THE NORTHERN HAWAIIAN DEEP AND ARCH: INTERPRETATION OF GEOLOGIC HISTORY FROM REFLECTION PROFILING AND ECHO CHARACTER MAPPING

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ABSTRACT

Analyses of reflection profiles across the Hawaiian Deep and Arch north of Kauai and Oahu, Hawaii are consistent with the major elements of earlier models devised by Menard and by Normark and Shor to explain the geologic features of these areas. These models suppose that tensional faulting on the Arch, a result of crustal loading by the Hawaiian Ridge 6-2 Ma, provided conduits for magmas to rise to the sea floor and create lava flows and volcanoes. The lavas were presumed to have been extruded atop a faulted, more than 200-m thick, archipelagic apron comprised of eroded Hawaiian Ridge material. These sediments were thought to have been deposited across the Arch prior to the formation of the present-day, sediment-trapping Deep. In this paper shallow subbottom and sea floor lithologies are investigated through the analysis of 3.5-kHz echograms, seismic reflection profiles, and deep sea core and drilling results. The nature of some shallow crustal and sea floor reflectors within the study area suggests the presence of lava flows and/or sills and accumulations (40-60 m) of volcaniclastic sediment. Other sections of sea floor within the study area appear to have experienced relatively stable and uninterrupted conditions of pelagic sedimentation over a long period of time. The stratigraphy of the Hawaiian Deep and Arch is correlated with features on the Arch interpreted to be sea floor and buried lava flows or sills. Although much of the volcanism on the Arch is probably Eocene and older, the age of most sea floor lava flows may be closer to 6-2 Ma, the time of formation of the Hawaiian Ridge. Our model differs from previous models in that: (1) The presence of Eocene and older volcanism on the Arch is recognized. Volcanism of this age, which is unrelated to the much younger formation of the Arch, includes all the large seamounts present on the Arch. (2) the lateral extent of the Hawaiian archipelagic apron is small north of Oahu; it does not extend north of 23°30′N, and (3) the sea floor of the Arch was probably characterized by an erosional unconformity before or during the construction of the Hawaiian Ridge. A comparison of present Antarctic Bottom Water (AABW) flow with the distribution of this unconformity suggests that the unconformity may be due to erosion by an intensified flow of AABW deflected around the SE-end of the Hawaiian Ridge. The possible continuation through the northern Arch area of volcanic and tectonic trends related to those of the Musicians Seamounts province to the north and the Necker Ridge to the SW is considered. Extensions of two of these linear trends (Musicians NW-SE seamount trend and the Necker Ridge) have been ruled out. If a proposed third trend (Musicians N-S 162°W seamount trend) does cross the area, the structural complexity it may have introduced appears to be small.

TABLE OF CONTENTS

ACKNOWLEDGEMENTS iii

ABSTRACT iv

LIST OF ILLUSTRATIONS. vii

PREFACE. ix

I. INTRODUCTION 1

II. THE NORTHERN HAWAIIAN ARCH: SEA FLOOR LITHOLOGY FROM 3.5-KHZ ECHO CHARACTER MAPPING, SEISMIC REFLECTION PROFILING, AND DEEP SEA CORE AND DRILLING RESULTS. 5

- Introduction. 5
- Acoustic Stratigraphy 15
  - 3.5-kHz Echograms. 15
  - Lithologic Interpretation of 3.5-kHz Echo Types. 29
    - Seismic Reflection. 34
- Observations of Shallow Crustal Structure 38
- The Origin of Anomalous Reflectors and Volcaniclastic Sediment. 61
    - Anomalous Reflectors and the 3.5-kHz Opaque Echo Type. 61
    - Volcaniclastic Sediment 66
  - Discussion 67
  - Conclusions. 70

III. IMPLICATIONS FOR PALEOSEDIMENTATION AND AGE OF VOLCANISM ON THE NORTHERN HAWAIIAN ARCH 72

- Introduction. 72
- Acoustic Stratigraphy 83
- Observations. 87
- The Significance of Reflector III 105
- The Nature and Age of Other Reflectors. 107
- Erosion and Bottom Water Flow Around the Hawaiian Ridge . 109
- The Age of Volcanism on the Arch. 114
- Discussion and Conclusions. 115

IV. SUMMARY AND RECOMMENDATIONS FOR FUTURE WORK. 121

REFERENCES CITED 125

LIST OF ILLUSTRATIONS

Figure Page

II-1 Location of the northern Hawaiian Arch study area. 7

II-2 Bathymetry of the northern Hawaiian Arch and Deep. 9

II-3 Seismic reflection track control, locations of deep-sea core and drilling results, and the locations of profiles discussed in the text. 14

II-4 Examples of the 3.5-kHz transparent layer. 18

II-5 Examples of the 3.5-kHz stratified-prolonged echo type. 20

II-6 Examples of the 3.5-kHz hyperbolic echo type 23

II-7 Examples of the 3.5-kHz opaque echo type 26

II-8 Distribution of the transparent, stratified-prolonged, opaque, and hyperbolic echo types in the study area. . . . 28

II-9 Seismic reflection profile YY′ 33

II-10 Seismic reflection profile QQ′ 37

II-11 Seismic reflection profile RR′ 40

II-12 Seismic reflection profile SS′ 42

II-13 Seismic reflection and 3.5-kHz profiles TT′. 46

II-14 Seismic reflection profile UU′ 49

II-15 Seismic reflection profile VV′ 51

II-16 Seismic reflection profile WW′ 54

II-17 Seismic reflection profile XX′ 58

II-18 Sediment isopach map of the northern Hawaiian Arch and Deep north of the principal eastern Hawaiian Islands . 60

LIST OF ILLUSTRATIONS (Continued)

Figure		Page
III-1	Location of the study area within the central Pacific and the locations of selected deep-sea core and DSDP sites discussed in the text	74
III-2	Bathymetry north of Kauai and Oahu, Hawaii showing seismic reflection track control and the location of profiles discussed in the text.	76
III-3	Schematic depiction of the Normark and Shor model for development of the northern Hawaiian Deep and Arch	79
III-4	Sediment isopach map of the northern Hawaiian Arch and Deep north of the eastern Hawaiian Islands	82
III-5	Seismic reflection profile XX′	85
III-6	Seismic reflection profile ABCD.	89
III-7	Interpretation of seismic reflection profile ABCD	91
III-8	Seismic reflection profile EFG	94
III-9	Interpretation of seismic reflection profile EFG	96
III-10	Seismic reflection profile YY′	99
III-11	Seismic reflection profile ZZ′	102
III-12	Seismic reflection profile HH′	104
III-13	Proposed flow of AABW in the central Pacific (after Edmond et al., 1971).	111
III-14	Schematic representation of the formation of the northern Hawaiian Arch and Deep (modified from Normark and Shor, 1968).	118

PREFACE

This thesis is a composite of two papers. The first paper, appearing as Chapter II, was co-authored with L. N. Frazer; the second paper, appearing as Chapter III, was co-authored with K. Nemoto. Each paper was submitted to the journal Marine Geology prior to the the completion of this thesis. The initial topic of the thesis and plan for marine field work was developed by R. Moberly, J. F. Campbell, and J. M. Sinton. I formulated the basic goals, objectives, and science of the the thesis. L. N. Frazer read innumerable drafts and provided support and advice. K. Nemoto shared in the interpretation of the seismic reflection and 3.5-kHz data, particularly that in Chapter III, and also helped develop many of the ideas in both Chapters II and III. To all of the above people, I give my sincere thanks.

CHAPTER I

INTRODUCTION

The northern Hawaiian Deep and Arch are thought to be products of the lithosphere's elastic response to the load of the Hawaiian Ridge (Menard, 1964; Walcott, 1970; Crough, 1978). The crust surrounding this large sea floor load is depressed into an encircling moat, the Hawaiian Deep, which was first discovered in the eastern Hawaiian Islands from transects of early recording echo-sounding bathymetry, and from analyses of gravity data. Later, as good bathymetry became available, the Hawaiian Deep was found to be a somewhat continuous feature around the Hawaiian Islands (Dietz and Menard, 1953; Hamilton, 1957). The Hawaiian Deep is itself surrounded by a broad upwarp of sea floor known as the Hawaiian Arch, an artifact of the flexure of an elastic crust. The Hawaiian Deep and Arch are more prominent on the north side of the Hawaiian Ridge than on the south; this is probably due to infilling of the Deep on the south by Hawaiian volcanic debris delivered from prevailing winds.

In addition to these features, the earliest investigators also recognized that the Hawaiian Ridge, Deep, and Arch are situated on a anomalously shallow broad section of sea floor, parallel in trend to the Hawaiian Ridge, making even the deepest portions of the Deep shallower than the average 5500-m depth of the main Pacific basin. This regional depth anomaly, together with the Hawaiian Ridge, Deep, and Arch have been collectively termed the Hawaiian Swell; the depth anomaly is not well understood, but is thought to be a young thermal feature related to the presence of the Hawaiian hot-spot (Crough, 1978; Von Herzen et al., 1982).

In the early 1960's, the northern Hawaiian Deep and Arch were investigated through numerous geological and geophysical projects motivated by the search for a potential site to drill to the Mohorovicic discontinuity. Additional projects followed in the late 1960's including seismic reflection and refraction experiments, Deep Tow magnetics, side-scan sonar, and bathymetry (Scripps Institution of Oceanography), bottom photography and current determinations, and deep-sea coring. Work in these areas culminated with the drilling of Deep Sea Drilling Project (DSDP) Site 67 on the Arch near the proposed Mohole Site; there has been nominal effort since.

Some of the fundamental observations of the sea floor in these areas are as follows:

(1) The sea floor is smooth in the Deep, changing to an abruptly rougher terrain on the Arch. In addition to numerous seamounts and oriented ridges, the sea floor is characterized by a general second-order roughness (varying 0-30 m).

(2) Sediment cover has been found to be thin (<200 m). Because of acoustically reflective sea floor and subbottom layers, lateral inhomogeneity, and thin sediment, easily interpretable seismic

reflection records are difficult to obtain.

(3) There are many small ridges and seamounts on the Arch, most of which exhibit linear trends, predominately of ENE-strike, but also of E-strike and perhaps SE-strike. Their origins are unknown.

(4) There are a few scattered large seamounts on the Arch. Their origins are unknown.

(5) Three investigations have concluded that the products of local volcanism are at or near the sea floor on the Arch; the first two (Normark and Shor, 1968; Speiss et al., 1969) concluded it was the result of late Cenozoic-age activity, and the third, drilling at DSDP Site 67 (Winterer et al., 1971), interpreted volcanic sandstones and mudstone to be Eocene in age, but did not discount the possibility of late Cenozoic activity.

The activities of this thesis have been directed, in general, toward explaining the five observations/conclusions listed above. I have evaluated data of three differing types: seismic reflection profiling, 3.5-kHz echograms, and deep-sea core and drilling results. Most of the reflection and 3.5-kHz data used were collected by the Hawaii Institute of Geophysics on two cruises to these areas in 1980 (R/V KANA KEOKI), and by the USGS during a 1978 transit of the R/V LEE. All available deep sea core and drilling results were used; the majority are from Scripps Institution of Oceanography and Lamont-Doherty Geological Observatory. Chapter II discusses the present sea floor lithology of the region as interpreted from the mapping of 3.5-kHz echo character, interpretation of seismic reflection records, and correlation with deep sea core and drilling results. The distribution of sea floor lava flows, interpreted from 3.5-kHz echo character mapping and reflection records, is mapped and presented along with other sediment facies boundaries. Chapter III begins with the analysis of seismic reflection records in the Hawaiian Deep, where the stratigraphy is thickest and least disturbed, and traces this stratigraphy up the inner flank of the Hawaiian Arch, relating the probable nature and age of subbottom and sea floor reflectors to the sea floor lithologic types established in Chapter II. A summary of results and some recommendations for future work are presented in Chapter IV.

CHAPTER II

THE NORTHERN HAWAIIAN ARCH: SEA FLOOR LITHOLOGY FROM 3.5-KHZ ECHO CHARACTER MAPPING, SEISMIC REFLECTION PROFILING, AND DEEP SEA CORE AND DRILLING RESULTS

INTRODUCTION

The Hawaiian Arch is the broad gentle upwarp forming the outer boundary of an inner flanking Deep around the Hawaiian Ridge (Figure II-1). The fine scale bathymetry of the Arch is complex, populated by numerous relatively small (200-1000 m) faulted and constructional sea floor features. Other investigators have noted the fact that groups of these sea floor structures exhibit preferred linear trends and many patterns can be seen in the bathymetry of Figure II-2. The Necker Lineations (Naugler, 1968) strike ENE, while a different group of lineations trends E-W (Menard, 1959), and perhaps yet a third group may trend NW-SE (Speiss et al., 1969). In this paper we examine the shallow crustal structure of a portion of the northern Arch using seismic reflection profiles and 3.5-kHz echograms.

The Hawaiian Ridge, Deep, and Arch are superimposed on the broad elongate Hawaiian Swell (Betz and Hess, 1942; Dietz and Menard, 1953). The Swell is a large shallow area of sea floor that is about 1300 km wide (Dietz and Menard, 1953) and crests at a depth of 4250 m (Crough, 1978), well above the regional 5500-m depth of the main Pacific basin.

Figure II-1: Location of the northern Hawaiian Arch showing the study area enclosed by a heavy black line and the locations of the Musicians NW-SE seamount trend, N-S 162°W seamount trend, and Necker Ridge.

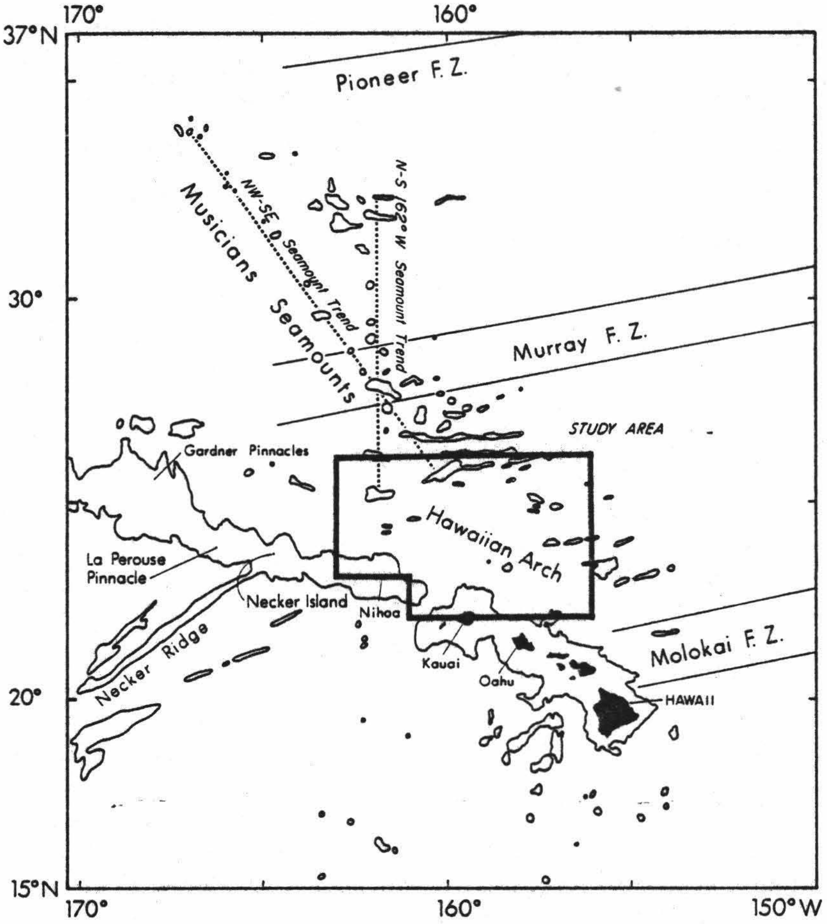
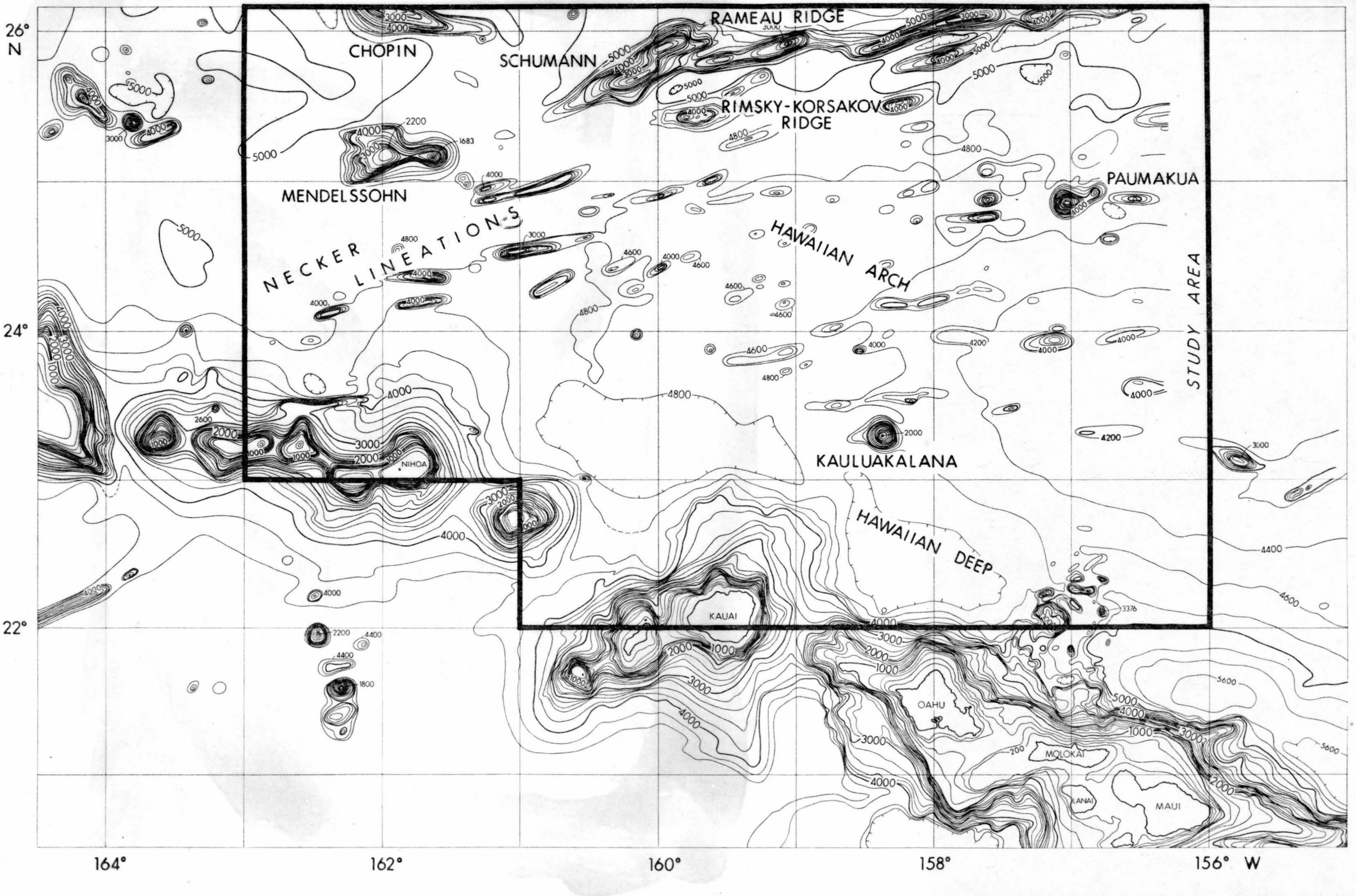

170°
160°
37°N
30°
20°
15°N
170°
160°
150°W
Pioneer F. Z.
NW-SE Seamount Trend
N-S 162° W Seamount Trend
Musicians Seamounts
Murray F. Z.
STUDY AREA
Gardner Pinnacles
Hawaiian Arch
La Perouse Pinnacle
Necker Island
Nihoa
Necker Ridge
Kauai
Oahu
Molokai F. Z.
HAWAII

Figure II-2: Bathymetry of a portion of the principal Hawaiian Islands and the seafloor to the north. Compiled from Naugler (1968), Wilde et al. (1980), and unpublished HIG data. The contour interval is 200 m.


RAMEAU RIDGE
CHOPIN
SCHUMANN
RIMSKY-KORSAKOV RIDGE
MENDELSSOHN
NECKER LINEATIONS
HAWAIIAN ARCH
PAUMAKUA
STUDY AREA
KAULUAKALANA
HAWAIIAN DEEP
NIHOA
KAUAI
OAHU
MOLOKAI
LANAI
MAUI
26° N
24°
22°
164°
162°
160°
158°
156° W
5000
4800
4600
4400
4200
4000
3000
2200
2000
1683
1000
5600
3376
1800

The Deep and Arch are considered to be secondary features created by elastic flexure of the lithosphere, caused by the load of the Hawaiian Ridge on the hot-spot Swell (Menard, 1964; Walcott, 1970; Crough, 1978). Although the amplitude of the Arch does vary considerably, it is generally about 500 m shallower than the axis of the Deep and 1400 m shallower than the main Pacific basin (Watts, 1976). North of the Hawaiian Ridge at 156°W, it is about 1200 m shallower than the Deep, whereas farther to the west, between 161° and 163°W, there is a saddle in the Arch and its bathymetric amplitude is virtually nil.

The lithosphere underlying the southern Musicians area and the northern Hawaiian Arch and Deep was formed during the Cretaceous magnetic quiet interval, so its age is not well known. A simple interpolation between anomaly 34 to the east (80 Ma; Ness et al., 1980) and Mesozoic anomaly M-0 far to the west (109 Ma; Larson and Hilde, 1975) results in a Late Cretaceous age (80-90 m.y.) for this portion of oceanic crust between the Murray and Molokai Fracture Zones.

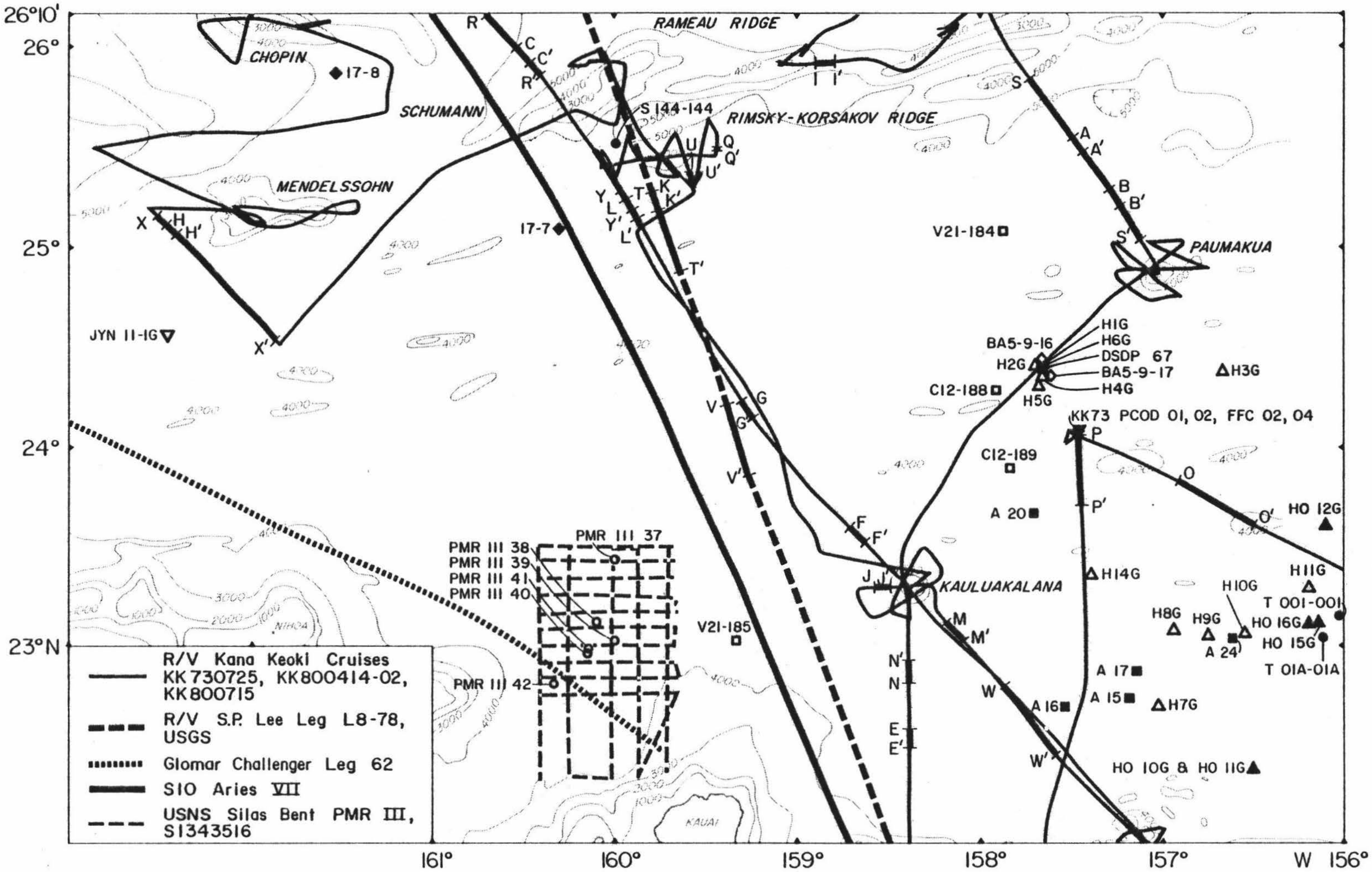
As a potential Mohole project site, the northern Hawaiian Arch was the focus of numerous geological and geophysical investigations in the early to mid-1960's. Evidence that the products of relatively young volcanism may be present on the Arch is abundant and supported by results from seismic reflection profiles (Normark and Shor, 1968), deep-sea cores, Deep Tow magnetics, side-scan sonar, bottom photographs (Speiss et al., 1969), and other deep-sea core samples (Schreiber, 1968; Horn et al., 1970). Subsequent Deep Sea Drilling Project (DSDP) drilling at Site 67 on the Arch encountered a sequence of volcanic sandstones and mudstones to about 60-m depth where a hard, cherty layer stopped the bit. Displaced radiolarians in mud from a core at 60 m were taken to indicate that sediments of Eocene-Paleocene boundary age are present somewhere above 60-m depth (Winterer et al., 1971). Because the section from which these samples were recovered partially onlaps and buries a nearby small ridge, the ridge must be of Eocene-Paleocene boundary age or older. These results suggest that perhaps a portion of the numerous constructional and faulted sea floor morphologies on the Arch are not of late Cenozoic age, as Normark and Shor postulated (1968), but much older.

