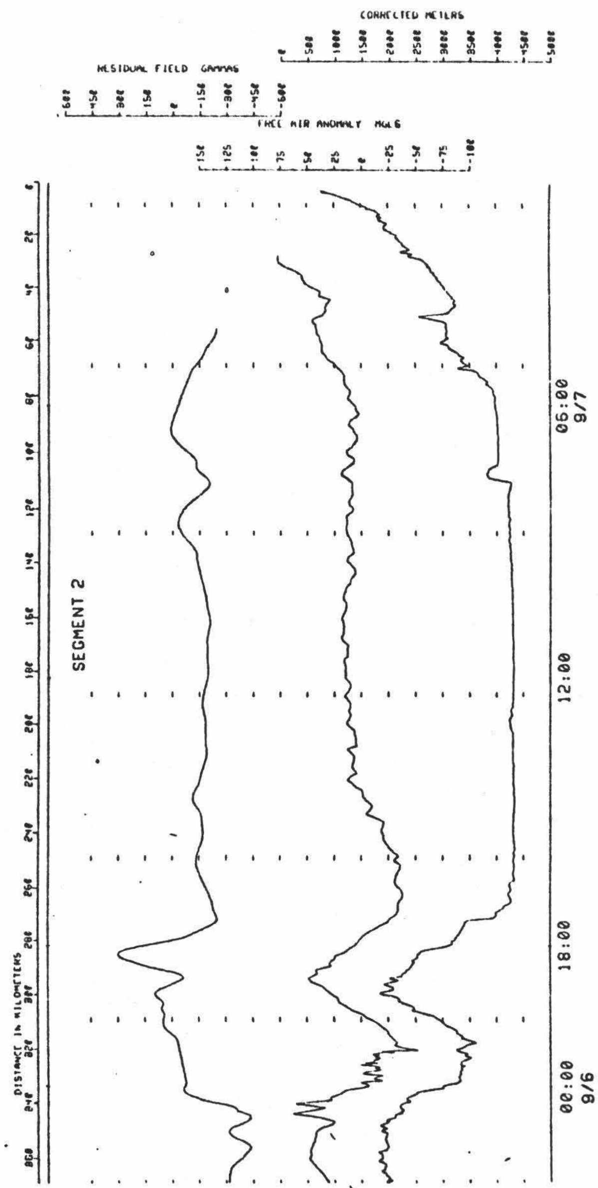
TUAMOTU RIDGE



CORRECTED METERS
RESIDUAL FIELD GAMMAS
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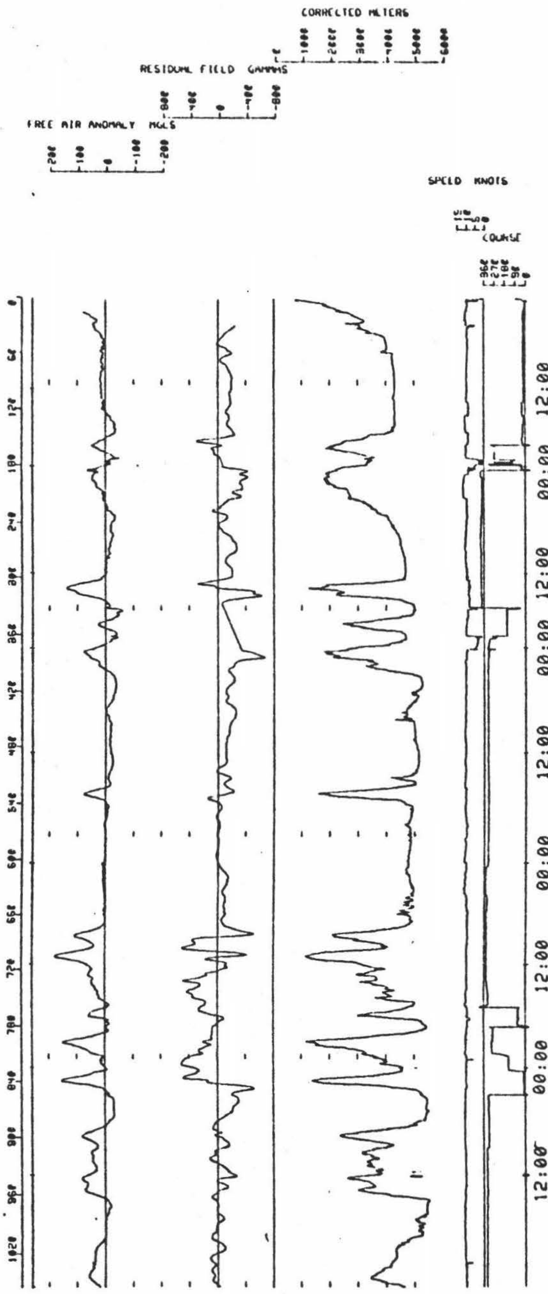
9/6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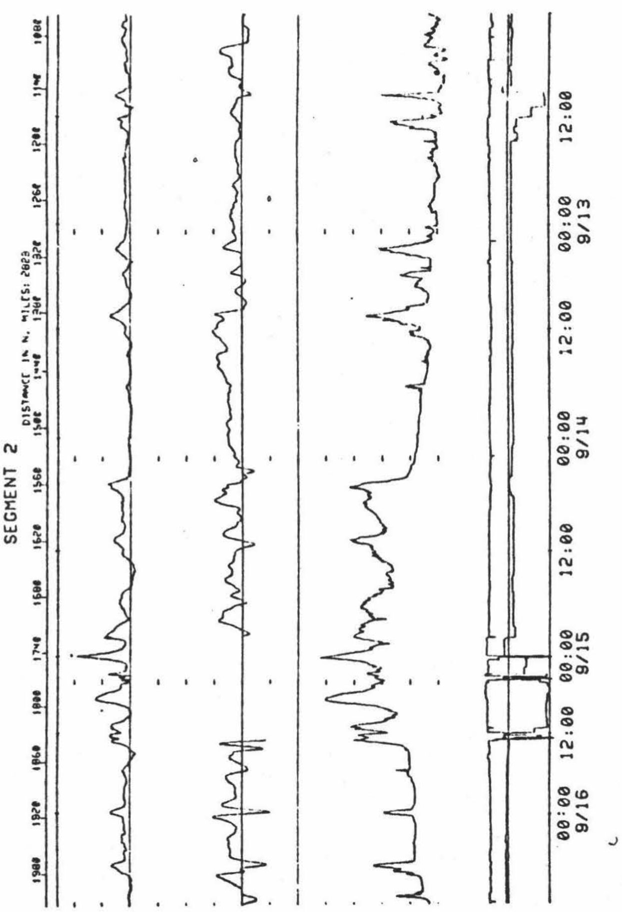

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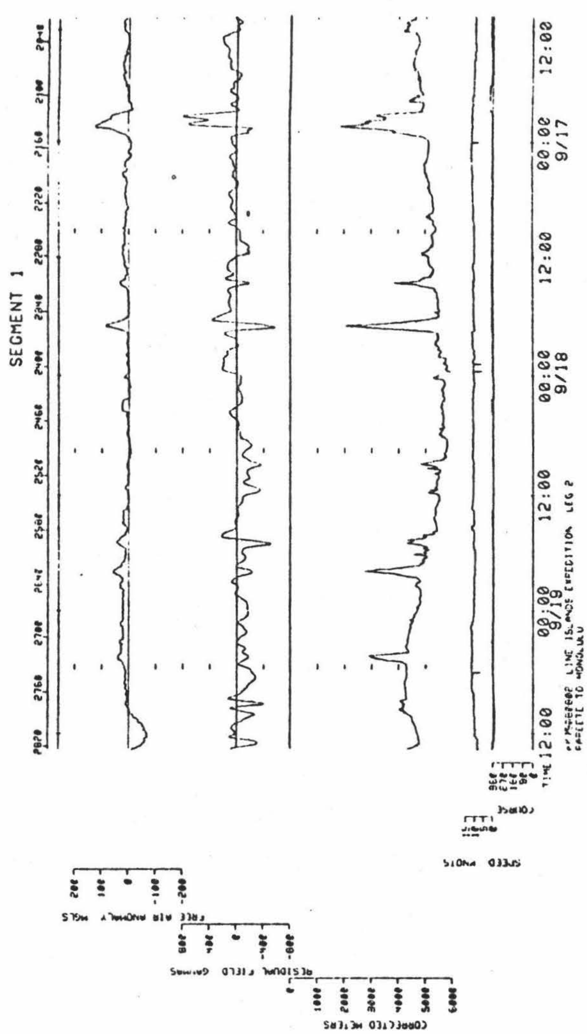
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APPENDIX D