The proximity of a major volcanic region, the Musicians Seamount province, immediately to the north of the northern Arch, makes it possible that the Arch region has experienced volcanic and tectonic events related to those of the Musicians. The true southern boundary of the Musicians Seamount province is not clear; generally it has been considered to lie south of Mendelssohn Seamount at 25°N, continuing to the ENE along Schumann Seamount and Rameau Ridge to 26°N. Moberly et al. (1982, submitted) suggest that elements of the Musicians province may extend to the south underneath the Hawaiian Ridge; they note the occurrence of clusters of seamounts and individual seamounts there, some of which align well with linear trends in the Musicians Seamount province. The locations of two prominent linear seamount trends in the Musicians, the NW-SE trend and the N-S 162°W trend (Rea and Naugler, 1971), are shown in Figure II-1. The Musicians province, although composed of many disparate seamount trends, ridges, and individual seamounts, seems to be predominately Late Cretaceous in age (Clague and Dalyrmple, 1975; M. Pringle, personal communication, 1982). Ar 40/39 total fusion dates of dredged rocks from two seamounts on the northern Hawaiian Arch show Late Cretaceous ages for both (M. Pringle, personal communication, 1982) and conventional K-Ar dating of rocks from some of the seamounts south of the Hawaiian Ridge has also given Late Cretaceous ages (Dymond and Wyndom, 1968).

Taken together, the trends and ages of the surrounding physiographic elements, the complicated bottom morphologies, and other geophysical and geological data suggest that the northern Hawaiian Arch and Deep has experienced a variety of volcanic and tectonic events since 90-80 Ma. We have identified three basic questions which pertain to a study of shallow crustal structure here: (1) What is the nature, distribution, and age(s) of volcanic activity subsequent to the formation of the underlying oceanic crust? (2), a related question, What are the origins of the various assorted groups and individual edifices? and (3) Do any of the seamount chains and structural trends associated with the Musicians Seamount province and the Necker Ridge cross this region?

To address these questions, two 1980 Hawaii Institute of Geophysics (HIG) cruises investigated a portion (22° to $26^{\circ}10'$N, 156° to 163°W; Figure II-3) of the Hawaiian Arch north of the principal Hawaiian Islands. The collected underway geophysical data include 3.5-kHz Precision Depth Recorder (PDR) echograms, seismic profiler

Figure II-3: Simplified bathymetry of the study area showing seismic reflection and 3.5-kHz track control, the locations of profiles discussed in the text, and the locations of deep-sea core and drilling samples. The representation of the core symbols is as follows: solid squares, Scripps Institution of Oceanography (SIO) SHOW-A expedition; open squares, Lamont-Doherty Geological Observatory (LDGO) cruises V-21 and RC-12; solid circles, Oregon State University (OSU) cruises SU 421 and TT 028; open circles, SIO PMR III cruise S1343516; solid diamonds, Lair and Sanko (1968); open diamonds, Schreiber (1968); solid triangles, SIO HILO expedition; open triangles, SIO SHOW-H expedition; open inverted triangle, JAPANYON expedition; solid inverted triangle, HIG cruise KK730725; and solid star, DSDP Site 67. Seismic reflection profiling was available for all cruises with the exception of KK730725 and S1343516. 3.5-kHz track control was provided by data from cruises KK800715, KK800414-02, KK730725, S1343516, and USGS L8-78.



26°10'
26°
25°
24°
23°N
161°
160°
159°
158°
157°
W 156°
RAMEAU RIDGE
CHOPIN
17-8
SCHUMANN
RIMSKY-KORSAKOV RIDGE
S 144-144
MENDELSSOHN
17-7
V21-184
PAUMAKUA
JYN 11-1G
BA5-9-16
H2G
H5G
H1G
H6G
DSDP 67
BA5-9-17
H4G
H3G
C12-188
KK73 PCOD 01, 02, FFC 02, 04
C12-189
A 20
HO 12G
H14G
H11G
H10G
T 001-001
H8G
H9G
HO 16G
HO 15G
A 24
T 01A-01A
A 17
A 15
A 16
H7G
HO 10G & HO 11G
KAULUAKALANA
V21-185
PMR III 37
PMR III 38
PMR III 39
PMR III 41
PMR III 40
PMR III 42
NIHOA
KAUAI
R
R'
C
C'
I
I'
S
S'
A
A'
B
B'
U
U'
Q
Q'
Y
Y'
L
L'
T
T'
K
K'
X
X'
H
H'
V
V'
G
G'
F
F'
J
J'
M
M'
N
N'
E
E'
W
W'
P
P'
O
O'
3000
4000
5000
2000
1000
R/V Kana Keoki Cruises KK730725, KK800414-02, KK800715
R/V S.P. Lee Leg L8-78, USGS
Glomar Challenger Leg 62
SIO Aries VII
USNS Silas Bent PMR III, S1343516

records, and digital seismic reflection lines using airgun and MAXIPULSE (explosive) sound sources. Additional seismic profiling and 3.5-kHz bathymetry data were obtained from other ship transits of the area. The ship tracks and deep-sea core and drilling sample locations used in this study appear in Figure II-3.

ACOUSTIC STRATIGRAPHY

This study evaluates seismic reflection data, in the frequency range of 10-250 Hz, and 3.5-kHz PDR echograms. Because methods of describing and interpreting these data differ, it is appropriate to consider the nomenclature and methods of study of each separately. To avoid confusion, the higher frequency PDR echograms will be referred to as "3.5-kHz echograms" and the lower frequency reflection data will be called "seismic reflection" records. For estimating sediment thicknesses, we assume a sediment sonic velocity of 1.7 km/sec. This was the average velocity of the upper part of the sediment column at DSDP Site 67 (Winterer et al., 1971).

3.5-kHz Echograms

Numerous studies have shown that the high-frequency PDR can be a sensitive indicator of near-bottom sedimentation processes on the deep-sea floor (Damuth, 1975; 1980; Shipley, 1978). For this study area we have developed a fourfold classification of acoustic layers or units, based on the character of the returning echo. The units are:

(1) a transparent layer, (2) a stratified-prolonged layer, (3) a hyperbolic echo type with three different subtypes, and (4) an opaque echo type.

The transparent layer (Figure II-4, AA′, BB′, CC′, DD′) is "transparent" to the frequencies of the 3.5-kHz PDR, MAXIPULSE, and airgun systems. It is characterized by a moderate to strong sharp bottom echo, thickness commonly 30 m but ranging from 20 to 55 m, and occasional internal stratification only in the upper 15 m. This echo type is similar to the transparent layer described by Nemoto and Kroenke (1981) around the Hess Rise. Sometimes a thin transparent layer (less than 10 m thick), different from the one described above, can be observed atop the stratified-prolonged echo type. When present, it thins and disappears over relatively short distances. We consider this second transparent layer to be of minor importance and thus ignore it in the following discussion.

The stratified-prolonged echo type (Figure II-5, EE′, FF′ ,GG′ ,HH′) is characteristically found in areas of smooth seafloor and is distinguished by a semi-prolonged to very prolonged bottom echo. It is termed both "stratified" and "prolonged" because the echo type is gradational from a semi-prolonged stratified layer, through a increasingly prolonged layer with discontinuous stratification, to a fully prolonged echo with no stratification evident. When observable, the stratified layer ranges in thickness from 20 to 35 m. At some locations the stratified-prolonged layer wedges onto the transparent layer (as in Figure II-4, CC′).

Figure II-4: Examples of the 3.5-kHz transparent layer. The locations of profiles are shown in Figure 3. AA′ NW of Paumakua Seamount shows a moderate to strong sharp bottom echo, thickness of 25 m, and stratification in the upper 12 m. At the SE end of AA′ the transparent layer is overlain by a small accumulation of sediment of stratified-prolonged acoustic character. BB′ NW of Paumakua Seamount shows a transparent layer which maintains a relatively constant thickness and is progressively buried to NW by sediment of stratified-prolonged acoustic character. CC′ from NW of Schumann Seamount shows a transparent layer in the NW becoming progressively obscured to the SE by sediment of stratified-prolonged acoustic character. Total penetration is about 30 m. DD′ from NE of Bach Ridge in the southern Musicians province shows distinct bottom reflection, no apparent stratification within transparent layer, and relatively constant thickness of layer (25 m). The location of the profile is 27°30′N, 158°W, within the southern Musicians province and south of the Murray Fracture Zone.

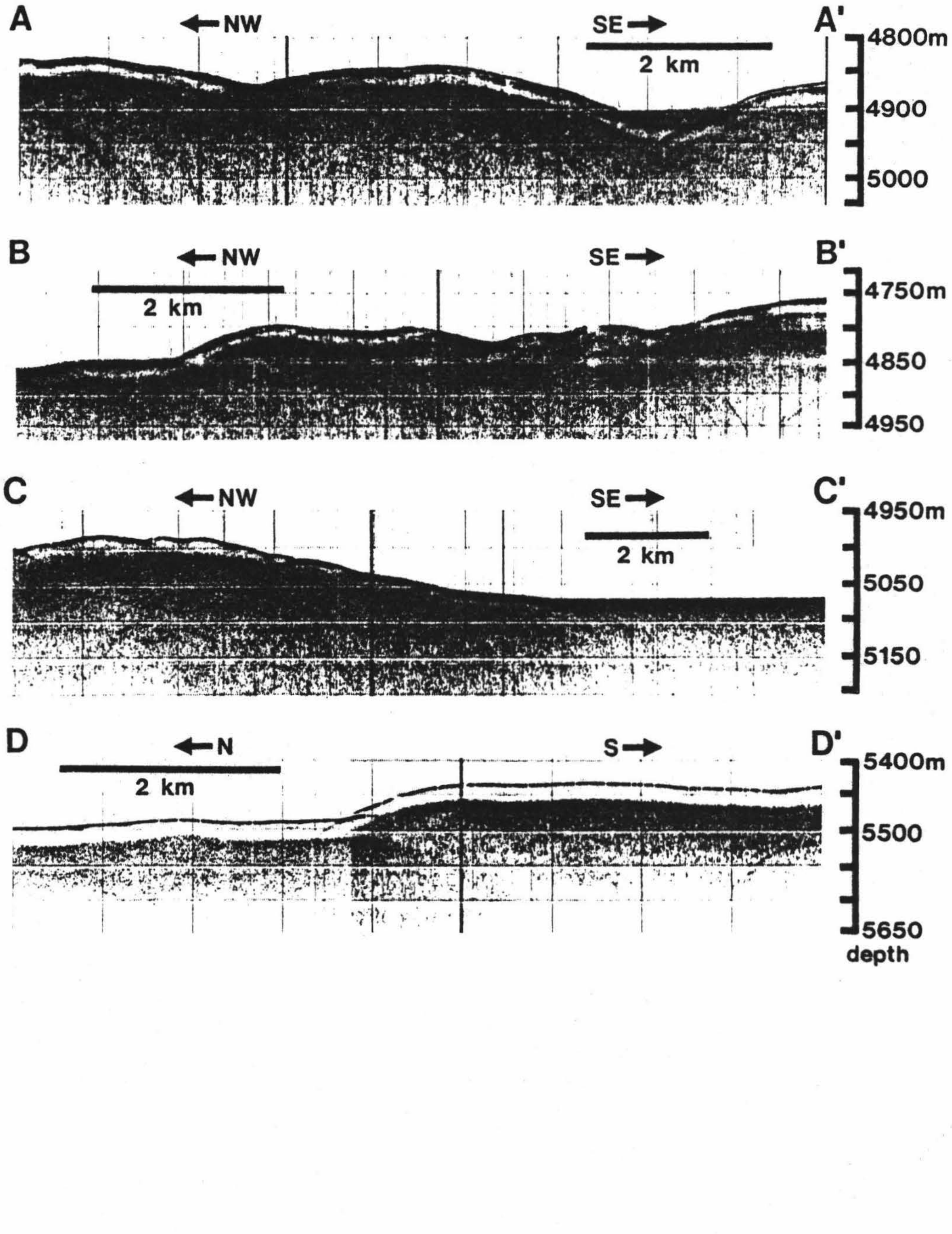
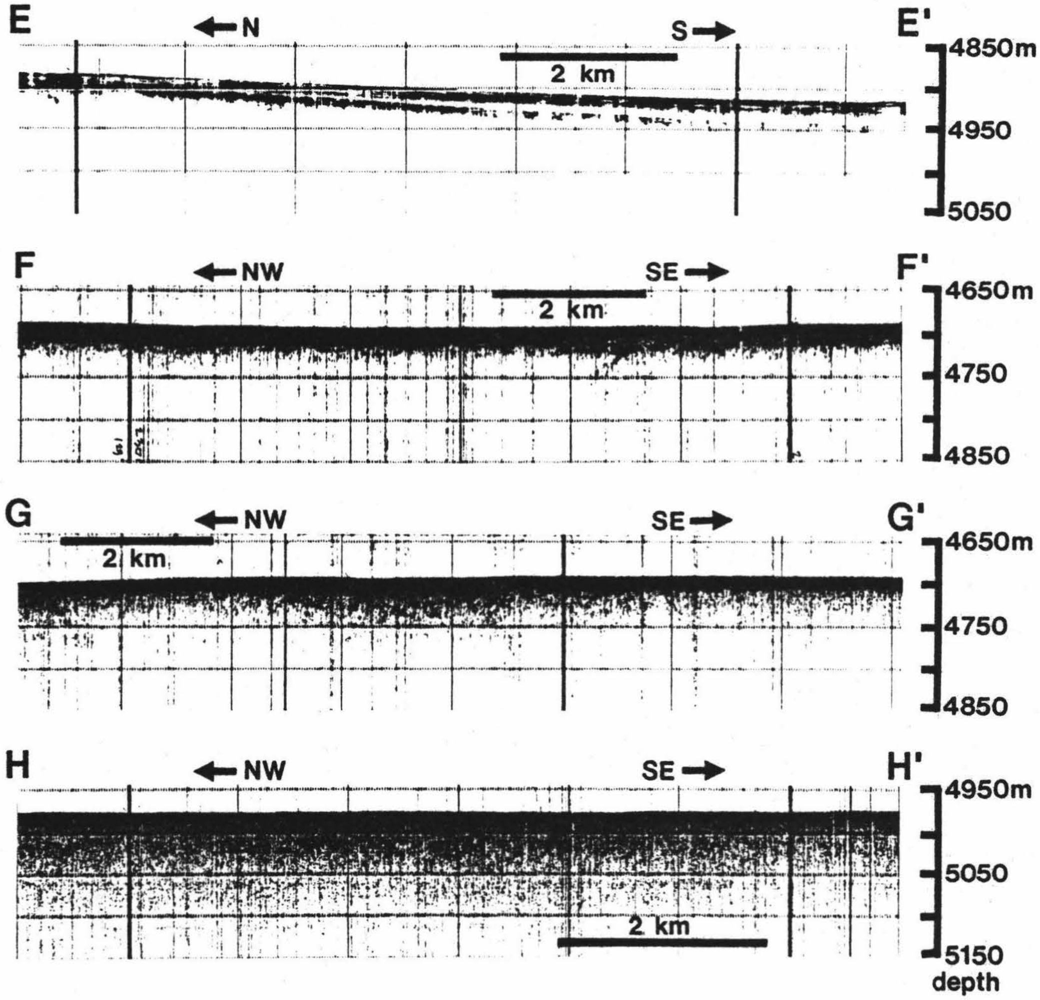

A
← NW
SE →
A'
2 km
4800m
4900
5000
B
← NW
SE →
B'
2 km
4750m
4850
4950
C
← NW
SE →
C'
2 km
4950m
5050
5150
D
← N
S →
D'
2 km
5400m
5500
5650
depth

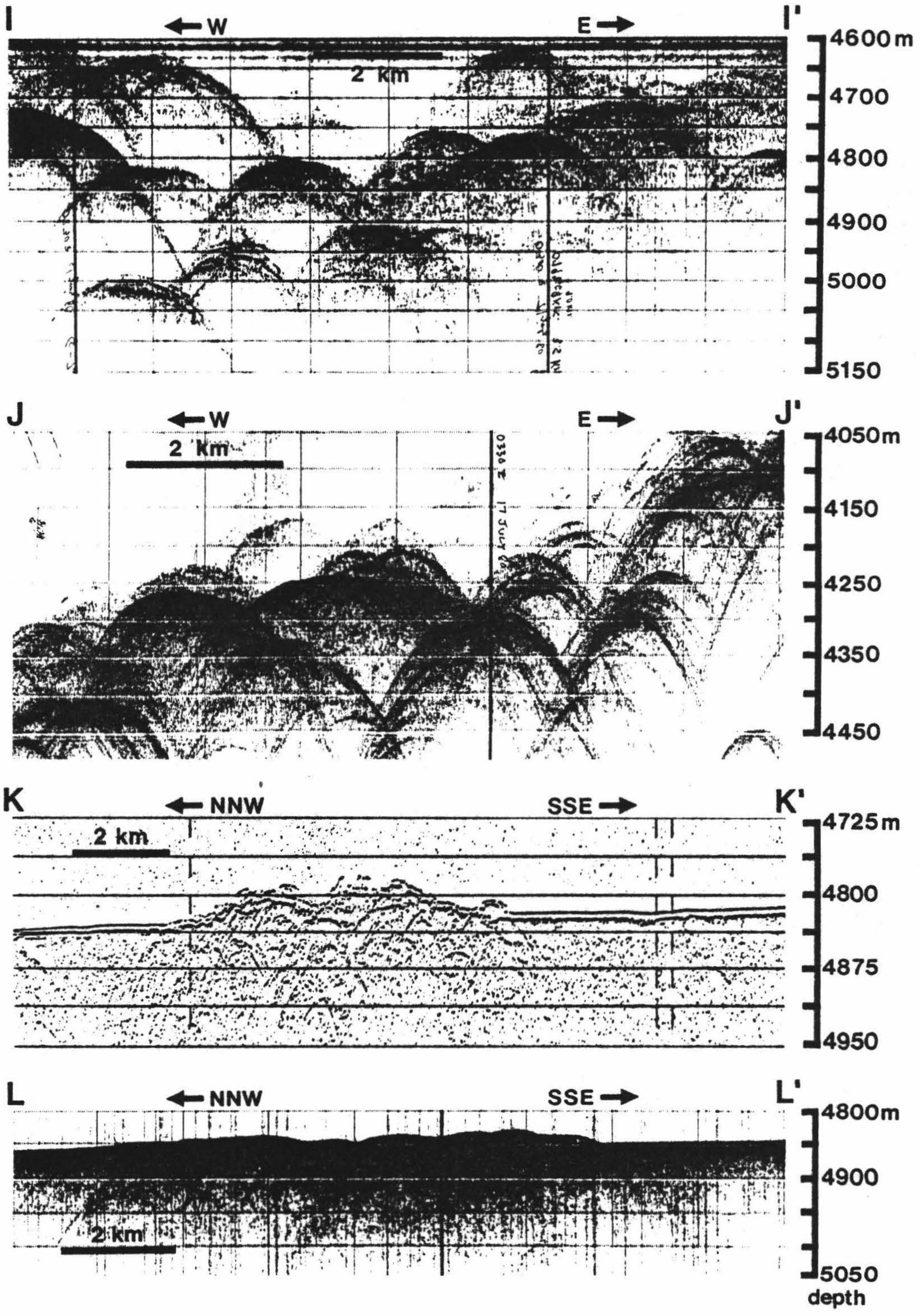
Figure II-5: Examples of the 3.5-kHz stratified-prolonged echo type. In every occurrence, this echo type is associated with a smooth sea floor bathymetry. EE′ south of Kauluakalana Seamount in the Hawaiian Deep shows numerous closely spaced indistinct subbottom reflectors that wedge out northward toward the Arch. Maximum penetration is about 35 m. FF′ NW of Kauluakalana Seamount shows discontinuous intermittent stratification of numerous closely spaced reflectors, and a more prolonged character of the returning echo. GG′ in the central Arch region shows an increasingly prolonged echo with occasional indistinct stratification. In HH′ south of Mendelssohn Seamount, the prolonged character of the echo obscures any stratification which may be present.


E
← N
S →
E'
2 km
4850m
4950
5050
F
← NW
SE →
F'
2 km
4650m
4750
4850
G
← NW
SE →
G'
2 km
4650m
4750
4850
H
← NW
SE →
H'
2 km
4950m
5050
5150
depth

In general, the degree to which the returning echo is prolonged increases toward the bathymetric center of the Arch. In the Hawaiian Deep the stratified-prolonged unit shows numerous parallel to subparallel reflectors (Figure II-5, EE´) that are often too closely spaced to be resolved. Some of these upper reflector beds can be observed to thin and pinch out northward toward the Arch. To the north, across the Arch, subbottom reflectors become progressively more difficult to discern (Figure II-5, FF´, GG´), particularly north of 24°N. Farther to the north and northwest, away from the Hawaiian Ridge, stratification is usually not evident (Figure II-5, HH´), except in some low areas surrounding major edifices. The stratified-prolonged echo series is similar to an echo type series that Damuth and Hayes (1977) and Damuth (1978) observed in the Atlantic (echo types IB, IIA, and IIB; Damuth and Hayes, 1977).

The hyperbolic reflectors (Figure II-6, II´, JJ´, KK´, LL´) can be divided into three subtypes based on the sizes of the hyperbolae displayed and the relationships of their vertex elevations. We have included only the first subtype in our mapping of the hyperbolic echo types. The first and most common subtype (II´, JJ´) consists of large, irregular, overlapping or single hyperbolae with widely varying vertex elevations above the sea floor. A second subtype of hyperbolic unit (KK´, LL´) consists of regular, overlapping hyperbolae with vertex elevations that vary by only 10 to 70 m. This subtype is rare, occurring only on the outer limb of the Arch. A third subtype consists of regular overlapping hyperbolae with vertices tangent to the sea

Figure II-6: Examples of 3.5-kHz hyperbolic echo types. II′ from Rameau Ridge shows strong irregular hyperbolae of widely varying vertex elevations and wavelength. JJ′ from the west flank of Kauluakalana Seamount shows irregular hyperbolae with widely varying vertex elevations and wavelength. KK′ and LL′ south of Rimsky-Korsakov Ridge show regular overlapping hyperbolae with vertex elevations which vary by 20-70 m. Distribution of hyperbolae is laterally restricted and no subbottom reflectors can be observed.