SAMPLE DESCRIPTIONS AND PALEONTOLOGIC DATA

FROM THE SOUTHERN LINE ISLANDS

TABLE 4. SAMPLES STUDIED FROM THE SOUTHERN LINE ISLANDS

ROCK DREDGE	SAMPLE	SLIDES STUDIED	AGE	DESCRIPTION
44	KK79-44-01	5	Late Paleocene	Manganese-rimmed volcanic conglomerate
	-02	2	Late Cretaceous	Volcanic breccia
	-03	2	Paleocene	Volcanic breccia
45	KK79-45-01	4	Middle Eocene	Manganese-coated phosphatic foraminiferal limestone
	-02	2	Maestrichtian	Phosphatized pebbly limestone
	-03	1	Middle Eocene	Phosphatized foraminiferal limestone
	-05	2	Undiagnostic	Phosphatized sandy limestone
	-06	2	Early Campanian	Phosphatized sandy limestone
	-08	24	Campanian/Maestrichtian	Coquina
	-10	2	Middle Eocene	Phosphatized foraminiferal limestone
	-11	2	Middle Eocene	Phosphatized foraminiferal limestone
	-12	1	Campanian	Phosphatized foraminiferal limestone
	-13	4	Maestrichtian	Phosphatized pebbly limestone
	-14	1	Undiagnostic	Phosphatized sandy limestone
	-15	1	Middle Eocene	Phosphatized foraminiferal limestone
	-16	2	Middle Eocene	Manganese infiltrated phosphatized foraminiferal limestone
	-17	5	Early Campanian	Phosphatized pebbly limestone
	-18	4	Middle Eocene	Phosphatized foraminiferal limestone
	-19	1	Paleocene	Volcanic breccia
	-20	2	Campanian	Coquina-crust on mugearite
	-21	1	Paleocene?	Volcanic breccia
	-22	2	Undiagnostic	Highly altered volcanic sandstone
	-23	6	Late Cretaceous	Densely phosphatized pebbly mudstone
	-24	6	Late Campanian	Phosphatized foraminiferal limestone

TABLE 4. (Continued) SAMPLES STUDIED FROM THE SOUTHERN LINE ISLANDS

ROCK DREDGE	SAMPLE	SLIDES STUDIED	AGE	DESCRIPTION
45	KK79-45-25	4	Middle Eocene	Phosphatized foraminiferal limestone
	-26	2	Middle Eocene	Peperite
	-28	2	Middle Eocene	Phosphatized foraminiferal limestone
46	KK79-46-02	2	Undiagnostic	Coral
	-03	13	Early Miocene	Limestone breccia
	-04	6	Miocene to Recent	Algal-coral incrustate limestone
	-05	1	Undiagnostic	Coral
	-06	1	Undiagnostic	Coral incrustate limestone
	-07	1	Miocene to Recent	Algal incrustate limestone
	-08	1	Miocene to Recent	Algal incrustate limestone
	-09	1	Miocene to Recent	Coral incrustate limestone
	-10	1	Miocene to Recent	Algal-coral incrustate limestone
	-11	1	Undiagnostic	Coral incrustate limestone
	-12	1	Miocene to Recent	Algal incrustate limestone
	-13	1	Undiagnostic	Sclerosponge-coral incrustate limestone
	-14	2	Undiagnostic	Sclerosponge-coral incrustate limestone
	-15	1	Undiagnostic	Sclerosponge-coral incrustate limestone ,
	-16	1	Undiagnostic	Coral
	-17	2	Eocene	Phosphatized foraminiferal limestone with volcanic rock fragments
47	KK79-47-01	6	Early Miocene	Foraminiferal microbreccia
	-02	3	Miocene to Recent	Algal-coral breccia
	-03	4	Early Miocene	Foraminiferal microbreccia
	-06	1	Miocene to Recent	Foraminiferal-algal microbreccia
	-07	7	Early Miocene	Foraminiferal paracoquinite

TABLE 4. (Continued) SAMPLES STUDIED FROM THE SOUTHERN LINE ISLANDS

ROCK DREDGE	SAMPLE	SLIDES STUDIED	AGE	DESCRIPTION
47	KK79-47-08	10	Early Miocene	Foraminiferal microbreccia
	-09	5	Early Miocene	Foraminiferal microbreccia bearing cobbles of microparacoquinites and coral
	-11	2	Oligocene	Foraminiferal microbreccia
	-13	2	Miocene to Recent	Algal-foraminiferal breccia
	-14	3	Miocene to Recent	Algal-foraminiferal breccia
	-15	2	Oligocene/Miocene	Foraminiferal-algal microbreccia
	-17	2	Pliocene	Foraminiferal microbreccia
	-18	2	Middle Miocene	Foraminiferal microbreccia
	-19	4	Oligocene/Miocene	Foraminiferal microparacoquinite
	-20	2	Early Miocene	Foraminiferal-algal breccia
	-21	2	Early Miocene	Foraminiferal algal microbreccia
	-22	2	Middle Miocene	Foraminiferal microbreccia with coral cobbles
48	KK79-48-01	9	Plio/Pleistocene	Coral breccia
	-02	6	Pliocene	Foraminiferal paracoquinite
50	KK79-50-01	14	Miocene?	Hyaloclastite
	-02	4	Miocene?	Hyaloclastite
51	KK79-51-01	3	Middle Eocene	Hyaloclastic sandstone
	-02	2	Middle Eocene	Hyaloclastic sandstone
	-03	2	Undiagnostic	Hyaloclastic sandstone
52	KK79-52-01	2	Undiagnostic	Hyaloclastite

TABLE 5. DISTRIBUTION OF VOLCANIC MATERIAL, INVERTEBRATE FOSSILS AND FOSSIL PRESERVATION IN SAMPLES FROM THE SOUTHERN LINE ISLANDS

SAMPLE	VOLCANIC MATERIAL: Altered Glass	VOLCANIC MATERIAL: Rock Fragments	PLANKTONIC FORAMINIFERA: Abundance	PLANKTONIC FORAMINIFERA: Preservation	radiolarians	calcispheres	ostracods	MACROFOSSILS: gastropods	rudists	other mollusks	echinoids	bryozoans	corals	ALGAE: *Halimeda*	dasycladacean algae	*Lithothamnium*	other Melobesieae algae	Corallineae algae	FORAMINIFERA: miliolids	*Cibicides*	*Amphistegina*	*Lepidocyclina*	*Spiroclypeus*	*Cycloclypeus*	*Heterostegina*	*Operculina*	*Acervulina*	*Homotrema*	*Carpenteria*	*Rupertina*
KK79-47-14													●									●					●			●
KK79-47-13			VR	M								●	●	●															●	
KK79-47-06											●	●	●		●			●				●						●		
KK79-47-02	VR		VR	M				●			●	●	●	●							●							●		
KK79-46-12			VR	M									●					●		●										
KK79-46-10								●					●				●	●												
KK79-46-09													●																	
KK79-46-08			VR	M									●																	
KK79-46-07			VR	M									●																	
KK79-46-04					●	●		●					●			●														
KK79-48-01			R	M		●		●			●	●	●			●			●											●
KK79-47-17			C	M		●							●																	
KK79-48-02	VR		C	M							●	●	●			●					●				●	●	●			●
KK79-47-18			C	M									●	●	●												●			
KK79-47-22			C	M							●	●	●	●		●					●	●					●			●
KK79-50-01			R	VP	●	●	●												●											
KK79-47-09			C	M				●			●	●	●	●	●	●					●	●	●			●	●	●		●
KK79-47-08	VR		C	M				●			●	●	●	●	●	●		●	●	●		●		●			●			●
KK79-47-03			C	M			●						●			●	●				●	●				●				●
KK79-47-01	VR		C	M							●		●		●	●		●			●	●	●					●		
KK79-47-21			C	M							●	●	●								●									●
KK79-47-07		R	C	M				●			●	●	●	●	●	●	●			●	●	●	●			●	●	●		●
KK79-46-03			C	M				●		●	●	●	●				●				●	●			●	●				
KK79-47-20			C	M				●			●	●	●	●		●		●				●								●
KK79-47-19			C	M				●				●		●		●					●				●	●				●
KK79-47-15		VR	C	M							●	●	●	●	●	●			●			●					●			●
KK79-47-11			C	M			●									●	●				●	●				●			●	
KK79-51-01	A	A	C	P			●																							
KK79-51-02	A	A	C	P																										
KK79-45-28	F		A	M																										
KK79-45-25	F		A	M																										
KK79-45-10	F		A	M																										
KK79-45-16	F	"	A	M																										
KK79-45-11	F		A	M																										
KK79-45-15	F		A	M																										
KK79-45-01	F		A	M																										
KK79-45-26	A	A	C	P																●										
KK79-46-17		C	C	M															●											
KK79-45-19		C	R	P																										
KK79-44-03		C	R	P																										
KK79-44-01	F	C	C	P					●										●											
KK79-44-02		C	R	VP																										
KK79-45-20		C	C	P					●																					
KK79-45-02		C	C	P																										
KK79-45-13		C	C	P					●																					
KK79-45-08		C	R	M					●						●															
KK79-45-12		C	C	P					●																					
KK79-45-24	C	C	A	M																										
KK79-45-06	C	C	A	P					●																					
KK79-45-17	C	C	A	P																										