I
← W
E →
I'
2 km
4600 m
4700
4800
4900
5000
5150
J
← W
E →
J'
2 km
4050 m
4150
4250
4350
4450
K
← NNW
SSE →
K'
2 km
4725 m
4800
4875
4950
L
← NNW
SSE →
L'
2 km
4800 m
4900
5050
depth

floor or subbottoms. This subtype is present along the bottom and subbottoms in the Hawaiian Deep and on the outer limb of the Arch south of Rimsky-Korsakov Ridge. These three hyperbolic echo subtypes appear in the classification scheme of Damuth and Hayes (1977) as echo types IIIA, IIIC, and IIID, respectively.

The opaque unit (Figure II-7, MM′, NN′, OO′, PP′) is an unusually strong and prolonged reflection that completely masks any subbottom reflectors that may be present. The prolonged quality is associated with the increasing roughness of the sea floor in the opaque echo type areas, in which bathymetric variations are on the order of 10-30 m. Sea floor reflectivity also increases abruptly in the opaque echo type areas, as indicated by the greater number of water column multiples on seismic reflection records. The opaque echo type is usually observed adjacent to the stratified-prolonged echo type; the transition is sharp and often characterized by a strong hyperbola (as in profiles MM′,OO′; Figure II-7). At these transitions the more prolonged character of the opaque echo type, when compared to the stratified-prolonged echo type, is clearly evident.

The distribution of the four acoustic units is shown in Figure II-8. Initially we mapped the echo types along the ship tracks only, but later, as we discovered the unique association of certain echo types with specific sea floor bathymetric types, we were able to map some areas for which we had no 3.5-kHz echograms. A study of sea floor character by Harian (1967, his Figure 9) was helpful in mapping the echo type distribution for areas in which data were sparse. It can be

Figure II-7: Examples of the 3.5-kHz opaque echo type. MM′ SE of Kauluakalana Seamount shows areas of opaque echo type abutting zones of stratified-prolonged echo type. Note the rougher sea floor topography (10-30 m) and prolonged echo associated with the areas of the opaque echo type. NN′ south of Kauluakalana Seamount in the Hawaiian Deep shows stratified-prolonged echo type areas abutting areas of opaque echo type. OO′ east of Kauluakalana Seamount shows a central elevated area of hyperbolic echo type surrounded by a margin of opaque echo type. On the NW side the transition of stratified-prolonged echo type to the opaque echo type is abrupt and the indistinct subbottom reflectors in the stratified layer terminate at the boundary. PP′ from the inner flank of the Arch NE of Kauluakalana Seamount shows a small seamount 450-m high flanked by a margin of opaque echo type.

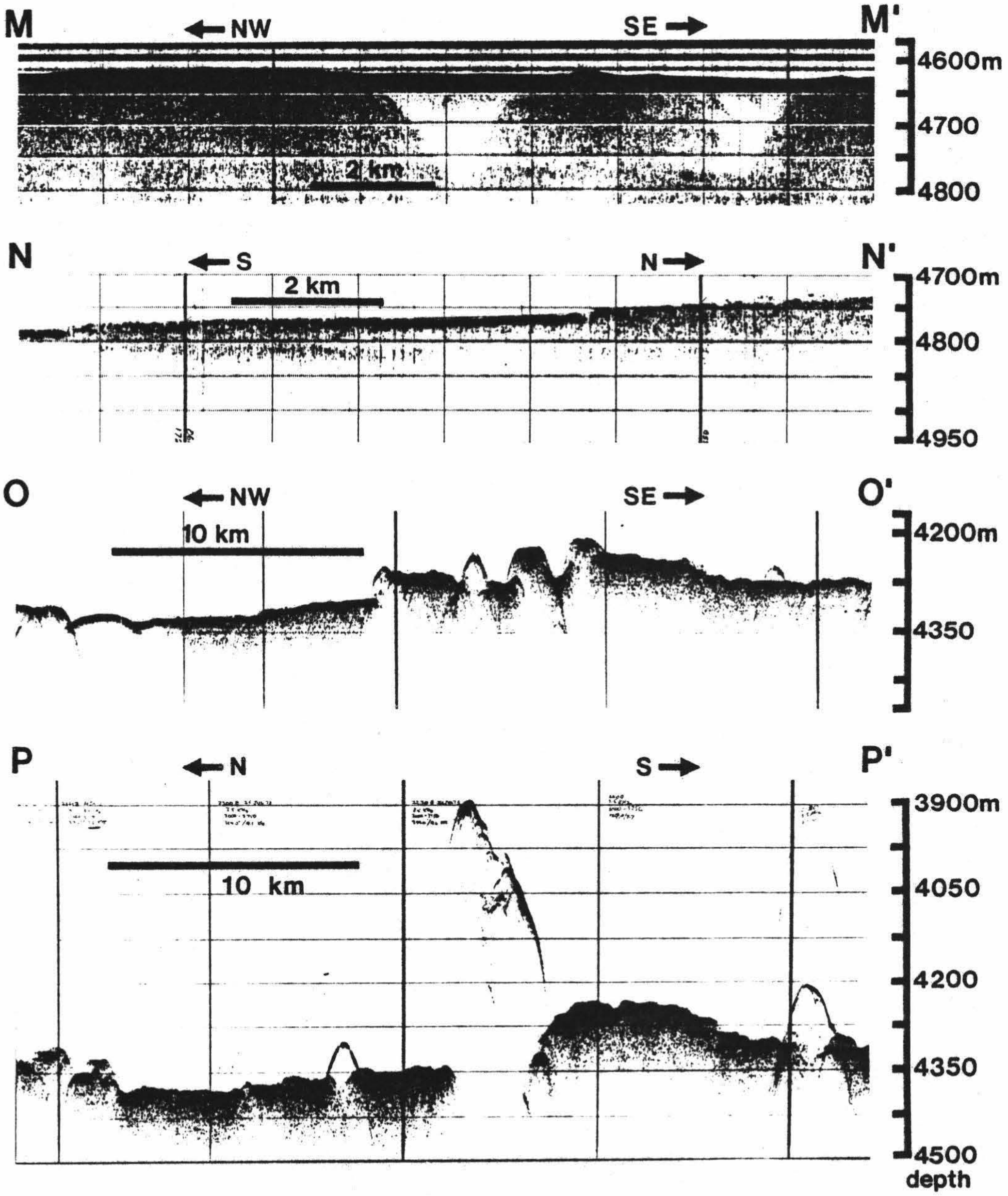
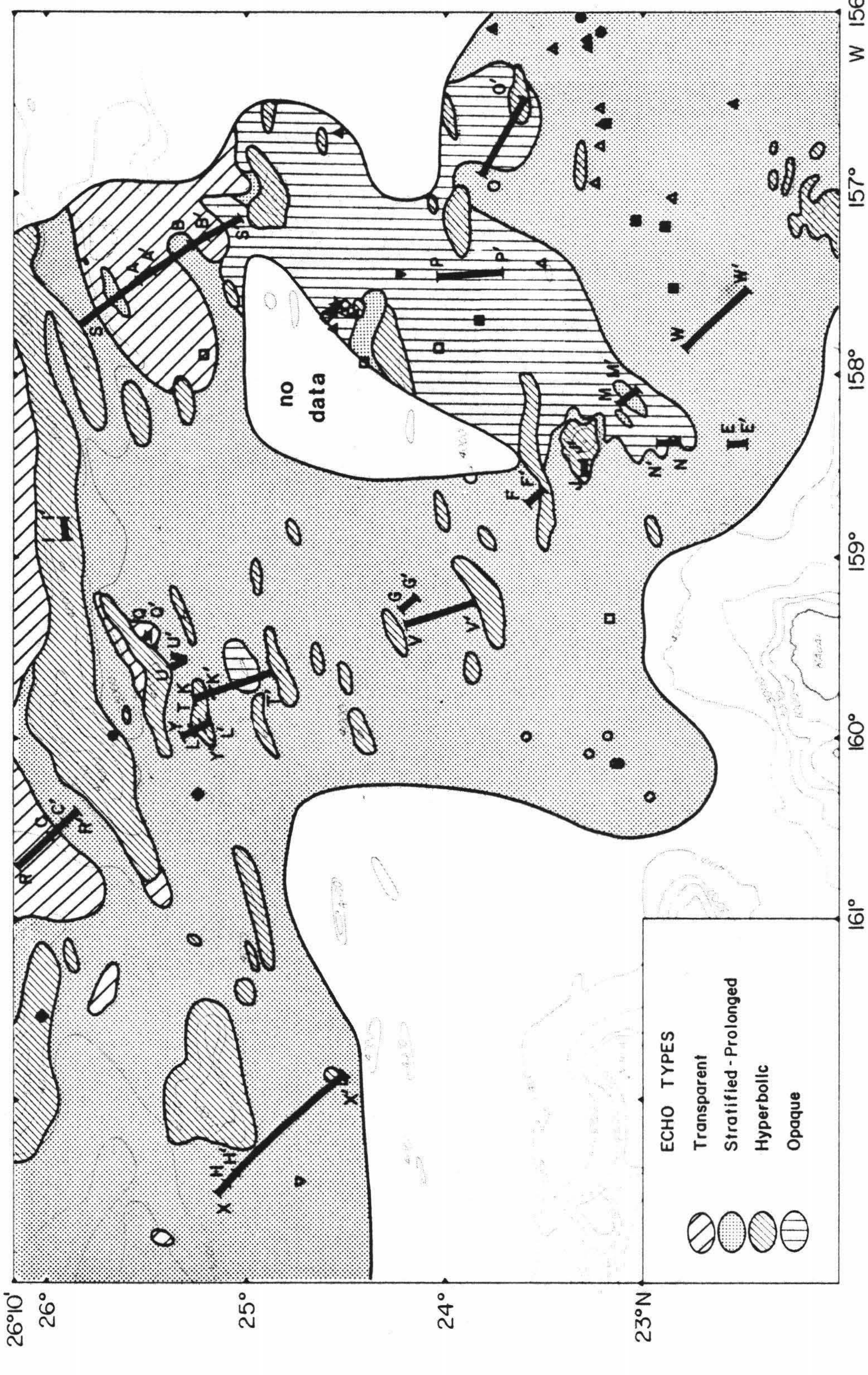

M
← NW
SE →
M'
4600m
4700
4800
2 km
N
← S
N →
N'
2 km
4700m
4800
4950
O
← NW
SE →
O'
10 km
4200m
4350
P
← N
S →
P'
10 km
3900m
4050
4200
4350
4500
depth

Figure II-8: Distribution of the transparent, stratified-prolonged, opaque, and hyperbolic echo types in the study area. Symbols as in Figure 3. Data from Harian (1967) were especially helpful in ascertaining echo type character in the region of 24° to 25°30′N, 157° to 159°W, for which our 3.5-kHz track control was poor. Most of the study area is characterized by the stratified-prolonged echo type. The transparent layer occurs only in the north of the study area and the opaque echo type is an important constituent in the east. The hyperbolic echo type is mapped on or in proximity to most sea floor edifices.


26°10'
26°
25°
24°
23°N
W 156°
157°
158°
159°
160°
161°
no data
ECHO TYPES
Transparent
Stratified - Prolonged
Hyperbolic
Opaque

seen at once that the stratified-prolonged echo is by far the most widespread echo type. The opaque layer is generally confined to the central Arch region and the transparent layer occurs only in the north. The hyperbolic echo type is mapped on or in proximity to most sea floor edifices. We discuss the significance of these units in the following section.

Lithologic Interpretation of 3.5-kHz Echo Types

Examination of the available deep-sea core data for this region (Theyer and Mato, 1977; R/V VEMA cruise 21, cruise 32, and R/V CONRAD cruise 12 megascopic core descriptions; Kelly et al., 1975; Schreiber, 1968; Lair and Sanko, 1968; NGSDC core curator file descriptions-OSU cruises SU421 and TT028, and SIO SHOW-A, SHOW-H, HILO, and JAPANYON expedition core descriptions) and drilling results (Winterer et al., 1971) indicate the presence of a particular lithology or sea floor morphology for each 3.5-kHz echo type.

The transparent layer is a largely unfossiliferous brown pelagic clay. It blankets wide areas of sea floor to the north (Ewing et al., 1968; Hayes, 1975) and in the Musicians province and its thickness varies from 25 to 40 m (Figure II-4, profile DD′ is from the southern Musicians). The layer is transparent because it lacks sharp acoustic impedance boundaries. It is frequently covered by thicknesses of sediment associated with the younger stratified-prolonged echo type (as in Figure II-4, CC′). The lack of reflectors within the transparent layer, coupled with the low sedimentation rates typical for this area

?

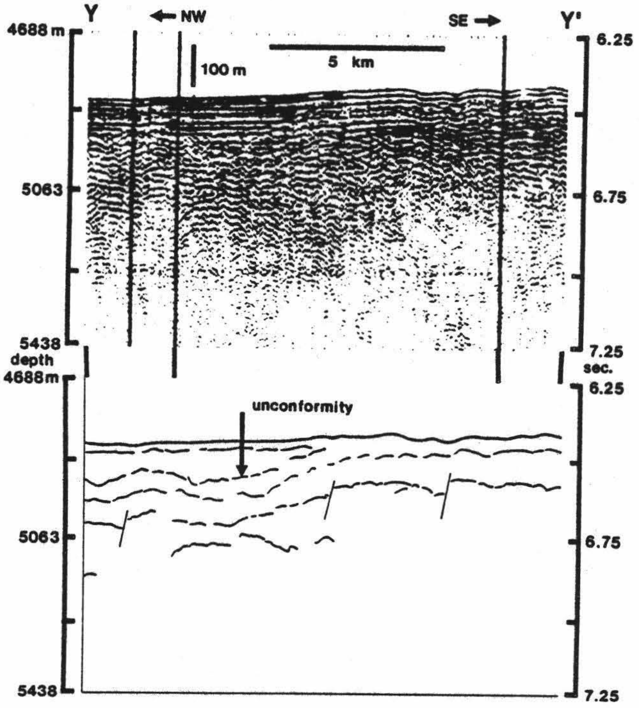
(less than 1 m/my; Winterer et al. 1971; Hayes, 1975; Prince et al., 1980) suggest that relatively stable and uninterrupted conditions of sedimentation have existed over a long period of time (Shipley, 1978).

When cored, the stratified-prolonged layer shows a diverse range of compositions from a uniform brown clay to a coarse reworked semi-indurated volcaniclastic sand. Generally fossils are rare and calcium carbonate is absent. Stratification of the layer is most clearly developed near large sea floor edifices or the Hawaiian Ridge. Examination of cores from these areas reveals mottled clays with indefinite contacts, layers of varying density, rare reworked fossils, some silt stringers, and occasional turbidite zones. Primary depositional agents in these areas appear to be bottom currents and gravity-controlled mass flows (such as turbidity currents and slumps). Near the bathymetric center of the Arch, where the echo type shows a more prolonged character, the sediment is a semi-indurated heterogenous mixture of silty clay beds, volcaniclastic sands, and ash layers containing interspersed basalt fragments, volcanic glass, palagonite, and manganese crusts and nodules. The presence of manganese material and indurated sediments at the sea floor, as was found at Site 67, suggests that this area has a long history of nondeposition or erosion or perhaps both (Winterer et al., 1971). The progressively prolonged character of these echograms toward the center of the Arch probably results from increased scattering by erosional or depositional bedforms and by poor sorting and large coarse fractions in the sediment (Ewing et al., 1973; Damuth, 1975).

Irregular hyperbolae of widely varying vertex elevations are caused by point reflections from peaks of rugged sea floor. These peaks are interpreted to be outcropping igneous rocks. Successful dredge hauls by the R/V KANA KEOKI in areas characterized by this echo type commonly contained igneous rock fragments, often manganese-encrusted.

The second subtype of hyperbolic echo appears to be a result of reflections from small sedimentary bedforms caused by bottom current scour (Heezen et al., 1966; Hollister et al., 1974; Damuth and Hayes, 1977; Nemoto and Kroenke, 1981). Although depositional bedforms resulting from gravity-induced mass flows are thought to be responsible for some occurrences of this echo type elsewhere (Damuth, 1975), we find that the surface generating these hyperbolae correlates with a laterally continuous seismic reflector. Seismic reflection profile YY′ (Figure II-9) partially overlaps 3.5-kHz echogram profile LL′. On profile YY′ reflections from a rough hyperbolic surface (SE side) may be traced to the NW beneath a stratified sediment cover. The wide lateral extent of this irregular hyperbolic reflector, and the manner in which reflections from the overlying sediment cover onlap it, suggest that the irregular reflector represents a buried erosional surface. This erosional unconformity is interpreted to be caused by intense bottom water flow over the central and outer portions of the Arch. Measurements of present-day bottom water flow (Lair and Sanko, 1968) and photographs of sea floor sediment cover (Schreiber, 1968)

Figure II-9: YY′ (50-150 Hz). Seismic reflection profile south of Schumann Seamount which partially overlaps echogram profile LL′. Tracing of seismic reflectors shows a laterally continuous, irregular reflector that can be followed to the SE where it emerges at the sea floor, at the locality which corresponds to occurrences of the second subtype of hyperbolic echo visible on 3.5-kHz echograms (LL′). This irregular hyperbolic reflector is interpreted to be an erosional unconformity. Reflectors from the stratified accumulations of sediment on the NW side of the hyperbolic zone onlap this lower irregular reflector.


Y
← NW
SE →
Y'
4688 m
5063
5438
depth
4688m
5063
5438
100 m
5 km
6.25
6.75
7.25
sec.
6.25
6.75
7.25
unconformity

suggest that past, and not present-day, bottom water currents are responsible for most of this erosion.

The third subtype of hyperbolic unit also results from reflections off a surface microtopography. The lack of variation in vertex elevations indicates that the sedimentary bedforms are small and confined to a single surface. In the Hawaiian Deep where this echo type mainly occurs, the structural setting suggests that a combination ot depositional and erosional bedforms, or perhaps deformational irregularities in the sediment surface, are responsible for the buried bedforms.

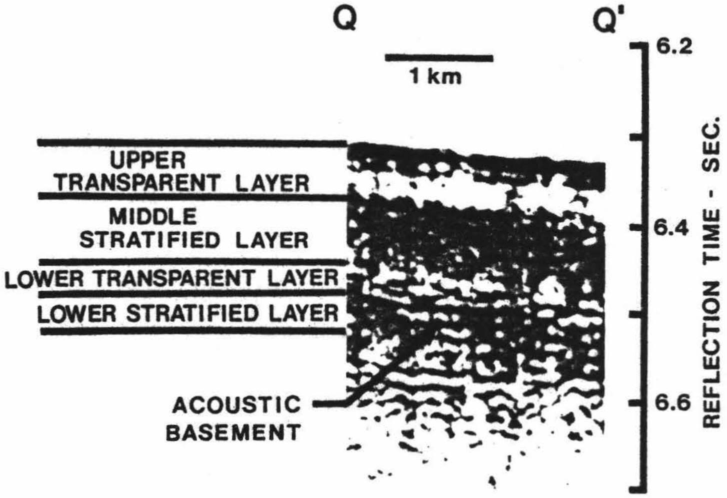
The lithology of the opaque echo type is not directly apparent, due to the limited length and poor sediment recovery of the deep-sea coring to date. Coring attempts in sea floor characterized by the opaque echo type seem to end in either bent coring devices, or recovery of a brown mineral-rich clay often accompanied by large glassy rock fragments. The origin of the 3.5-kHz opaque echo type and its corresponding anomalous near-surface seismic reflection is discussed at length in a later section.

Seismic Reflection

In the northern region of the Arch it is possible to identify sections ot sediment that apparently have been undisturbed for a relatively long period of time. Within these sections we have identified five acoustic layers or surfaces similar to those described by Ewing et al. (1968) for the North Pacific. They are: (1) an upper transparent layer, (2) a middle stratified layer, (3) a thin lower transparent layer, (4) a lower stratified layer, and (5) acoustic basement. These acoustic layers can be seen in a profile NE of Rimsky-Korsakov Ridge (Figure II-10, QQ′)

The term "transparent" has been used to describe sediment layers which generate few internal reflections. The seismic reflection upper transparent layer is a thicker unit (50 to 65 m) than the transparent NB! layer of the 3.5-kHz echograms. The seismic reflector which we correlate with the base of the 3.5-kHz transparent layer is weak in amplitude compared to the reflector at the base of the seismic reflection upper transparent layer and as a result, the seismic reflection upper "transparent" layer appears relatively reflection-free. The middle stratified layer is typically 50 m thick. The lower transparent layer does not generate reflections because it, like the upper transparent layer, lacks sharp acoustic impedance boundaries. The boundary between it and the stratified middle layer is poorly defined. ? Long source pulses, diffraction hyperbolae, and variations in the reflectivity of overlying layers degrade its sharpness. Frequently the lower transparent layer cannot be discerned. The lower stratified layer is thin and directly overlies acoustic basement. Acoustic basement is taken to be the deepest traceable reflector observed on the profiles; it usually appears as an irregular, hyperbolic, low-frequency reflector.

Figure II-10: QQ´ (100-250 Hz). Detail of seismic reflection profile from NE of Rimsky-Korsakov Ridge, showing the location of the upper transparent layer, the middle stratified layer, the lower transparent layer, the lower stratified layer, and acoustic basement.


Q
Q'
1 km
UPPER TRANSPARENT LAYER
MIDDLE STRATIFIED LAYER
LOWER TRANSPARENT LAYER
LOWER STRATIFIED LAYER
ACOUSTIC BASEMENT
6.2
6.4
6.6
REFLECTION TIME - SEC.

South of 25°N, seismic reflection profiles from the Deep and Arch areas do not display a uniform sequence. This nonuniformity is apparently caused by a combination of three factors: the presence of an upper layer of highly reflective stratified sediment that partially masks the layers below; the presence of numerous discontinuous strong surface and subbottom reflectors of differing character; and finally, the removal of sediment by erosional processes.

OBSERVATIONS OF SHALLOW CRUSTAL STRUCTURE

The seismic reflection sequence described above can usually be traced beneath a cover of stratified sediment (as in Figure II-11, RR′; Figure II-4, CC′) Although it seems probable that this sequence everywhere underlies the stratified cover, it cannot be recognized beneath the cover on reflection sections anywhere south of 25°N in the study area.

The sequence also appears on a seismic MAXIPULSE profile, shot oblique to Rameau Ridge (Figure II-12, SS′), as the section of draped sediments displaying internal layering between km 54 and km 66 of the profile. Depth to acoustic basement is approximately 150 m. A seismic reflection upper transparent layer 50 m thick overlies a middle stratified layer. A thinner transparent layer (25 m thick) is observed on the 3.5-kHz echograms (Figure II-4, AA′). The transparent layers are in turn overlain locally in the downfaulted lower areas (such as km 25 to km 42, profile SS′; profile AA′) by accumulations of a stratified

Figure II-11: RR′ (100-250 Hz). Seismic reflection profile north of Schumann Seamount. Tracing of seismic reflectors shows how the seismic reflector sequence on NW continues beneath stratified sediment cover to SE. Low downfaulted area to SE is associated with the presence of Schumann Seamount. A simultaneously recorded low-frequency filtered (50-150 Hz) playout was useful in preparing the tracing of reflectors.

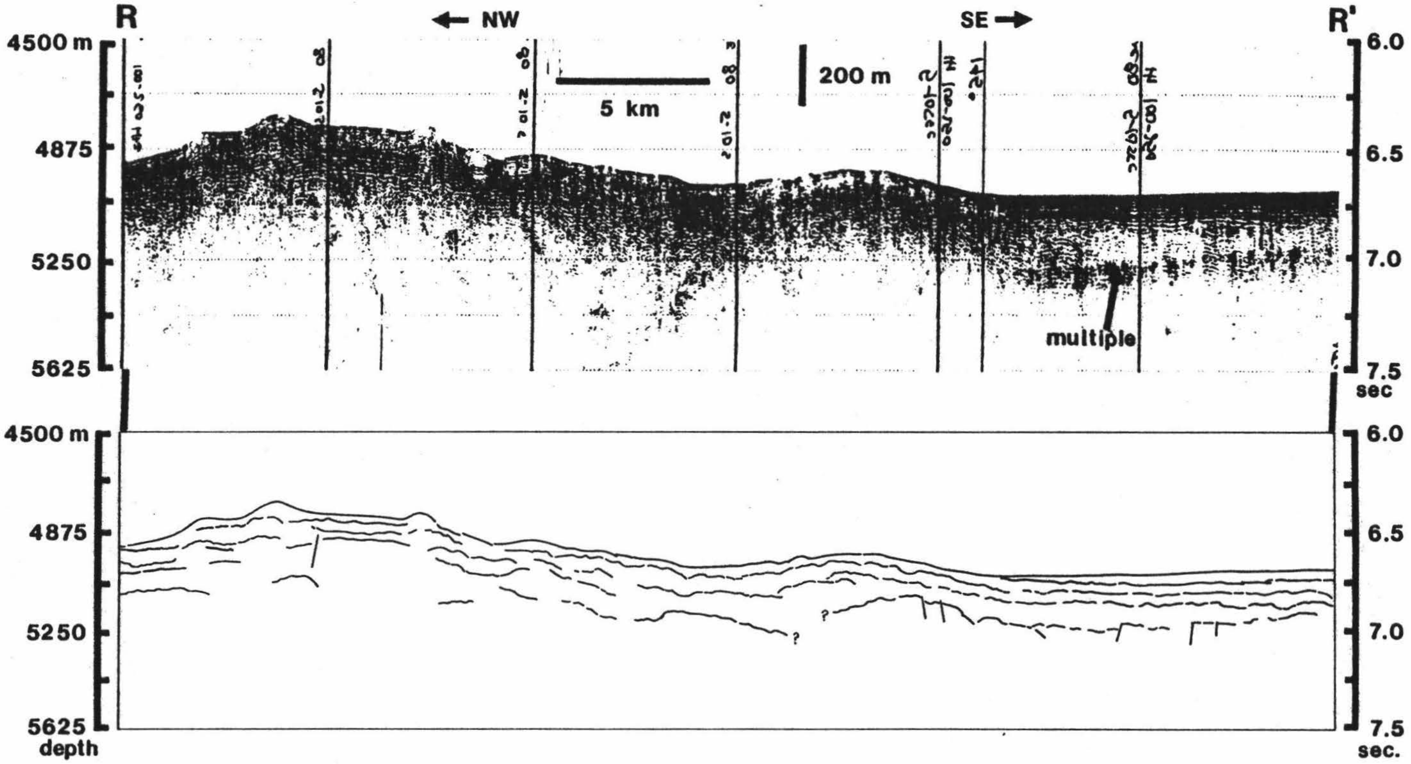
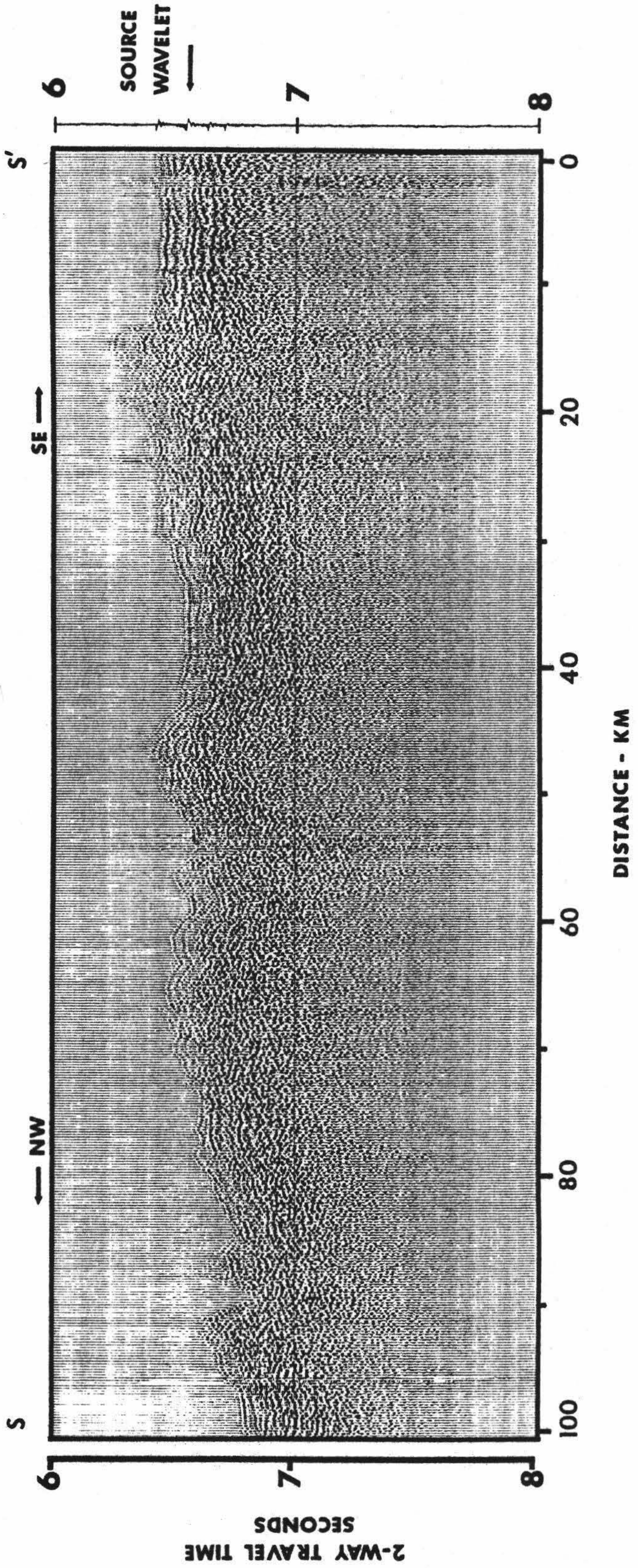

R
← NW
SE →
R'
4500 m
4875
5250
5625
6.0
6.5
7.0
7.5
sec
200 m
5 km
multiple
4500 m
4875
5250
5625
depth
6.0
6.5
7.0
7.5
sec.
?
?

Figure II-12: SS′ (10-175 Hz, unprocessed data) Seismic reflection profile between Paumakua Seamount and Rameau Ridge using MAXIPULSE acoustic source. Profile shows a central region of draped sediments (between km 54 and km 66), a small downfaulted basin (km 20 to km 47), a highly reflective, apparently sediment-free area on the SE end, and an accumulation of stratified sediments on the NW in a bathymetric low adjacent to a small ridge. Approximate MAXIPULSE source wavelet is shown on right side of figure at the same time scale as the reflection section.


SOURCE WAVELET
6
7
8
S'
S
SE
NW
0
20
40
60
80
100
DISTANCE - KM
2-WAY TRAVEL TIME
SECONDS

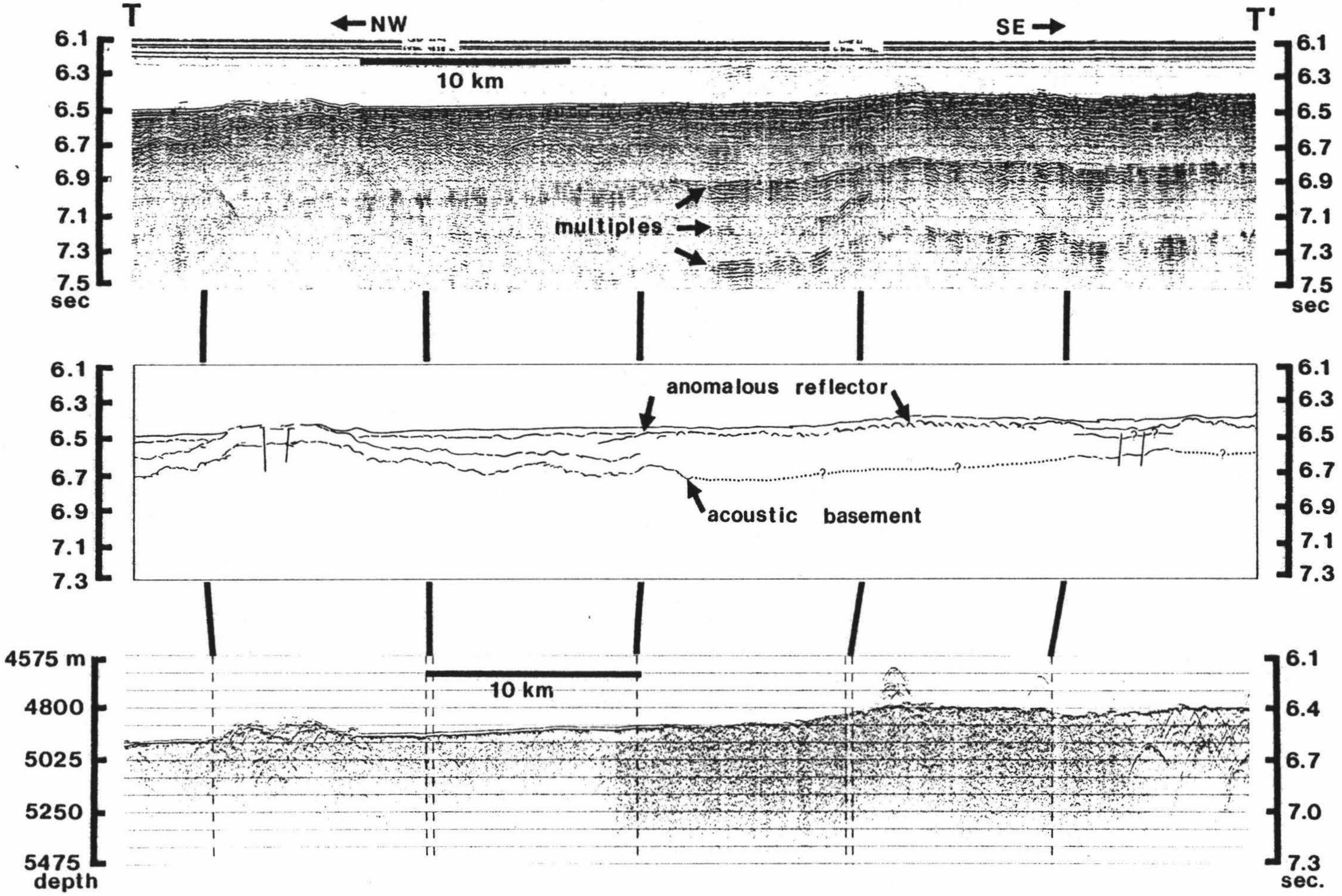
sediment, which creates the stratified-prolonged echo on the 3.5-kHz records. The southeast end of the line adjoins an area of opaque echo type which is highly reflective to the frequencies of both the MAXIPULSE system and the 3.5-kHz PDR. Because the seismic penetration is so poor it is not possible to tell whether a sediment section is present and masked, or whether the area is sediment free. To the NW, sediments of the stratified-prolonged echo type fill a crustal depression at the base of a small ridge which is sympathetic in trend to the larger Rameau Ridge.

Schumann Seamount, a large ENE trending structure at the western end of Rameau Ridge, lies in the north central part of the study area. It is bordered on the south by a deep linear depression, 5100 m in depth. Although the well-stratified sediment layers in the depression weaken the acoustic basement reflector, total sediment thickness is about 250 m. South of the depression is a east-west trending edifice herein named Rimsky-Korsakov Ridge. The transition between Rimsky-Korsakov and the depression is marked by an east striking high-angle fault that has downfaulted the depression at least 200 m. Other faults with similar strike can be observed in the area. Paleomagnetic poles, calculated for Rimsky-Korsakov Ridge and other eastern Musicians edifices, indicate about 20° of northward drift (Sager, 1981; Sager, in prep.) which, when used with the paleomagnetic data of Gordon (1982) for the Pacific plate, results roughly in a Cretaceous-Tertiary boundary age.

The central Arch region everywhere shows a reflective sediment cover as manifested by the large number of seismic reflection multiples and high 3.5-kHz reflectivity. In specific areas, however, bottom reflectivity and fine-scale roughness increase abruptly, suggesting that either a sea floor or a shallow subbottom reflector has changed in composition. The seismic reflection records show numerous strong, shallow, discontinuous horizontal reflectors unlike the reflectors noted in the undisturbed sections. Although the reflectors are generally flat and smooth in the first order, they are accompanied by numerous intense hyperbolae at or just below the reflector surface, which indicate that the reflector surface is rough and irregular. Their horizontal extent is often great; several can be confidently traced for 20 km or more.

Profile TT′ (Figure II-13) typifies one of these unusual reflectors. The increased reflectivity of the rough surface (center right) is manifested on the seismic reflection record by more water column multiple reflections, and on the accompanying 3.5-kHz records by an abrupt increase in the prolongment of the echo. The shallow anomalous reflector has limited lateral extent; "normal" seismic penetration returns to the SE along the section where acoustic basement can again be recognized. The roughness of this reflector is indicated by numerous overlapping hyperbolae with vertex elevations that vary by at most 30 m. A tracing of the seismic reflectors in profile TT′ shows how the acoustic basement reflector may be traced beneath the anomalous reflector, overlapping it. Under the central area of the reflector

Figure II-13: TT′ (80-160 Hz). Seismic reflection profile south of Rimsky Korsakov Ridge (top). Interpretative tracing of reflectors (middle) shows how acoustic basement can be followed from NW to SE, beneath the anomalous near-surface reflector. Farther to the SE, acoustic basement reappears beneath this anomalous reflector. A dotted line denotes the inferred location of a masked acoustic basement reflector. A compositional change in the near-bottom sediments at the onset of the anomalous reflector is implied by indications of a reflectivity change. This reflectivity change is evidenced by increased water column multiples over the near-surface reflector even though the bottom is rougher and a more effective scatterer of seismic energy. The transition is characterized on the 3.5-kHz echogram (bottom) by the increased reflectivity and bathymetric roughness of the opaque echo type (on SE) versus the stratified-prolonged echo type (on NW).


T
NW
SE
T'
6.1
6.3
6.5
6.7
6.9
7.1
7.3
7.5
sec
10 km
multiples
anomalous reflector
acoustic basement
4575 m
4800
5025
5250
5475
depth
6.4
6.7
7.0
7.3
sec.

there is no seismic penetration and the location of an inferred acoustic basement is indicated by a dotted line.

A similar reflector occurs south of Rimsky-Korsakov Ridge, 25 km NNE of the area just discussed for profile TT′. This reflector, shown in profile UU′, Figure II-14, also terminates laterally in an abrupt manner. Two ship crossings in the area suggest that it is roughly circular in plan. Acoustic basement, at a depth varying between 100 and 200 m, is clearly visible beneath this reflector. This mid-sediment column reflector shares several qualities with the reflector discussed above for profile TT′: lateral termination, horizontal attitude, and a recognizable basement reflector beneath it. It is noteworthy that the low-frequency reflection from this laterally terminating body is similar to the low-frequency reflection from acoustic basement on either side of it. The ability to trace basement up onto Rimsky-Korsakov Ridge on this profile (NNW side) and on profile TT′ indicates that these anomalous buried surfaces, which lie within or on top of the sediment column south of the Ridge, were created after the formation of the Ridge itself.

Farther south, a thin layer of stratified sediment veneers other shallow anomalous reflectors that cover most of the Arch. Seismic reflection profile VV′ (Figure II-15) lies between two relatively small edifices on the Arch. A thin cover of smooth stratified sediment overlies a level of "chaotic" or discontinuous incoherent reflections. At an apparent break or decrease in reflectivity of the anomalous chaotic reflector, a lower acoustic basement reflector appears. The

Figure II-14: UU′ (100-250 Hz). Seismic reflection profile south of Rimsky-Korsakov Ridge shows mid-sediment column, low-frequency reflection that terminates laterally to NNE and NNW.

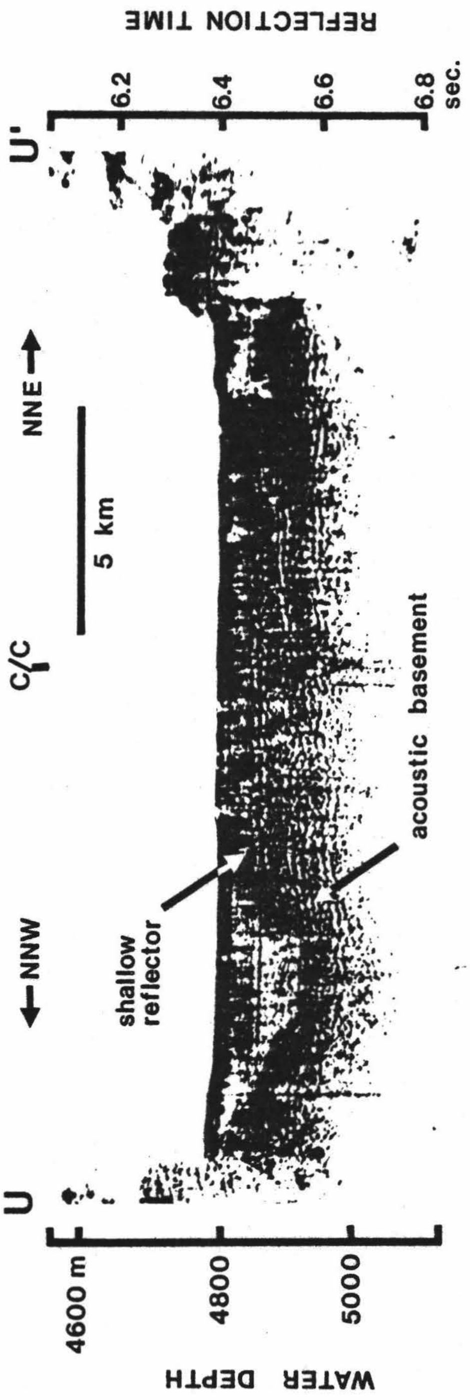
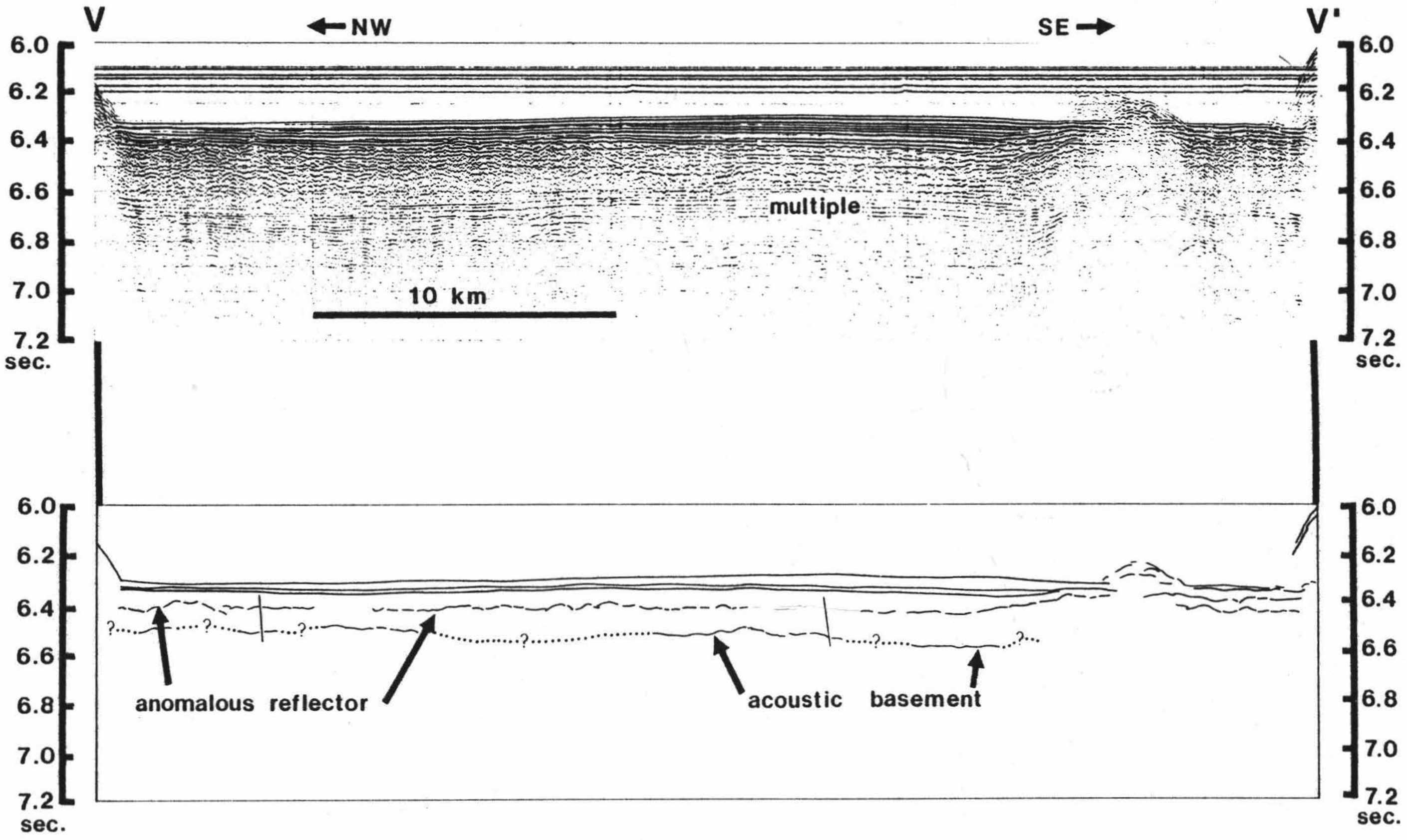

REFLECTION TIME
6.2
6.4
6.6
6.8
sec.
U'
NNE →
5 km
℄
← NNW
shallow reflector
acoustic basement
U
4600 m
4800
5000
WATER DEPTH

Figure II-15: VV′ (80-160 Hz). Seismic reflection profile on central Arch between two edifices. Note anomalous chaotic acoustic basement reflectors at 115 ms (98 m) depth, and transitions to deeper acoustic basement reflector at 230 ms (200 m) depth. The edifices at the far NW and SE ends of the profile are small ridges that trend roughly ENE.

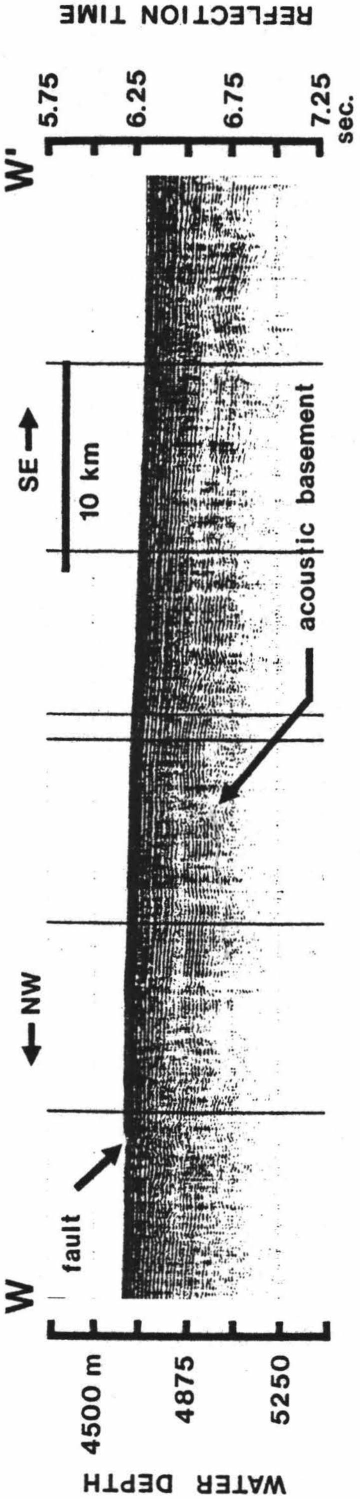

V
← NW
SE →
V'
6.0
6.2
6.4
6.6
6.8
7.0
7.2
sec.
multiple
10 km
?
anomalous reflector
acoustic basement

tracing of seismic reflectors in Figure II-15 demonstrates how acoustic basement can from here be traced back to the NW and SE under the anomalous chaotic reflectors. The acoustic impedance of this chaotic layer is sufficiently different from that of the overlying sediment that strong reflections are generated and coherent seismic returns from beneath the layer are absent or considerably weakened.

To the east of this area are two major seamounts which we have named Kauluakalana and Paumakua, in honor of two navigators of Hawaiian folklore (see Figure II-2 for locations). Although there appears to be little sediment cover between these seamounts, rare sediment pockets do exist, and it was one of these which DSDP drilled at Site 67.