A = ABUNDANT M = MODERATE
C = COMMON P = POOR
F = FEW VP = VERY POOR
R = RARE
VR = VERY RARE

TABLE 6

DISTRIBUTION OF CRETACEOUS TO EOCENE PLANKTONIC FORAMINIFERA IN SAMPLES FROM THE SOUTHERN LINE ISLANDS

SAMPLE	*Marginotruncana coronata*	*Marginotruncana sinuosa*	*Heterohelix* sp.	*Globotruncana* sp.	*Globotruncana bulloides*	*Globotruncana fornicata*	*Globotruncana linneiana*	*Globotruncana arca*	*Globotruncana stuartiformis*	*Globotruncana elevata*	*Globotruncana rosetta*	*Pseudotextularia elegans*	*Rugoglobigerina* sp.	*Globotruncana calciformis*	*Globotruncana tricarinata*	*Globotruncana stuarti*	*Globotruncanella havanensis*	*Planoglobulina* sp.	*Globotruncana contusa*	*Racemiguembelina fructicosa*	*Stensioina* sp.	*Pyramidina* sp.	*Aragonia* sp.
KK79-51-01																							
KK79-51-02																							
KK79-45-28																							
KK79-45-25																							
KK79-45-10																							
KK79-45-16																							
KK79-45-11																							
KK79-45-15																							
KK79-45-01																							
KK79-45-26																							
KK79-46-17																							
KK79-45-19																							
KK79-44-03																							
KK79-44-01				R			R																•
KK79-44-02			•	•					•				•										
KK79-45-20			•	•												•	•	•	•	•			
KK79-45-02								•	•			•			•	•		•		•			
KK79-45-13				•			•	•	•		•	•			•								
KK79-45-08				•		•	•	•	•	•													
KK79-45-12			•	•	•		•	•	•	•	•	•				•		•			•		•
KK79-45-24			•	•		•	•	•	•		•	•		•	•		cf.	•			•		
KK79-45-06	•	•	•	•		•	•	•		cf.	•										•	•	•
KK79-45-17	•	•	•	•	•		•	•		•		?									•	•	•

SAMPLE	*Subbotina praecursoria*	*Subbotina pseudobulloides*	*Morozovella pusilla*	*Morozovella velascoensis*	*Planorotalites pseudomenardii*	*Morozovella aequa*	*Acarinina mckannai*	*Acarinina nitida*	*Morozovella formosa*	*Subbotina inaequispira*	*Acarinina pseudotoplensis*	*Morozovella broedermanni*	*Morozovella aragonensis*	*Acarinina pentacamerata*	*Planorotalites palmerae*	*Globigerina senni*	*Globogerina boweri*	*Acarinina densa*	*Morozovella crassata*	*"Globorotalia" bolvariana*	*Globigerinatheka* sp.	*Globigerina yeguaensis*	*Truncorotaloides topilensis*	*Morozovella lehneri*	*Hankenina* sp.	AGE (ZONE)
KK79-51-01																•		?	•			•	•		•	middle Eocene (P 11-14)
KK79-51-02																			•							middle Eocene (P 11-14)
KK79-45-28																•		•		•	•	•			•	middle Eocene (P 14?)
KK79-45-25																•	•						•	•	•	middle Eocene (P 11)
KK79-45-10												•	•	•		•	•	•	•	•	•		•	•	•	middle Eocene (P 11)
KK79-45-16													?			•	•	•			•					middle Eocene (P 10?-11)
KK79-45-11												•				•		•	•				•		•	middle Eocene (P 10?-11)
KK79-45-15												•				•	•	•	•	•			•		•	middle Eocene (P 10?-11)
KK79-45-01											?	•	•			•	•	•			•		•	•		middle Eocene (P 10?-11)
KK79-45-26												•	•			•		?	•			•			•	middle Eocene (P 10?)
KK79-46-17														•		•			•			•				Eocene
KK79-45-19			•		•		•	•																		Paleocene
KK79-44-03		•	?	•				•																		Paleocene
KK79-44-01	cf.	•		•	?	•				I	I	I	I	I	I	I										Paleocene with reworked Cretaceous, infill Eocene (P 8-10)
KK79-44-02																										Late Cretaceous
KK79-45-20																										Maestrichtian
KK79-45-02																										late middle Maestrichtian (*Globotruncana contusa* Zone)
KK79-45-13																										late middle Maestrichtian (*Globotruncana contusa* Zone)
KK79-45-08																										Campanian/Maestrichtian
KK79-45-12																										Campanian/Maestrichtian
KK79-45-24																										late Campanian
KK79-45-06																										early Campanian (*Globotruncana elevata* Zone)
KK79-45-17																										early Campanian (*Globotruncana elevata* Zone)