Seismic reflection records gathered on four of the cruise tracks traversing the Hawaiian Deep north of Oahu indicate a thick section of sediments which thin and become progressively disrupted northward. Although the sediments in the Deep were found to be highly stratified throughout the section, four major reflectors can be discerned. Acoustic basement is an irregular surface dipping southwesterly toward the Hawaiian Ridge (Figure II-16, WW′), which becomes progressively weaker in amplitude toward the axis of the Deep, making it difficult to trace. Lying approximately 150 m above acoustic basement is a smooth, undulating, strong reflector. The thickness between this reflector and the acoustic basement reflector remains relatively constant over the distance we can trace (110 km). Subparallel to this reflector are two other smooth, discrete reflectors higher in the section. The thickness of sediment above each reflector thins to the north. As this smooth

Figure II-16: WW′ (50-150 Hz). Seismic reflection profile from the Hawaiian Deep north of Oahu. The acoustic basement reflector is weak in amplitude and difficult to discern. Smooth strong reflector (6.4 to 6.7 sec) dipping to the SE side of the profile maintains a constant 150-m thickness above acoustic basement. There are two prominent reflectors above this reflector and the thickness of sediment above each thins to the NW. Note disruptions in the sediment section on NW side of profile. A recent fault is indicated.


REFLECTION TIME
5.75
6.25
6.75
7.25
sec.
W'
SE →
10 km
acoustic basement
← NW
fault
W
4500 m
4875
5250
WATER DEPTH

reflector sequence is traced northward toward the Arch, it is frequently disrupted, sometimes exhibiting simple offset, other times disappearing completely into a mass of chaotic reflections and emerging on the other side of the chaotic area offset or changed in attitude. The disruptions in the reflector sequence usually correspond to those areas overlain by the 3.5-kHz opaque echo type and begin to occur frequently northward from a point 50 km south of Kauluakalana Seamount.

In the northwestern corner of the study area, near Mendelssohn Seamount, the observed sediment accumulation is much greater than on other areas of the Arch to the SE. This region lies within a saddle, noted above, where the depth of the crest falls below 4900 m (Naugler, 1968). In addition to this regional crustal depression, reflection lines in the vicinity of Mendelssohn Seamount indicate that it is surrounded by a sediment-filled moat. Maximum sediment accumulation is on the order of 300 m directly west, 550 m southwest, and 400 m north of Mendelssohn. This compares to an average sediment thickness of 150 m at a distance of 60 km west of the seamount. West and northwest ot Mendelssohn, faulting patterns in the sediment and basement indicate that the dominant structural patterns strike northeast. Southwest of Mendelssohn, an airgun line was run perpendicular to a hypothetical extension of the Necker Ridge through that area. Necker Ridge is a long linear ridge of ENE strike which intersects the Hawaiian Ridge from the southwest at 23°N, 165°W (see Figure II-1). Some investigators have speculated that a buried extension of the Ridge might exist beneath the sediments of the

Hawaiian Ridge, perhaps related to the Necker Lineations. Airgun profile XX′ (Figure II-17), which crosses a projection of that trend, does not show any evidence for a buried ridge here. Sediment thickness varies from 300-550 m and acoustic basement, although smooth in some regions, is at other locations faulted and highly irregular. Acoustic basement is probably igneous basement, or closely overlies it, as shown by the irregular topography, numerous hyperbolae, and low-frequency content.

A puzzling feature of this profile is the strong shallow reflector next to the small seamount at the SE end of the profile. Over the 22 km in which it can be traced, it is smooth in character, highly reflective, and seems to overlie a weaker acoustic basement reflection. This reflector appears to be of the same class of shallow anomalous reflectors as observed in seismic reflection profiles TT′, UU′, and VV′.

Figure II-18 is a sediment isopach map of the northern Hawaiian Arch compiled from the seismic reflection profiles of this study. The stippled areas denote areas of little or no sediment (0-50 m). The salient feature of subbottom profiling across the northern Arch is the observation of abrupt changes in the level of acoustic basement; these transitions are reflected in Figure II-18 by closely spaced isopach contours. The distribution of these acoustic basement offsets and the general degree of shallow subbottom complexity suggest that the saddle region of the west has not experienced the magnitude of tectonic and volcanic disturbances that the central Arch area has, even though it is

Figure II-17: XX′ (20-100 Hz). Seismic reflection profile collected S and SW of Mendelssohn Seamount using a 300 in^3 airgun acoustic source. The subbottom character of this profile does not support the hypothesis that a buried extension of the Necker Ridge crosses normal to the profile. Note shallow reflector on SE end of profile adjoining small seamount with smooth morphology and high reflectivity.

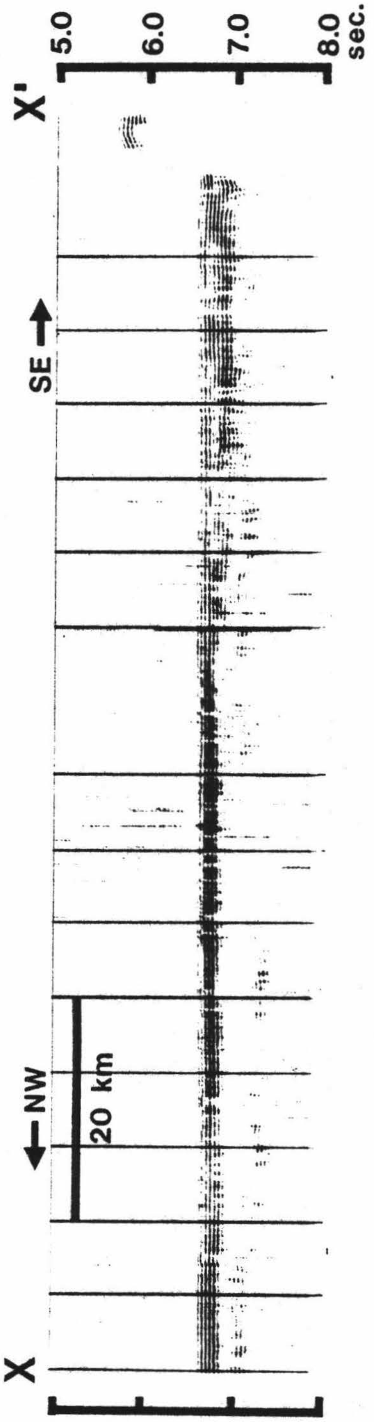
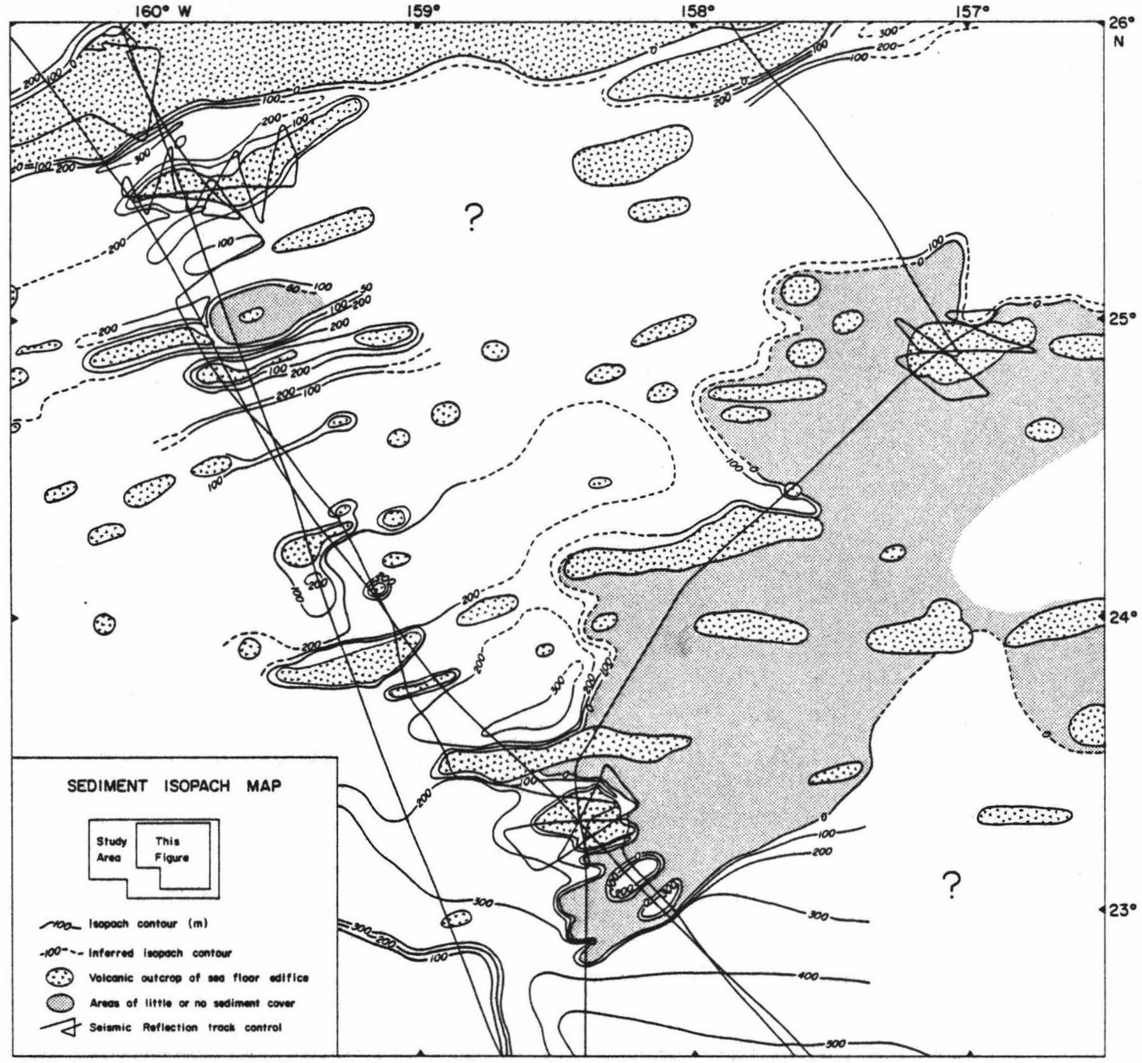

X'
X
SE
NW
20 km
5.0
6.0
7.0
8.0
sec.

Figure II-18: Sediment isopach map of a portion of the northern Hawaiian Arch and Deep. Isopach contours are in meters; the stippled areas indicate regions covered by little or no sediment (determined from distribution of 3.5-kHz opaque echo type and analysis of seismic reflection profiles) and thought to be covered by lava flows; and the v-pattern denotes outcropping igneous rocks associated with sea floor edifices (determined from the distribution of the first hyperbolic subtype, analysis of seismic reflection profiles, and examination of sea floor bathymetry). A sediment sonic velocity of 1.7 km/sec was used to estimate sediment thickness.


160° W
159°
158°
157°
26° N
25°
24°
23°
?
?
SEDIMENT ISOPACH MAP
Study Area
This Figure
100 Isopach contour (m)
-100- Inferred isopach contour
Volcanic outcrop of sea floor edifice
Areas of little or no sediment cover
Seismic Reflection track control
0
50
100
200
300
400
500

no farther from the axis of the Hawaiian Ridge.

THE ORIGIN OF ANOMALOUS REFLECTORS AND VOLCANICLASTIC SEDIMENT

Anomalous Reflectors and the 3.5-kHz Opaque Echo Type

A review of the acoustic properties and associations of the shallow anomalous seismic reflectors and 3.5-kHz opaque echo type areas ("reflector units") points to a single origin. In the central Arch area these reflector-unit areas are large; outward from the center they become isolated and small. Each mappable body has a slight bathymetric elevation above adjoining areas and usually displays a progressive shoaling toward the center. Often at the center the existence of a small constructional edifice is indicated by occurrences of the first subtype of hyperbolic echo (Figure II-7, OO′, PP′; Figure II-13, TT′). The boundaries between these reflector units and surrounding areas are abrupt and do not show any relationship to sea floor depth changes.

Seismic reflection penetration of these reflector units, whether near-surface or buried, is poor. Over the center of the reflector units subbottom reflectors are usually nonexistent; however, at the margins a horizontal overlap of the lower acoustic basement reflector and the upper reflector unit is often observed. We thus rule out faulting and offset of a single geologic surface as an explanation for the reflector configuration. The qualities of these reflector units, including their local extent, depth-independent and abrupt boundaries, and distinct compositional difference from surrounding sediment, strongly suggest that this material was not the result of an in situ process affecting sediment. We believe that the material causing the opaque echo type response was introduced from elsewhere and transported to its present locations.

Deep-sea core results here and the experience gained in other near-bottom geological studies offer several possibilities for the genesis of these bodies. Since the reflector units are compositionally different from the surrounding sediment some hypotheses to consider are: debris flows, turbidites, or other type of gravity controlled slide or flow, fields of reflective manganese nodules and micronodules, basement outcrops, sediment unconformities, areas of volcaniclastic sediment, and igneous flows, subsurface flows, or sills.

Most of these possibilities are clearly unsuitable. We reject the idea that these reflector units are allochthonous sediments for several reasons. Seismically, they do not resemble debris or mass flows, turbidites, current-deposited sediment, or other forms observed elsewhere (Embley, 1980; Nemoto and Kroenke, 1981), nor can these processes explain the disruption of seismic reflectors that so often occurs beneath the reflector units (as in NW side, WW′; Figure II-16). In addition, potential sources of supply for the transported sediments, such as a nearby seamounts or ridges, are often not present.

The presence of manganese-coated material on or near the sea floor, the result of an in situ manganese accretionary process, can prolong the returning echo on records of high-frequency profilers. Although such material is often found in core samples from these areas, we judge its total accumulation to be insufficient to cause the strong anomalous lower frequency seismic reflectors. This explanation also could not account for the irregular bathymetry and abrupt boundaries of these reflector units.

The hypothesis that these reflector units represent pre-existing basement outcrops (layer 2) can be effectively ruled out by the observation of an acoustic basement reflector below the anomalous reflector unit. In any case, it would be highly unlikely to find the upper surface of a faulted and deformed layer 2 nearly flat and conforming to the smooth first order bathymetry of the Hawaiian Deep and Arch.

As abrupt boundaries and local reflector-unit areas would be inconsistent with the hypothesis of sediment unconformities, we are left with two other explanations, each involving igneous processes. These two possibilities are: zones of volcaniclastic sediment, or hard igneous surfaces such as flows, subsurface flows, or sills. These reflector units bear virtually no resemblance to the seismic reflection profiles or 3.5-kHz echograms over the volcaniclastic section at DSDP Site 67. On the basis of this and other evidence presented in this paper, a volcaniclastic origin can be ruled out. We ascribe the cause of the 3.5-kHz opaque echo type and the anomalous seismic reflector units to reflections from igneous near-surface flows and sills. In most cases firm sequences of volcaniclastic sediments are present to provide the necessary support for the weight of surface flows. Other deeper anomalous seismic reflectors may represent sills fed by magma conduits associated with the eruptions, earlier lava flows covered by accumulations of volcaniclastic or other sediment, or perhaps subsurface flows which sank beneath sediment layers, expanding, and creating sill-like bodies when the support necessary for the flow was not present.

This interpretation is consistent with the work of other investigators. Menard (1964) discussed the idea that the products of young volcanism may be present on the northern Arch. Normark and Shor (1968) interpreted seismic reflectors on the Arch resembling the reflector units of this study as lava flows. Evidence assembled by Speiss et al. (1969), including seismic reflection profiling, sea floor photography, deep-sea core results, side-scan sonar textural information, and large local magnetic anomalies detected by the SIO Deep Tow instrument, led them to believe that the area north of Site 67 is covered by a lava flow.

The source of these lavas seems to be small eruptive centers on the Arch. Clues as to the origins of sea floor edifices in the central Arch area are provided by analysis of their morphologies and surrounding subbottom structure. One type of sea floor edifice is an igneous constructional form which extends down to the lowest traceable acoustic basement reflector. It may be an old sea floor edifice, or perhaps a younger form that has been buried by thick sediment accumulations. In the central Arch area many of these structures are ridges which display an ENE trend. The seamount immediately NW of profile VV′ (Figure II-15) is typical of these, as is the small seamount south of DSDP Site 67 (Normark and Shor, 1968; their Figure 6)

Frequently, sea floor edifices crossed by the three seismic lines in the central Arch area (between 158°30′ and 160°W) exhibit an asymmetric morphology. The structures commonly have high scarps on the south side and more gentle slopes on the north. In the seismic reflection sections, acoustic basement reflectors can usually be traced up onto these edifices from the north side (as in SE end of VV′, Figure II-15) but remain under several tens of meters of sediment on the south side and do not emerge. Our seismic reflection and 3.5-kHz crossings are roughly normal to the bathymetric trends of these lineations and therefore represent profiles across the structural grain. Evolution of these asymmetric edifices could logically have proceeded in one of two ways. If the steep southern side is due to faulting, then they may be simply tilted fault blocks. A second explanation is that they are constructional igneous ridges and small seamounts that have extruded lavas northward, creating the asymmetry observed on the seismic profiles. Preferred northward extrusion of lava could only be due to northward dipping sea floor at the time of eruption. This might be caused by tilting of small fault blocks, or by a regional northward dip of the sea floor.

Volcaniclastic Sediment

Notwithstanding the abundant evidence for late Cenozoic volcanism on the Arch which has been presented by some authors (Normark and Shor, 1968; Speiss et al., 1969), the source of the widespread volcaniclastic material present today on the Arch is not clear. In general, we must consider four possible sources: the Hawaiian Ridge, a local source on the Arch, or either of two perhaps genetically differing areas in the southern Musicians province; the southern east-west ridges, and the southern seamounts of the Musicians N-S seamount trend (such as Mendelssohn and Chopin).

It seems unlikely, for several reasons, that the source of the coarse volcaniclastic sediment is the Hawaiian Ridge. Analysis of sediment grain size suggests that many size components on the Arch are too coarse to have been transported the necessary distance by seafloor, current, or atmospheric agents. The volcanic sandstones and mudstones encountered at DSDP Site 67 were interpreted to be epiclastic, nonturbidite, and the product of a local source (Winterer et al., 1971).

The distribution of near-surface sediment types determined by 3.5-kHz echo character mapping precludes a source in the region of the southern Musicians Ridges. South of Rameau Ridge, the regional pelagic clay layer is exposed, not covered by the onlapping volcaniclastic sediment found farther to the south.

The southern seamounts of the Musicians N-S seamount trend have structural moats which are partially filled by volcaniclastic sediment. Dating of dredged rocks from Mendelssohn Seamount indicates that it is Late Cretaceous in age (M. Pringle, personal communication, 1982). The presence of eruption-synchronous volcaniclastics at the sea floor would be unexpected, as bottom current velocity determinations and bottom photographs have shown no evidence of active present-day bottom currents in this area (Lair and Sanko, 1968) that might cause the suspected unconformity. The volcaniclastic sediment surrounding Mendelssohn and Chopin seamounts probably represents redeposited volcanic debris which has been shed off the summit and flank areas of the seamounts. The large distance separating these seamounts from the eastern and central Arch areas (over 400 km to Site 67) would seem to imply that their role in supplying volcaniclastic sediment to the central Arch is minor. Thus, in the eastern part of the study area away from seamounts of the N-S trend, the logical sources of volcaniclastic sediment are either of two large Cretaceous seamounts on the Arch, or some of the smaller edifices there.

DISCUSSION

Substantial igneous and tectonic activity has occurred in the central Arch region since the formation of the ocean crust; however, the volcanism generally created only thin lava flows and minor edifices. Examination of several seismic reflection profiles SE of

Schumann Seamount does not reveal any singular large edifices which might be buried by sediments of the Hawaiian Ridge. We conclude that the Musicians NW-SE seamount trend does not continue south of 25°30′N.

The age ot the volcanism we detect is uncertain. If multiple igneous events should exist, their recognition is made difficult here by the presence of hiatuses or low rates of sedimentation or both (Moore et al., 1978). Such rates reduce the spatial separation between the products of igneous events, in some cases almost certainly below the ability of our seismic reflection tools to resolve them.

Nevertheless, we believe that the products of at least two "supra-plate" volcanic events are present on the Arch. Existence of one event, pre-55 Ma, is implied by the results of DSDP Site 67, where sediments of minimum Eocene-Paleocene boundary age onlap a small NW-SE trending ridge, and by dating on rocks from Paumakua, Kauluakalana, and Mendelssohn seamounts which gives Late Cretaceous ages (M. Pringle, personal communication, 1982).

Existence of a second event, probably younger in age, is suggested by several lines of evidence. Observations of 3.5-kHz echograms in the east central area of the study region, atop the bathymetric bulge of the Arch, support the notion that the age of supra-plate volcanism differs. Numerous small seamounts are present here, some of which have surrounding blankets of stratified sediment and 40-50 m thick sediment caps; however, a distinctly different population of other seamounts have no such cap or apparent thickness of sediment around them. Two examples of these edifices and the opaque echo type margins that surround them are shown in Figure II-7 (OO′ and PP′). We propose that one of these seamount groups was formed in pre Eocene-Paleocene time and the other group at some subsequent time.

Close examination of the transition between the lava flows and adjoining areas of stratified sediment (Figure II-7, MM′,NN′,OO′; Figure II-13, TT′) shows how shallow reflectors (5-30 m depth) visible within the stratified sediment terminate abruptly at the margin. In a few cases shallow reflectors that abut the opaque echo type areas may be traced southward, across a thickening wedge of Hawaiian Ridge sediment apparent on seismic reflection profiles (Figure II-16, WW′), and into the Hawaiian Deep. The manner in which internal reflectors of this young sediment abut the lava flows, rather than continuing over them, supports the notion that the flows are younger.

Two separate volcanic events would be consistent with the DSDP results. The Site 67 interpretation was that the volcanism responsible for the volcaniclastic sequence took place in Late Cretaceous or early Tertiary time. A look at the seismic reflection profile extending north of the DSDP site (Speiss et al., 1969; their Figure 13) suggests that if the feature interpreted to be a lava flow by Speiss et al. is actually of young age, it may represent lavas extruded on top of a pre-existing volcaniclastic section.

Chapter III presents evidence from seismic reflection profiles of the Hawaiian Deep and Arch which more tightly constrains the ages of the extrusive and intrusive volcanic products discussed in this chapter.

CONCLUSIONS

(1) Widespread volcanic activity has occurred over much of the northern Arch since the formation of the ocean crust 90-80 Ma. The volcanism created lava flows or intrusive sills or both, and constructed small edifices. The greatest density of these products occurs in the east central portion of the area we have examined. Stratigraphic relationships between sediment layers and the igneous extrusive and intrusive products suggest that the volcanism occurred in two separate episodes.

(2) Most of the study area is covered by volcaniclastic sediment, and a portion of it must be derived from volcanic sources on the Arch.

(3) The presence of sea floor and buried erosional surfaces suggests that bottom current activity has been more vigorous at some time in the past.

(4) The character ot supra-plate volcanism on the Hawaiian Arch differs from that of the Musicians Seamount province and its seamount trends. Therefore, regarding the possible extension of the different seamount trends and structural lineations:

  (a) There is no evidence to suggest that the Musicians NW-SE seamount trend extends SE of Schumann Seamount onto the Arch.

Supra-plate volcanism on the Arch has contributed to the construction of minor edifices and lava flows, but not to singular large edifices that may be buried by sediments of the Hawaiian archipelagic apron.

(b) The true southern extent of the Musicians N-S 162°W seamount trend is still in doubt. Apart from a suggestion of seamount volcanism south of Mendelssohn Seamount, we found no new evidence that might resolve this question.

(c) We were unable to locate any subbottom structure in the area south of Mendelssohn Seamount that might be associated with the ENE-trending Necker Ridge. We conclude that a buried extension of the Ridge does not exist.

CHAPTER III

IMPLICATIONS FOR PALEOSEDIMENTATION AND AGE OF VOLCANISM ON THE NORTHERN HAWAIIAN ARCH

INTRODUCTION

The Hawaii Institute of Geophysics (HIG) conducted seismic reflection surveys during 1980 over the northern Hawaiian Arch and Deep in order to clarify the geologic history of these areas (Fig.III-1). The Hawaiian Arch is the broad, gentle upwarp of sea floor forming the outer boundary of the inner flanking Hawaiian Deep around the Hawaiian Ridge (Betz and Hess, 1942; Dietz and Menard, 1953). The Arch and Deep are considered to be secondary features created by elastic flexure of the lithosphere, caused by the load of the Hawaiian Ridge (Menard, 1964; Walcott, 1970; Crough, 1978). The Hawaiian Ridge, Deep, and Arch are superimposed upon the broad (1000 km), elongate Hawaiian Swell (Betz and Hess, 1942; Dietz and Menard, 1953; Watts, 1976). Within the surveyed area (Fig.III-2) the axis of the Arch is ~600 m shallower than the axis of the Deep and ~1200 m shallower than the average regional 5500-m depth of the North Pacific. Bathymetry of the Arch is complex; numerous relatively small (200-1000 m) faulted and constructional sea floor features are concentrated around the axial region of the Arch.

FIGURE III-1: Bathymetry of the eastern Hawaiian Ridge and adjacent features (modified from Chase et al., 1971). The 2600 and 3000 m contours are used to delimit sea floor topography, except at the eastern end of the Hawaiian Ridge, where selected 2400 and 2800 m contours highlight the positions of the Hawaiian Deep and Arch. Box encloses portion of Hawaiian Deep and Arch examined (Fig.III-2). Selected deep sea core and Deep Sea Drilling Project (DSDP) sites are indicated by black squares; these are referred to in the text.

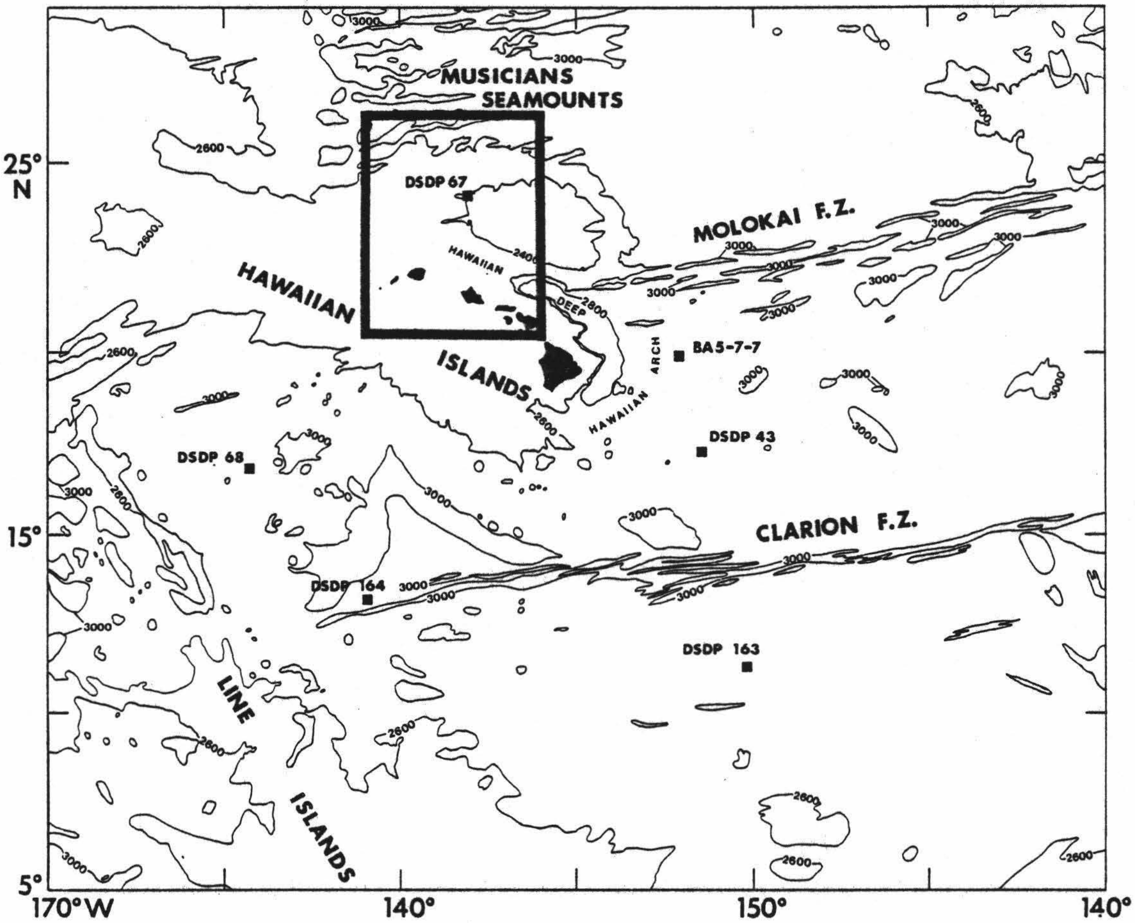
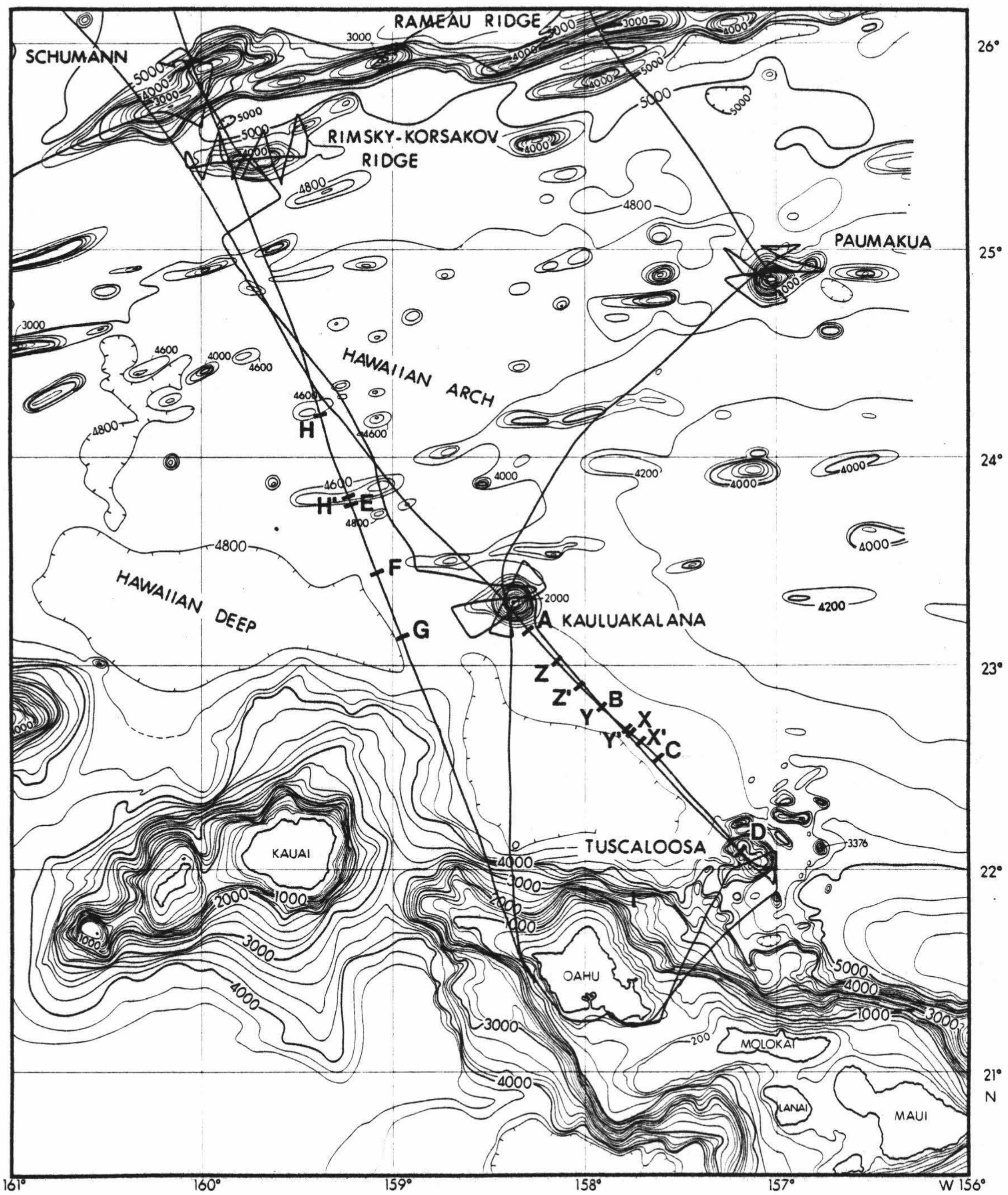

MUSICIANS
SEAMOUNTS
DSDP 67
HAWAIIAN
2400
HAWAIIAN
ISLANDS
DEEP
2800
MOLOKAI F.Z.
BA5-7-7
HAWAIIAN
ARCH
DSDP 43
DSDP 68
CLARION F.Z.
DSDP 164
DSDP 163
LINE
ISLANDS
3000
2600
25°
N
15°
5°
170°W
140°
150°
140°

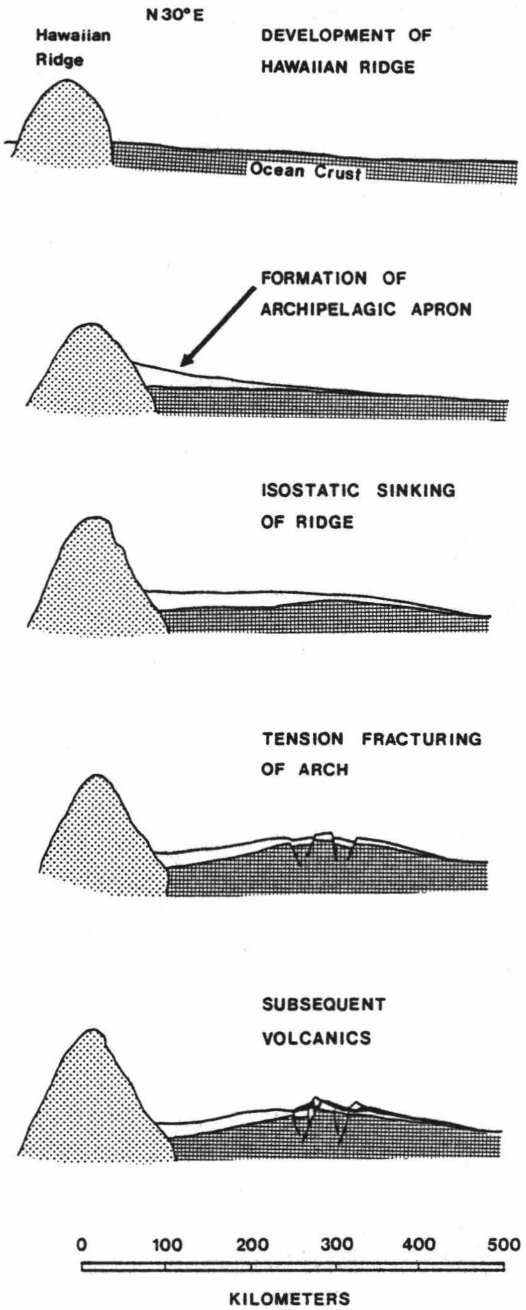
FIGURE III-2: Bathymetry north of Kauai and Oahu, Hawaii showing seismic reflection track control and the location of profiles discussed in the text. Bathymetry compiled from Naugler (1968), Wilde et al. (1980), and unpublished HIG data. The contour interval is 200 m.


RAMEAU RIDGE
SCHUMANN
RIMSKY-KORSAKOV
RIDGE
PAUMAKUA
HAWAIIAN ARCH
HAWAIIAN DEEP
KAULUAKALANA
TUSCALOOSA
KAUAI
OAHU
MOLOKAI
LANAI
MAUI
A
B
C
D
E
F
G
H
H'
X
X'
Y
Y'
Z
Z'
3000
4000
4600
4800
5000
4200
2000
1000
200
3376
26°
25°
24°
23°
22°
21°
N
161°
160°
159°
158°
157°
W 156°

The lithosphere underlying the northern Hawaiian Arch and Deep was formed during the Cretaceous magnetic quiet interval so its age is not well known. A simple interpolation between anomaly 34 to the east (80 Ma; Ness et al., 1980) and Mesozoic anomaly M-0 far to the west (109 Ma; Larson and Hilde, 1975) results in a Late Cretaceous age (80-90 m.y.) for this portion of oceanic crust between the Murray and Molokai fracture zones.

The observation of numerous bathymetric lineations on the northern Arch (such as in Fig.III-2 between 23° and 25°30′N) led Menard (1964) to speculate that tension in the crust resulting from arching may allow melting at depth, upward movement of magma, and creation of lava flows and volcanoes on the Arch. Since shield-building volcanism was active on the Kauai to Maui portion of the Hawaiian Ridge from ~5 to ~1 Ma (McDougall, 1979), the age of these sea floor edifices could then be expected to be quite young, compared with that of the approximate age of basement (90-80 Ma). Later, evidence from reflection profiling suggested the presence of sea floor lava flows on the Arch to Normark and Shor (1968), who elaborated on Menard′s idea and proposed a model for the development of the Arch. The essential features of this model are schematically depicted in Figure III-3. In this model, an archipelagic apron, created before the downwarping of the Hawaiian Deep into an effective sediment-trap, is faulted and partially covered by lavas emanating from conduits provided by tensional faults. Scripps Institution of Oceanography (SIO) Deep Tow experiments, subsequent to the investigation of Normark and Shor, added more evidence for the

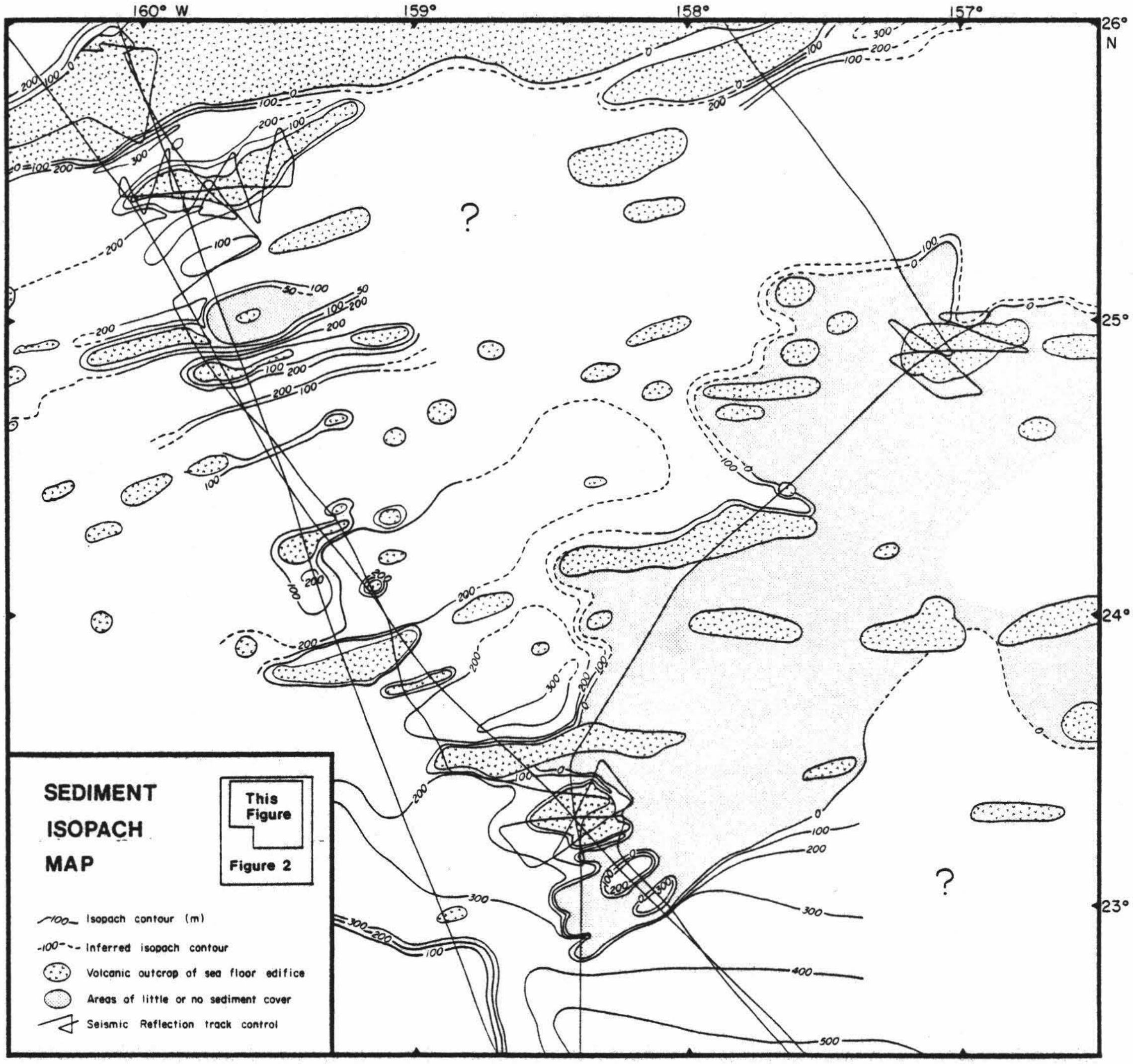
FIGURE III-3: Schematic depiction of Normark and Shor model for development of the northern Hawaiian Deep and Arch (redrafted from Normark and Shor, 1968). Formation of the Hawaiian Islands is accompanied by creation of an archipelagic apron around the base. Later, isostatic sinking of the Hawaiian Ridge causes downwarping of the Hawaiian Deep (between the Ridge and Arch) and bulging of the Hawaiian Arch, where tensional fracturing begins to occur. In the final stage, lava emanating from conduits provided by the tensional faults creates sea peaks and locally covers areas of low relief.


N 30° E
Hawaiian Ridge
DEVELOPMENT OF HAWAIIAN RIDGE
Ocean Crust
FORMATION OF ARCHIPELAGIC APRON
ISOSTATIC SINKING OF RIDGE
TENSION FRACTURING OF ARCH
SUBSEQUENT VOLCANICS
0
100
200
300
400
500
KILOMETERS

existence of young sea floor lava flows (Speiss et al., 1969). Subsequent drilling at DSDP Site 67, however, encountered a 60-m thick section of volcanic sandstones and mudstones, the base of which was interpreted to be early Eocene or Paleocene in age (~55Ma) (Winterer et al., 1971), and was therefore much older than expected. Moreover, because the sediments found there onlap and bury a nearby small ridge, the ridge, and perhaps other volcanism, should then be Eocene-Paleocene age or older.

Wallin and Frazer (Chapter II, this thesis) speculated that volcanism on the northern Arch occurred during at least two different episodes. Based on 3.5-kHz echo character mapping and interpretation of seismic reflection profiles, sea floor lava flows were found to rest upon an older 150 to 250-m thick sediment section, which, in turn, was found to onlap a different population of sea floor edifices (such as the ridge south of DSDP Site 67). Although the actual time span represented by the intervening sediment section is unknown, its thickness and composition suggest that it accumulated over a long period of time (Wallin and Frazer, Chapter II, this thesis). K/Ar age dating (of Paumakua, Kauluakalana, and Mendelssohn Seamounts; M. Pringle, personal communication, 1982), paleomagnetic pole determinations (of Paumakua and Rimsky-Korsakov; Sager, 1981; Sager, in preparation), and stratigraphic age control at DSDP Site 67 constrain the age(s) of the older volcanic event(s) to the Late Cretaceous or early Tertiary. A sediment isopach map (Fig.III-4) shows these contrasting areas of shallow lava flows and windows of older sediment

FIGURE III-4: Sediment isopach map of a portion of the northern Hawaiian Arch and Deep (from Chapter II). The areal relationship between the region covered by this map and the area of Figure III-2 is shown in the legend. Isopach contours are in meters; the light stippled areas indicate regions covered by thin or no sediment (interpreted as lava flows); and the v-pattern denotes outcropping igneous rocks associated with sea floor edifices. A sediment sonic velocity of 1.7 km/sec was used to estimate sediment thickness.


160° W
159°
158°
157°
26° N
25°
24°
23°
?
?
SEDIMENT ISOPACH MAP
This Figure
Figure 2
100 Isopach contour (m)
100 Inferred isopach contour
Volcanic outcrop of sea floor edifice
Areas of little or no sediment cover
Seismic Reflection track control
0
100
200
300
400
500

as regions of thin and thick sediments, respectively.

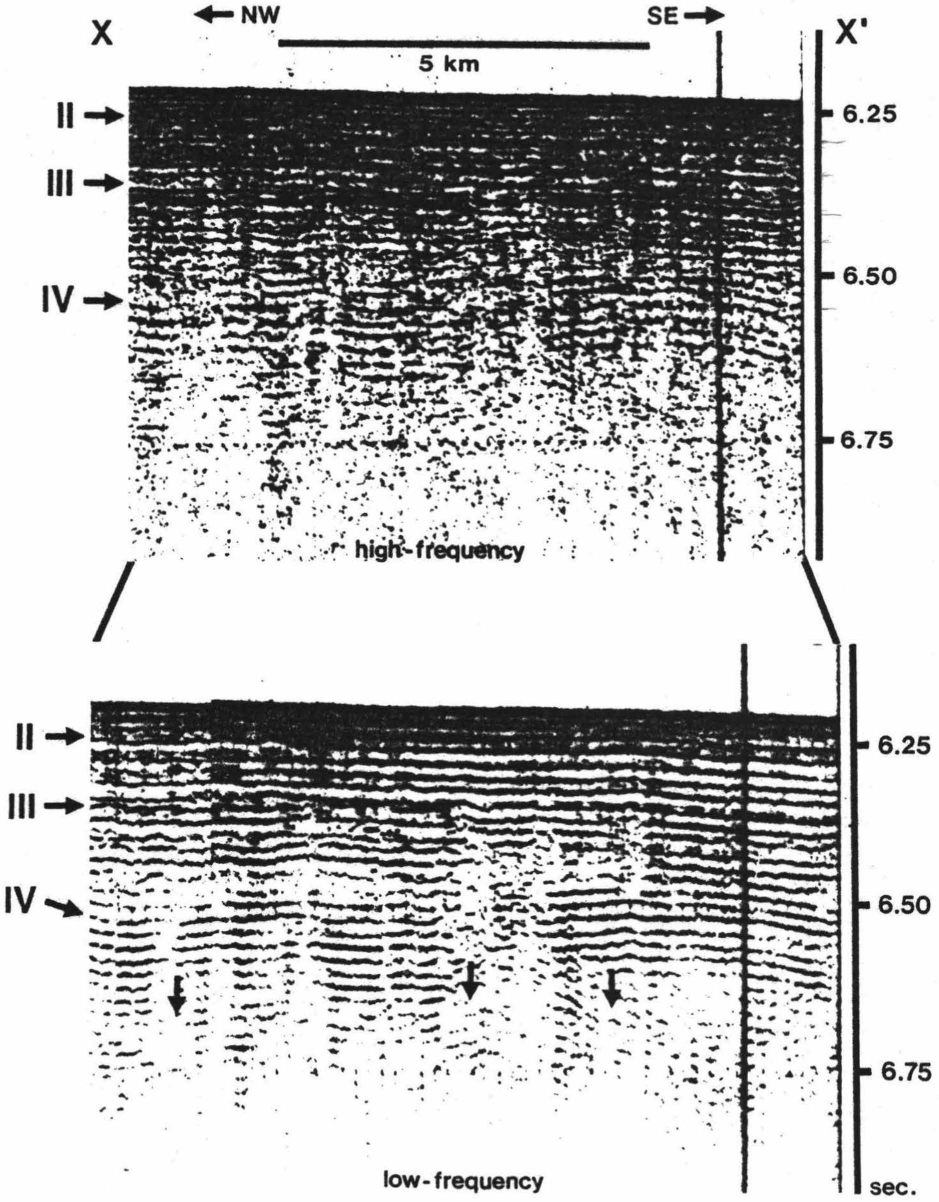
In this paper we use seismic reflection profiles to examine the shallow structure of the Hawaiian Deep north of Oahu and Kauai. After determining the probable nature and age of sediment layers in the Deep, we correlate these sediment layers with those on the Hawaiian Arch. This allows us to speculate as to the age and character of volcanism on the Arch and the past and present bottom current activity around the Hawaiian Ridge.

ACOUSTIC STRATIGRAPHY

Thick accumulation of sediment in the Hawaiian Deep was proposed by Menard (1956) on the basis of sea floor bathymetry. Later Shor and Pollard (1964), by means of a reversed refraction line, confirmed that upper sediment layers progressively thicken from the Hawaiian Arch toward the Hawaiian Deep. From seismic reflection profiles, Kroenke (1965) measured sediment thickness in the Deep north of Oahu to be in excess of 600 m, thinning to less than 100 m up the south flank of the northern Arch; he also reported as much as 1 km of sediment in the Deep north of Molokai. Harian (1967) and Normark and Shor (1968) reported similar thickening of sediment layers from the Arch to the Deep.