TABLE 7

DISTRIBUTION OF OLIGOCENE TO RECENT PLANKTONIC FORAMINIFERA IN SAMPLES FROM THE SOUTHERN LINE ISLANDS

SAMPLE	*Pseudohastigerina micra*	*Globorotalia increbescens*	*Globigerina ampliapertura*	*Globigerina tripartita*	*Globigerina officinales*	*Globigerina praebulloides*	*Cassigerinella sp.*	*Cassigerinella chipolensis*	*Globigerina ciperoensis*	*Globigerina angulisuturalis*	*Globigerina sp.*	*Globorotalia siakensis*	*Globorotalia kugleri*	*Globigerinoides primordius*	*Globigerinoides trilobus*	*Globorotalia peripheroronda*	*Globigerinoides altiapertura*	*Globigerina bromanensis*	*Globoquadrina sp.*	*Globoquadrina altispira*	*Globigerinoides subquadratus*	*Globigerinoides sp.*	*Praeorbulina sp.*	*Praeorbulina transitoria*	*Sphaeroidenellopsis sp.*	*Orbulina sp.*	*Orbulina bilobata*	*Globorotalia mayeri*	*Globorotalia praemenardii*	*Globorotalia lenguaensis*	*Globorotalia margaritae*	*Globorotalia tumida*	*Globigerina riverosa*	*Pulleniatina sp.*	*Sphaeroidinella sp.*	*Sphaeroidinella dehiscens*	*Globorotalia tosaensis*	AGE (ZONE)
KK79-47-14																																						
KK79-47-13																			•																			
KK79-47-06															•																							
KK79-47-02																																						
KK79-46-12																				•																		Miocene to Recent
KK79-46-10																																						
KK79-46-09																																						
KK79-46-08											•																											
KK79-46-07											•																											
KK79-46-04																																						
KK79-48-01																														•							•	Plio/Pleistocene
KK79-47-17																					•					•						•		•	•			Pliocene
KK79-48-02															•					•					•						•		•			•		Pliocene
KK79-47-18							•					•							•		•				•	•		•	•									middle Miocene (N 10-13)
KK79-47-22												•				•			•	•	•					•	•	•										middle Miocene (N 10)
KK79-50-01											•		?		•					?	•			•														Miocene?
KK79-47-09															•	•			•	•	•		•															late early Miocene (N 8)
" reef deb.				?				•	•		•	•	•		•		•																					early Miocene (N 5-8)
KK79-47-08								•	•						•				•	•	•		•															late early Miocene (N 8)
" pel. cl.								•	•																													late early Miocene (N 8)
" reef deb.				•				•	•			•					•																					early Miocene (N 5?)
KK79-47-03								•	•						•				•	•				•														late early Miocene (N 7/8)
KK79-47-01								•	•						•				•	•	•		•	•														late early Miocene (N 7/8)
KK79-47-21								•	•			•			•				•	•				?														early Miocene (N 6-8)
KK79-47-07				•		?		•	•		•		•	•					•	?	•	•																early Miocene (N 4-6)
KK79-46-03				•		•		•	•				•	•	•	•	•			•	•	•																early Miocene (N 4-6)
" pel. cl.				•				•	•	?				•		•	•				•	•																early Miocene (N 5)
" reef deb.				•		•								•	•		•			•	•																	early Miocene (N 4-6)
KK79-47-20						•	•	•			•		•	•		•																						early Miocene (N 4)
KK79-47-19							•				•		•				•													?								Oligocene/Miocene
KK79-47-15													•				•	•	•																			early Oligocene with Miocene
KK79-47-11	•	•	•		•	•	?				•								•																			Oligocene (P 19)

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