We find five prominent sea floor and subbottom reflectors on reflection profiles over the Hawaiian Deep north of Oahu which we refer to as Reflectors I, II, III, IV, and acoustic basement (Fig.III-5, profile XX′). Because Reflector I is locally confined to the region of

FIGURE III-5: XX′ (100-250 Hz upper section; 50-150 Hz lower section). Differently filtered profiles recorded simultaneously show four prominent reflectors traced across the Hawaiian Deep and Arch (Reflectors II, III, IV, and acoustic basement). A fifth prominent reflector (Reflector I) does not appear on either profile. Arrows on the low-frequency filtered profile (below) point to the acoustic basement reflector. This reflector is difficult to discern on the high-frequency filtered profile.


X
NW
SE
5 km
X'
II
III
IV
6.25
6.50
6.75
high-frequency
II
III
IV
6.25
6.50
6.75
low-frequency
sec.

the Deep nearest the Hawaiian Ridge, it does not appear on profile XX′ and will be discussed later. Reflector II is a moderately strong reflection off an undulatory and sometimes hummocky surface ~55 m beneath the sea floor (assuming a sediment sonic velocity of 1.7 km/sec from DSDP Site 67). The strong reflection off Reflector II is distinct from other weaker reflectors in the upper sediment column. Reflector III is a strong reflector ~70 m beneath Reflector II. It is either smooth and undulating or rough and irregular; the distribution of these two modes is significant and predictable and will be discussed later.

A change in general subbottom character occurs at Reflector III; above it the sediment column shows intense stratification upward to the sea floor; below it reflection character changes to one of more discrete reflectors bounded by generally reflection-free zones (e.g., low-frequency playout of XX′). Reflector IV, ranging in depth from 110 to 165 m beneath Reflector III, gives a strong reverberant reflection off a smooth to irregular surface. This reverberant character results from a series of closely spaced strong reflectors. Acoustic basement, ~160 m beneath Reflector IV, is the lowest continuously traceable reflector on the profile and is recognizable by its weak, irregular character and low-frequency signal. It becomes progressively more difficult to trace toward the axis of the Deep and in some cases completely disappears, leaving Reflector IV as the deepest reflector. Often acoustic basement does not appear on the high-frequency filtered profile but can be identified on a low-frequency filtered profile (Fig.III-5).

OBSERVATIONS

Reflection profile ABCD extends SE from Kauluakalana Seamount, across the Hawaiian Deep, and to a point near the base of the Hawaiian Ridge at Tuscaloosa Seamount (Fig.III-2). Fundamentally, profile ABCD (Figs.III-6 and III-7) shows upper sediment wedges (above Refls. I, II, and III) which thin northwestward, and lower sediment layers (above Refl. IV and acoustic basement) which do not display any systematic lateral variation in thickness. Reflector I, confined to the deepest portion of the Deep, is buried beneath 40 m of sediment at 1115Z and thins rapidly to the NW, emerging at the sea floor at ~1000Z. The thickness of sediment between Reflectors I and II and Reflectors II and III thins from 70 m to 30 m (1130Z to 1000Z) and 140 m to 80 m (1100Z to 0800Z), respectively. Between Reflectors III and IV the thickness of sediment is relatively constant (150 m) from the Deep to the Arch (at 0840Z); however, on the Arch (NW of 0840Z) it thins slightly. Although the general character of this sediment layer is non-wedging, this latter interval is of special interest and we discuss its significance later. The thickness of sediment between Reflector IV and acoustic basement ranges from 100 to 210 m and does not show any systematic variation or relationship to distance from the Hawaiian Ridge.

FIGURE III-6: ABCD (100-250 Hz from 0405Z to 0530Z; 50-150 Hz from 0530Z to 1423Z). Profile in three sections extends SE off the inner flank of the Arch near Kauluakalana Seamount to a point close to the base of the Hawaiian Ridge at Tuscaloosa Seamount. Seismic source used was 80 in^3 airgun.

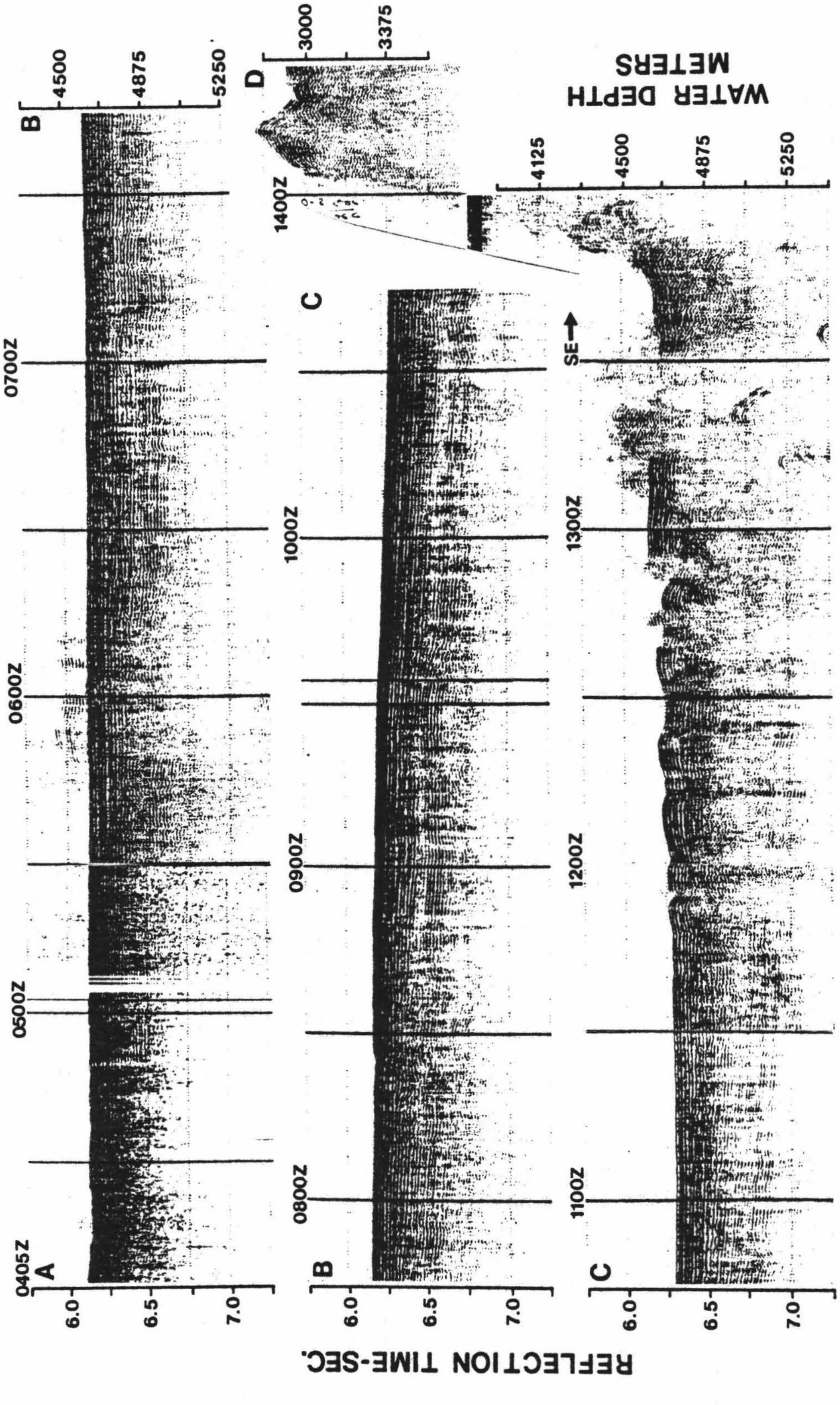
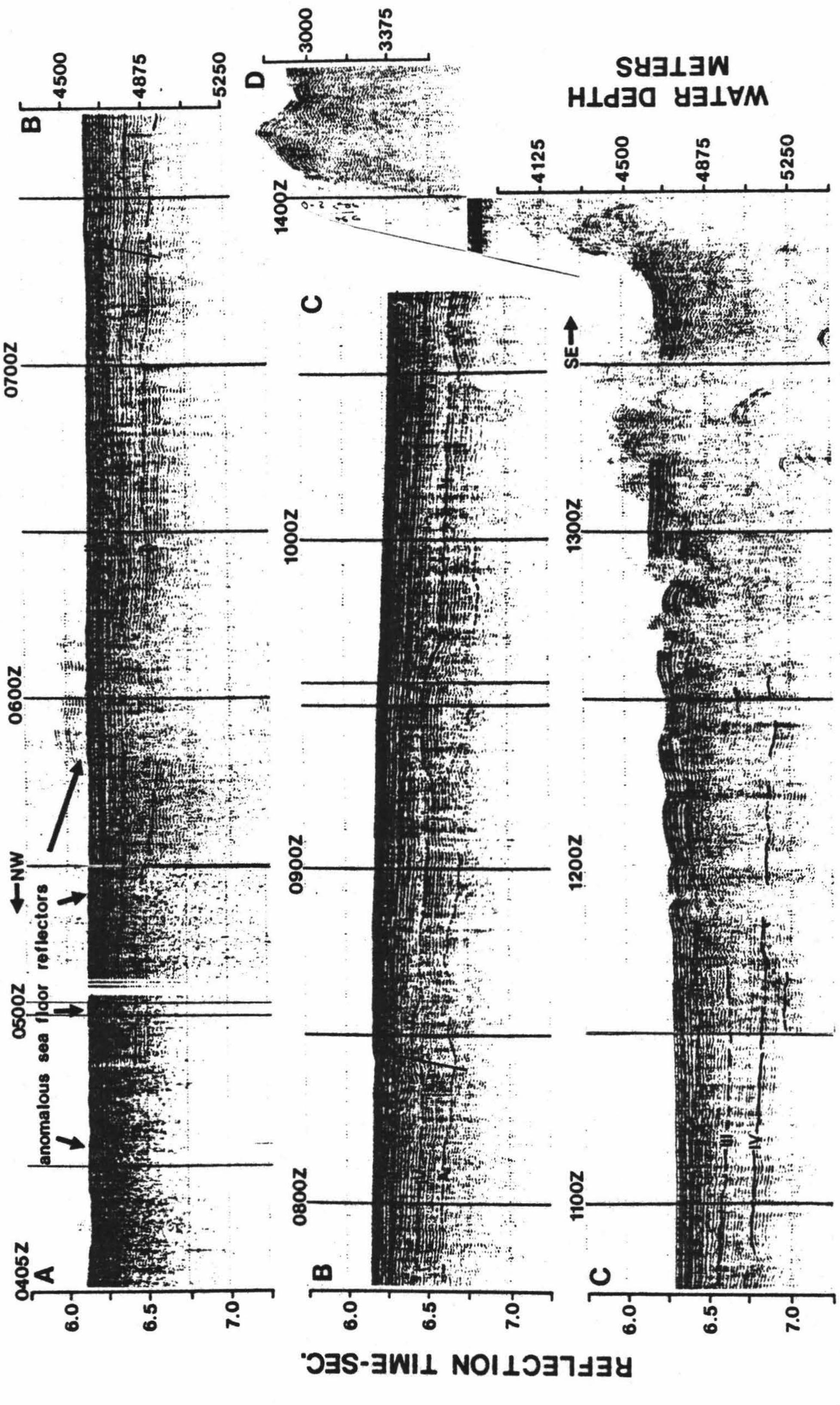

A
B
C
D
0405Z
0500Z
0600Z
0700Z
0800Z
0900Z
1000Z
1100Z
1200Z
1300Z
1400Z
SE→
4125
4500
4875
5250
3000
3375
6.0
6.5
7.0
WATER DEPTH
METERS
REFLECTION TIME-SEC.

FIGURE III-7: Interpretation of profile ABCD. The locations of Reflectors I, II, III, IV, acoustic basement (A), and anomalous sea floor reflectors are shown. The thickness of sediment above Reflectors I and II rapidly thins to the NW. Sediment thickness between Reflector III and IV from the Deep to the Arch (at 0840Z) is relatively constant at 150 m, after which it thins slightly (between 0840Z and 0615Z). The thickness of sediment between Reflector IV and acoustic basement ranges from 100 to 210 m and does not show any systematic variation or relationship to distance from the Hawaiian Ridge. Note the presence of several faults that penetrate the entire sediment column, and consistently display a NW-downthrown side. Reflector III, when shown as a wavy line, denotes sections of obvious top-discordant character and high variation in amplitude. Dashed lines of reflectors indicate inferred positions. Interpretation of reflectors between 0530Z and 1423Z was made with the assistance of a high-frequency filtered (100-250 Hz), simultaneously recorded playout.


A
B
C
D
0405Z
0500Z
0600Z
0700Z
0800Z
0900Z
1000Z
1100Z
1200Z
1300Z
1400Z
anomalous sea floor reflectors
NW
SE
III
IV
6.0
6.5
7.0
4125
4500
4875
5250
3000
3375
WATER DEPTH METERS
REFLECTION TIME-SEC.

Although subbottom reflectors west and northwest of Kauluakalana Seamount (profile EFG, Figs.III-8 and III-9) exhibit similar geometry and character, there are some differences in the thicknesses of sediment layers. NW of 0215Z (profile EFG), Reflector III becomes difficult to trace and the thickness of sediment between Reflectors III and IV thins from ~110 m to < 25 m. This is the thinnest interval observed between these reflectors; we note that it occurs at a location far up onto the Arch. The thickness of sediment between Reflector IV and acoustic basement varies from 60 to 150 m, not much different from the range observed for profile ABCD.

Sea floor and subbottom character change from a smooth, locally faulted (such as 0825Z and 0722Z, profile ABCD) terrain away from the Hawaiian Ridge to a rugged, highly deformed terrain in the Deep near the base of the Hawaiian Ridge. Nearing the disrupted area the entire reflector sequence below Reflector I progressively weakens in amplitude and disappears (profile ABCD at about 1230Z). Close to the base of the Hawaiian Ridge there are numerous faults (e.g., in the vicinity of 1245Z) and piercement structures (at 1245Z, 1255Z, 1320Z?). The large undulatory sediment surfaces (35-45 m in amplitude) on the floor of the Deep (between 1145Z and 1300Z) are underlain by generally flat-lying stratified sediments. These sediment accumulations must therefore be the result of erosional/depositional processes. Although such bedforms may be created by either deep thermohaline flow (Hollister et al., 1974; Damuth and Hayes, 1977; Damuth, 1980) or by downslope processes (such as turbidity currents and slumps) (Embley, 1976; Damuth, 1980),

FIGURE III-8: EFG (40-160 Hz). Profile extends SE from an ENE-trending ridge (partly visible at 0022Z) to a point near the base of the Hawaiian Ridge at Kauai. Seismic source used was 80 in^3 airgun. Data courtesy of the USGS (R/V LEE cruise L8-78).

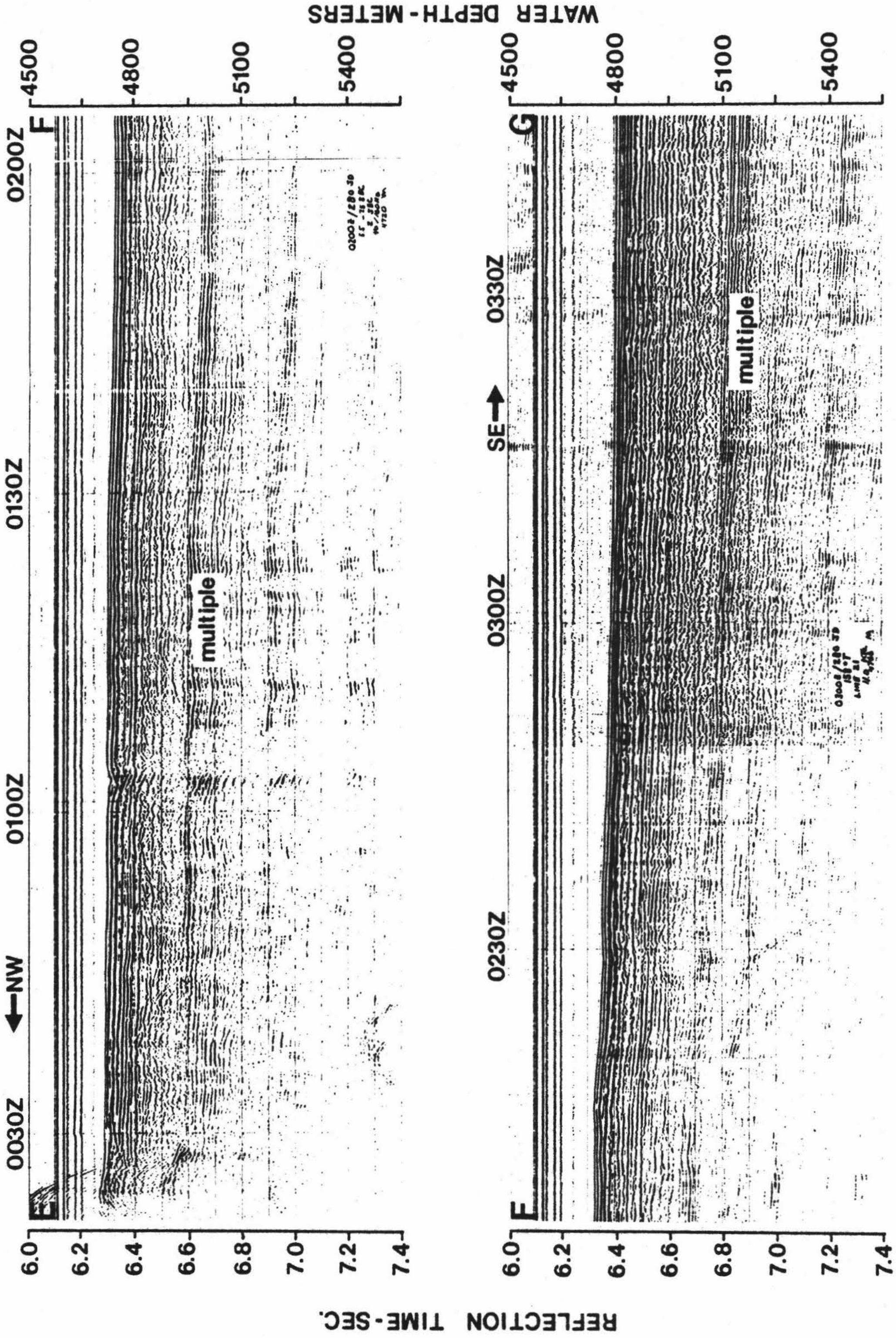
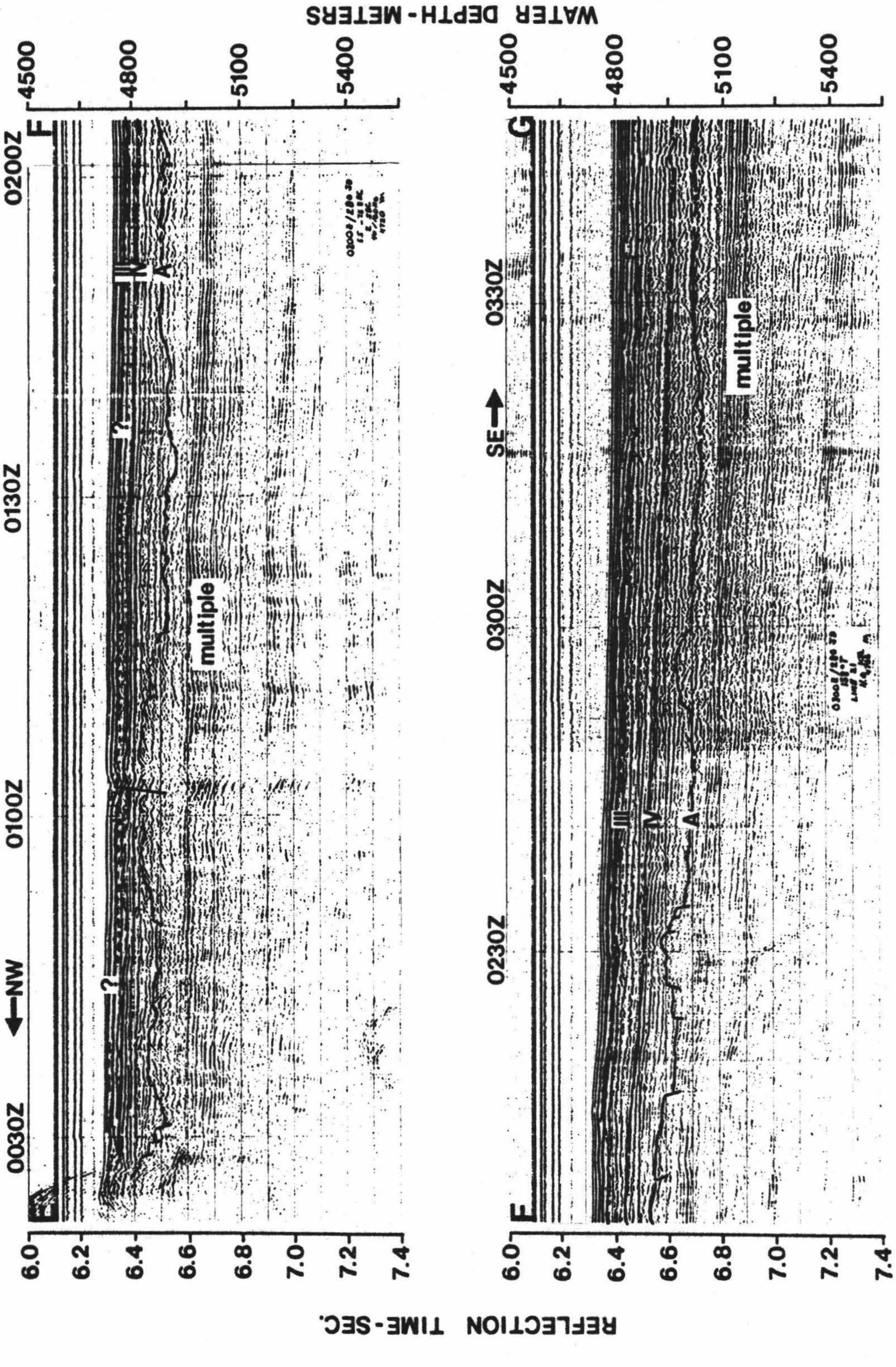

WATER DEPTH-METERS
4500
4800
5100
5400
F
0200Z
0130Z
0100Z
0030Z
E
NW
multiple
G
0330Z
SE
0300Z
0230Z
E
multiple
6.0
6.2
6.4
6.6
6.8
7.0
7.2
7.4
REFLECTION TIME-SEC.

FIGURE III-9: Interpretation of profile EFG. Reflector III, possessing an unusually rough character, displays a high-amplitude reflection ranging in depth from 20 to 75 m beneath the sea floor. Reflector IV is 25 to 110 m below Reflector III and its strong, characteristically reverberant reflection is diagnostic. The thickness of sediment between Reflectors III and IV thins rapidly NW of 0215Z. Acoustic basement (A) is a weak reflector which may be found 55 to 135 m beneath Reflector IV. The thickness of sediment between acoustic basement (A) and Reflector IV, although highly variable, does not show any systematic lateral trend. Reflectors I and II do not appear on EFG. One prominent fault near 0100Z shows a NW-downthrown side.

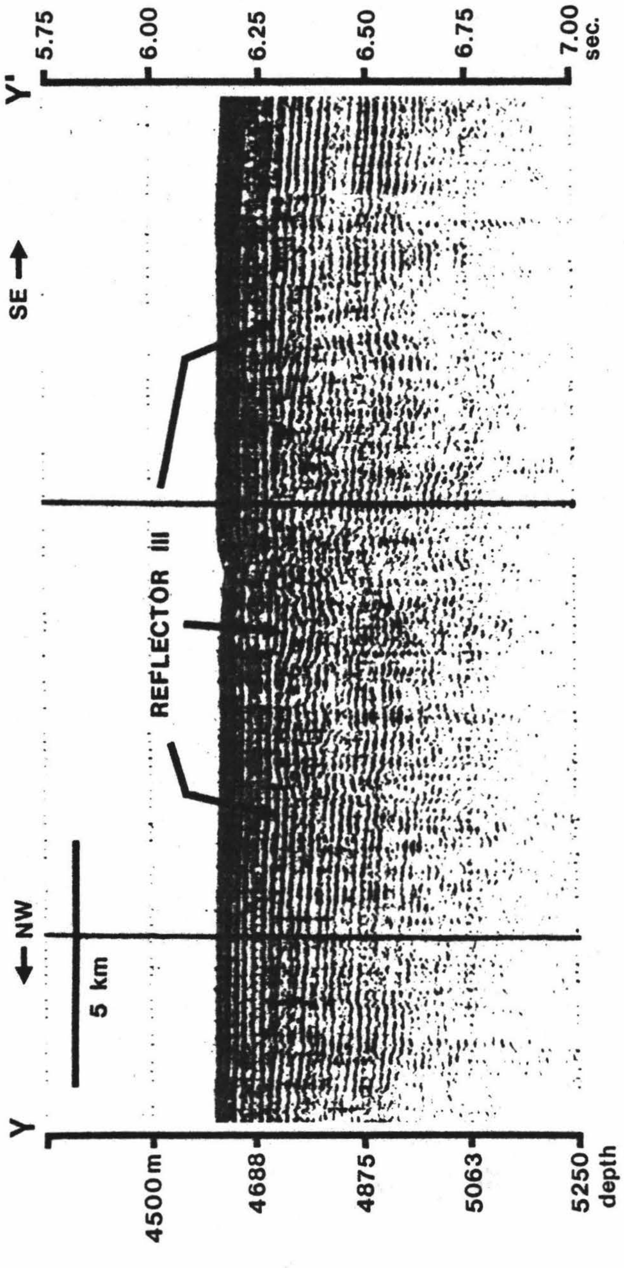

WATER DEPTH-METERS
4500
4800
5100
5400
F
0200Z
III
IV
A
?
0130Z
multiple
0100Z
NW
0030Z
E
G
0330Z
SE
multiple
0300Z
III
IV
A
0230Z
E
6.0
6.2
6.4
6.6
6.8
7.0
7.2
7.4
REFLECTION TIME-SEC.

occurrence of the bedforms here is laterally restricted to the area nearest the Hawaiian Ridge. Thus, they probably are comprised of debris shed off the flanks of the Hawaiian Ridge and reworked by bottom current.

An abrupt change in the character of Reflector III occurs to the NW at 0845Z along profile ABCD: this change coincides with the point at which the sediment thickness between Reflectors III and IV begins to thin slightly (see profile YY′ in Fig.III-10 for enlarged section). Reflector III gives a smooth, strong reflection in the Deep (SE of 0845Z, profile ABCD; SE of 0215Z, profile EFG), which changes to a weaker irregular reflection northwestward toward the Arch. Over the section in which one of these transitions occurs (profile YY′), the abrupt changes in amplitude of signals off Reflector III demonstrate this contrast. The geometry of Reflector III and the reflectors above it is such that a top-discordant relationship (Mitchum et al., 1977) is displayed; the vertical excursions of Reflector III terminate abruptly against reflections from overlying sediment layers, which themselves return smooth, subparallel reflections and do not share the deformation and irregularity of Reflector III.

Toward the Arch, sea floor is characterized by the local occurrence of rough terrain (typically varying 0-30 m). Within these rough areas (such as at 0405Z to 0448Z, 0550Z to 0614Z; profile ABCD), the sea floor is acoustically so reflective that the sequence of underlying reflectors traced northward from the Deep is partially, or in many cases totally, obscured. The termination of these rough

FIGURE III-10: YY′ (50-150 Hz). The abrupt changes in amplitude and top-discordant relationship which Reflector III displays in this profile indicate the presence of an erosional unconformity. Note fault in center of profile (dropping NW side) that penetrates uppermost sediment layers.


Y
Y'
← NW
SE →
5 km
REFLECTOR III
5.75
6.00
6.25
6.50
6.75
7.00
sec.
4500 m
4688
4875
5063
5250
depth

"anomalous" sea floor reflectors where there is a change to a smooth bathymetry allows the seismic sequence beneath to reappear (such as at 0448Z to 0458Z, 0614Z to SE; profile ABCD). An enlarged section of profile ABCD (profile ZZ′, Fig.III-11) shows one such area. On both sides of the strong anomalous surface reflector in profile ZZ′ (shown as "3.5-kHz opaque zone"), sediment is at least 250 m thick. No basement reflector is observed to emerge from beneath these sediment sections at the edge of the anomalous surface reflector. Examination of the first water column multiple of ZZ′ demonstrates the low-frequency character of the anomalous sea floor reflector and suggests the presence of Reflectors II and III on both sides of the reflector at 45 and 120 m depth, respectively. This anomalous reflective sea floor correlates with the opaque echo type recognized by Wallin and Frazer (Chapter II, this thesis) in 3.5-kHz echograms, and is interpreted to be the tongues of lava flows. A similar interpretation was made by Normark and Shor (1968) on the basis of seismic reflection profiles.

NW of Kauluakalana Seamount near the bathymetric crest of the Arch at 4725-m depth (Fig.III-2), the reflection character is slightly different (profile HH′, Fig.III-12). A highly stratified upper zone of sediment ~95 m thick and ponded to the SE rests on an irregular surface that returns discontinuous strong "chaotic" reflections. Within the stratified zone we are unable to identify with certainty Reflectors III or IV; one or both may be present within the zone, displaying somewhat atypical character, or one or both may be masked beneath the chaotic

FIGURE III-11: ZZ′(100-250 Hz). Profile south of Kauluakalana Seamount shows strong sea floor reflector (correlative with 3.5-kHz opaque zone) surrounded by margins of stratified sediment (>250 m thick). In the first water column multiple, these qualities are more clearly evident. The 3.5-kHz opaque echo type is believed to indicate the presence of igneous lava flows (as discussed in Chapter II).

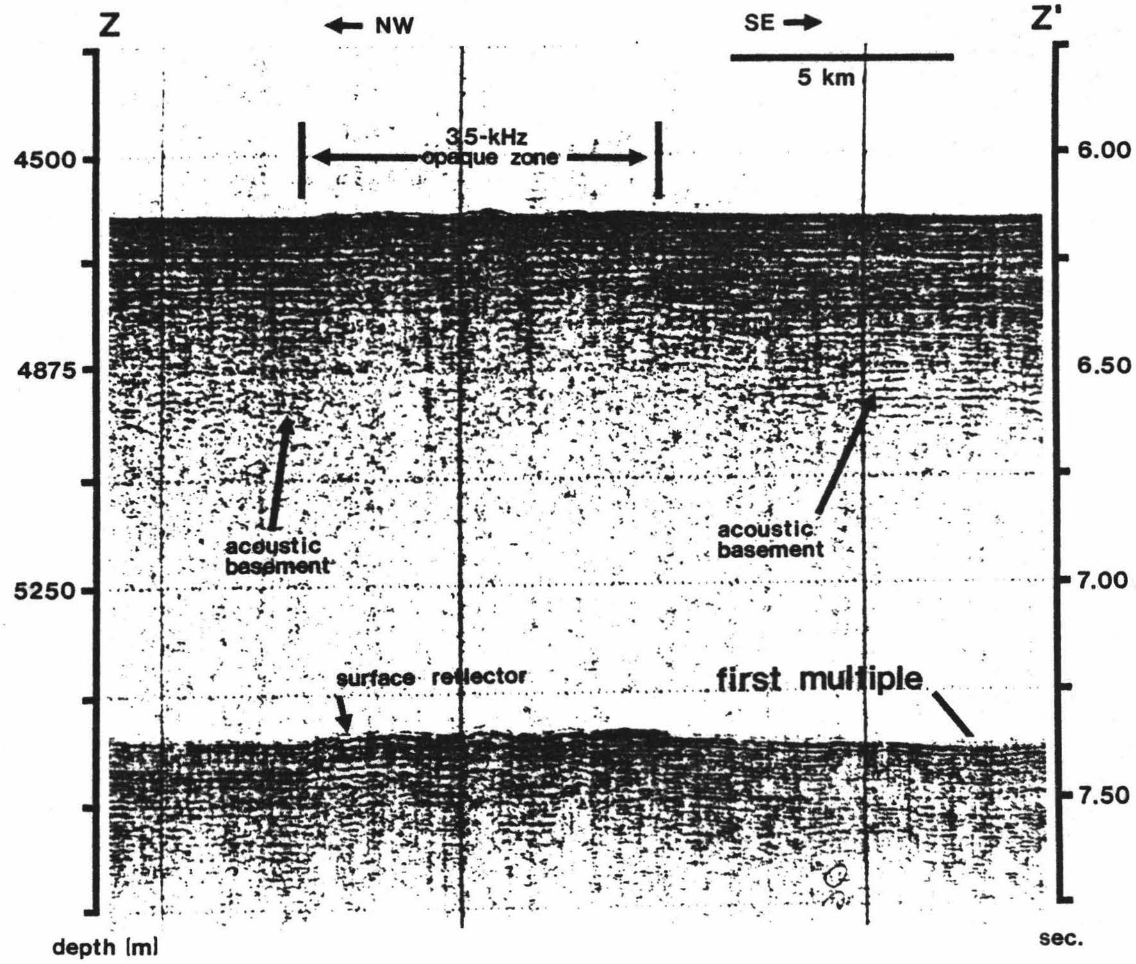
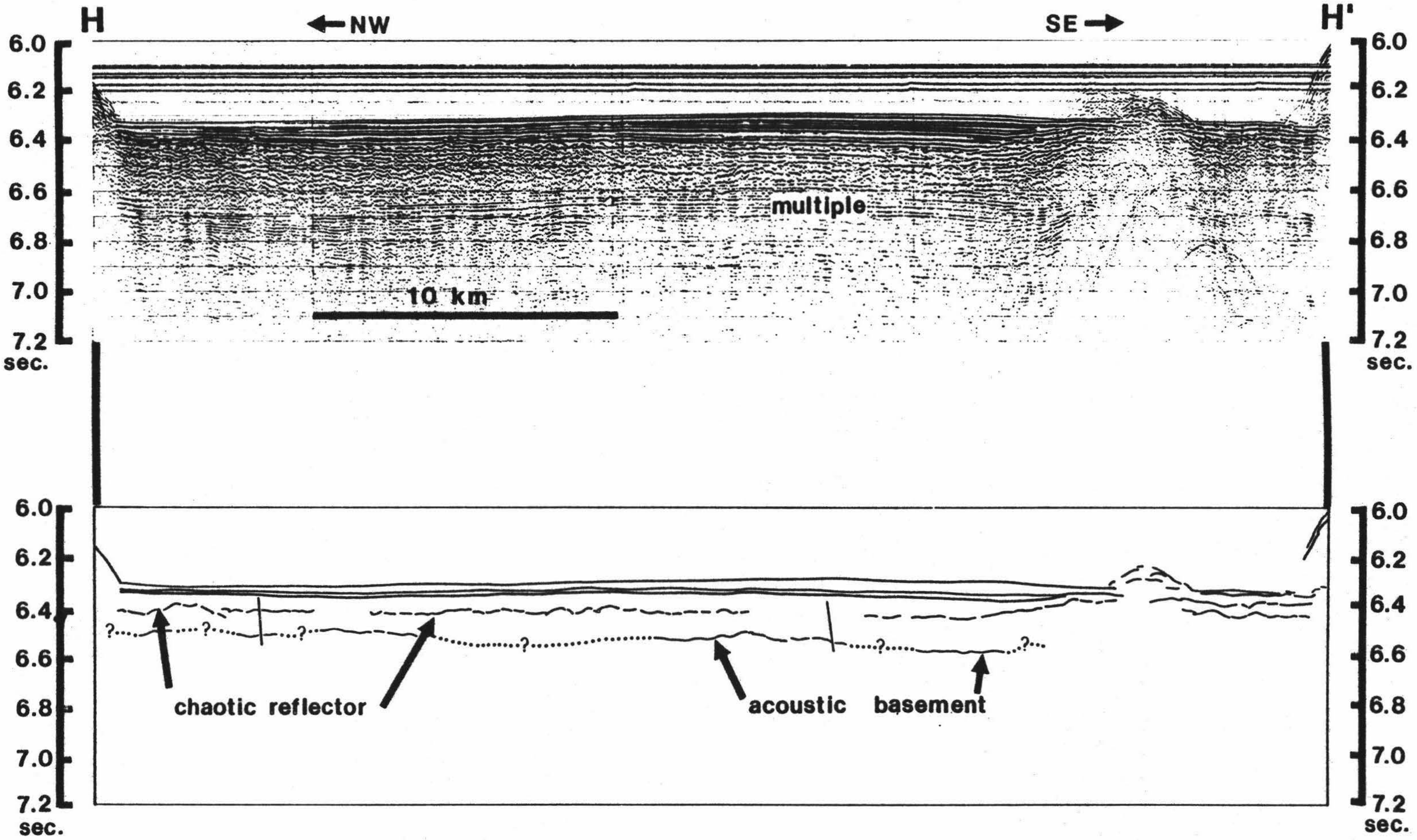

Z
← NW
SE →
Z'
5 km
3.5-kHz
opaque zone
4500
4875
5250
6.00
6.50
7.00
7.50
acoustic basement
acoustic basement
surface reflector
first multiple
depth [m]
sec.

FIGURE III-12: HH′ (80-160 Hz). Profile NW of Kaukuakalana Seamount (also in Chapter II as profile VV′) shows a stratified zone ~95 m thick and ponded to the SE above an irregular strong "chaotic reflector". ~100 m beneath the chaotic reflector there is a weak discontinuous acoustic basement reflector. Reflectors III and IV, prominent on nearby profiles, cannot be positively recognized on this profile. The possibilities exist that either one or both reflectors are above or below the chaotic reflector. Seismic source used was 80 in^3 airgun. Data courtesy of the USGS (R/V LEE cruise L8-78).


H
H'
← NW
SE →
6.0
6.2
6.4
6.6
6.8
7.0
7.2
sec.
multiple
10 km
chaotic reflector
acoustic basement
?

reflector. The chaotic reflector has a rough hyperbolic character and a high reflection coefficient, which makes seismic penetration difficult (the chaotic reflector is the lowest traceable reflector over some portions of the record). Beneath this chaotic reflector a weak acoustic basement reflector sporadically appears at ~200 m depth. The reflection characteristics of the chaotic reflector are similar to those usually associated with igneous basement. Because of this, and the fact that the chaotic reflector has limited lateral extent and overlies a lower acoustic basement reflector, Wallin and Frazer (Chapter II, this thesis) concluded that it is the surface of a lava flow.

THE SIGNIFICANCE OF REFLECTOR III

The geometry of the sediment layers from the Deep to the Arch indicates that the division between thick lower sediment layers, and upper sediment wedges that thin to the NW, occurs at Reflector III. Reflection sequences resembling those of the Hawaiian Deep have been recognized by Kroenke and Nemoto (in press, 1982) in the structurally similar Emperor Deep. In the Emperor Deep east of the Emperor Seamounts, a uniformly thick (250-300 m) pre-Senonian lower layer is overlain by a westward-thickening wedge of sediment composed of both Senonian-Paleogene middle and Neogene upper layers. From tracing these reflection profiles back to DSDP drill sites on the Hess Rise, Kroenke and Nemoto interpreted the Neogene upper wedging sediments as being the erosional products from the south-southeastward advancing Emperor Seamount chain.

This analogy with the Emperor Deep suggests that Reflector III north of the Hawaiian Ridge represents the surface of the sea floor at the time immediately before erosional products associated with the southeastward-advancing Hawaiian Ridge were deposited upon it. The anomalously thick accumulation of sediment in the Hawaiian Deep may be attributed to the deposition of erosional products in the Deep after its creation 6-2 Ma (Menard, 1956; 1964; Hamilton, 1957; Kroenke, 1965; Moberly and McCoy, 1966; Normark and Shor, 1968; Fan and Grunwald, 1971).

The character of Reflector III over particular areas (0845Z to NW, profile ABCD; 0215Z to 0330Z , profile EFG) and the top-discordant relationship between Reflector III and the overlying reflectors suggest that portions of Reflector III mark erosional unconformities (Dobrin, 1976; Fitch, 1976; Mitchum et al., 1977). These qualities of Reflector III are similar to qualities displayed by reflectors elsewhere, such as Horizon A^u of the North Atlantic (Tucholke, 1979), which drilling has confirmed to be an erosional unconformity (Ewing and Hollister, 1972). The variations in reflection amplitude of Reflector III are probably due to weak diffractions from rough eroded portions, alternating with strong coherent reflections from smooth upper portions. SE of profile YY′, the smooth morphology and concordant-bounding reflectors of Reflector III suggest that the erosional unconformity is not present in the Hawaiian Deep. In contrast, the convergence of Reflector III and

Reflector IV (NW of 0845Z, profile ABCD; NW of 0215Z, profile EFG) toward the Arch implies that an increasing quantity of sediment has been removed by erosion.

THE NATURE AND AGE OF OTHER REFLECTORS

Although the nature of Reflectors I and II is unknown, there are two logical sources for the anomalous thickness of sediment above Reflector III in the Hawaiian Deep, i.e., the Hawaiian Ridge and the Hawaiian Arch. Since quartz is extremely rare in Hawaiian rocks, a high quartz content is taken as evidence of exotic derivation (Rex and Goldberg, 1958; Moberly and McCoy, 1966). The boundary between sediment of normal quartz content (content similar to that observed in sediments all over North Pacific) and very low quartz content, inferred by the cores of Moberly and McCoy (1966) for this area, is situated close to the termination of Reflector I (at ~1000Z, profile ABCD). Therefore, we speculate that the low quartz content sediment above Reflector I is derived from the Hawaiian Ridge. Conversely, the sediment between Reflectors I and II appears to show a "normal" quartz content, suggesting a source other than the Hawaiian Ridge. We believe that erosion of sediment off the Hawaiian Arch may have supplied much of this material.

Thus, the low quartz content of sediment north of the termination of Reflector I (near the bathymetric axis of the Deep) suggests a relatively small Hawaiian archipelagic apron. This is consistent with the rarity of both $CaCO_3$ content and turbidites observed in cores north of the bathymetric axis of the Hawaiian Deep (Fan and Grunwald, 1971; Kelly et al., 1975; Wallin and Frazer, Chapter II, this thesis), the conclusions of previous investigators (Rex and Goldberg, 1958; Moberly and McCoy, 1966; Fan and Grunwald, 1971), and other evidence of Arch-derived downslope deposits in the Deep (Schreiber, 1968). In addition, reflection profiles show that the maximum lateral extent of the apron can not be beyond the NW limits of profiles ABCD and EFG; sediment thickness above Reflector III trends to near zero at these points.

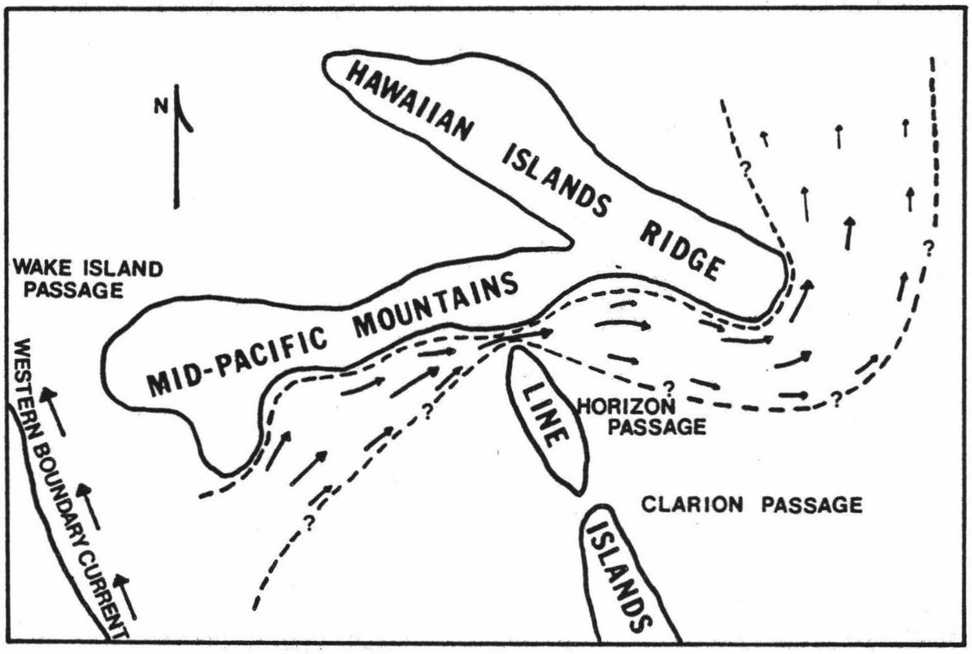
The numerous strong, closely-spaced, reverberant reflectors comprising Reflector IV indicate major acoustic impedance changes. Reflector IV is probably composed of chert lenses and layers similar to those encountered at DSDP Site 67 northeast of Kauluakalana Seamount, and at DSDP Sites 40 (McManus et al., 1970), 68 and 69 (Tracy et al., 1971), 163 (van Andel et al., 1973), and 164 (Winterer et al., 1973) south or east of the Hawaiian Ridge. The chert at these sites, either of Eocene or Late Cretaceous age, causes a strong, reverberant reflection on seismic records. The absence of any complete DSDP stratigraphy near this area hinders attempts to determine the composition of other sediment layers. However, we speculate that the layer between Reflector IV (chert) and Reflector III is predominately a radiolarian brown clay. This speculation is based on the stratigraphy at DSDP Sites 163 and 164 south of the Hawaiian Ridge, the transparent reflection character of the layer, and its apparent susceptibility to erosion. The only reflector deeper that Reflector IV is acoustic basement, which we interpret to be igneous, i.e., oceanic basaltic basement.

EROSION AND BOTTOM WATER FLOW AROUND THE HAWAIIAN RIDGE

Although the age of the unconformity may be as old as 55 Ma (probable age of Reflector IV), the coincidence between the formation of the Hawaiian Deep and Arch structure 6-2 Ma and the occurrence of the unconformity (Reflector III) on the sea floor of the Arch suggests that these two features are genetically related.

One of the main agents of abyssal floor erosion is bottom current, especially Antarctic Bottom Water (AABW) within the Pacific. Erosional unconformities on the Hess Rise (Nemoto and Kroenke, 1981), in the equatorial Pacific east of the Line Islands (Johnson, 1972), and in the Central Pacific Basin (Lonsdale and Smith, 1980) are attributed to erosion caused by AABW flow. The present-day flow of AABW in the Pacific near the Hawaiian Islands is shown in Figure III-13 (after Edmond et al., 1971). Northward flowing AABW penetrates to the eastern Pacific through Horizon Passage and also through gaps in the Line Islands (Mantyla, 1975; Normark and Speiss, 1976), and is then deflected around the SE end of the Hawaiian Ridge (Reed, 1969; Edmond

FIGURE III-13: Proposed flow of AABW south of the mid-Pacific mountains, through the Horizon passage and south and east of the Hawaiian Ridge (redrafted from Edmond et al., 1971). Arrows indicate direction and inferred relative intensity of AABW flow. At Horizon Passage the AABW is a 400 m-thick narrow current, the top of which is at about 4400 m (Edmond et al., 1971).


N
HAWAIIAN ISLANDS RIDGE
WAKE ISLAND PASSAGE
MID-PACIFIC MOUNTAINS
WESTERN BOUNDARY CURRENT
LINE ISLANDS
HORIZON PASSAGE
CLARION PASSAGE
?

et al., 1971; Mantyla, 1975).

From the diverted flow pattern and encounter of shallower Hawaiian Arch sea floor at the SE end of the Hawaiian Ridge, it could be expected that AABW velocity would increase (Fig.III-13), perhaps to an intensity sufficient to entrain and transport sea floor sediments. In fact, increased AABW velocity might occur not only in proximity to the end of the Ridge itself, but also over the broad area of shallower sea floor ("Hawaiian Depth Anomaly") identified by Mammerickx (1981) and extending at least 900 km southeast of the island of Hawaii. This shallow bulge ot sea floor is believed to be a precursory feature of the southeastward development of the Hawaiian Ridge (Mammerickx, 1981). The unconformity recognized on the Arch (Reflector III) may be caused by AABW erosion concomitant with and subsequent to the formation of the Hawaiian Ridge, Deep, and Arch 6-2 Ma. This scenerio suggests that while the Hawaiian Deep was receiving sediment infill by downslope agents (such as turbidity currents and slumps), bottom current deposition, and pelagic sources, the outer Deep and inner flank of the Arch were undergoing erosion.

Erosion and/or nondeposition around the Hawaiian Ridge is supported by the results of seismic reflection surveys, deep sea coring, and DSDP drilling. South and east of the eastern Hawaiian Ridge sediment thickness is generally less than 0.1 sec., although some areas are between 0.1 and 0.2 sec. thick (Ludwig and Houtz, 1979). At DSDP Site 68, SW of Oahu, middle Eocene brown clay was found beneath a few centimeters of reworked pelagic ooze that contained Quaternary, Miocene, and Eocene radiolaria (Tracey, et al., 1971). A piston core (BA 5-7-7, Fig.III-1), obtained east of Hawaii on the outer flank of the Arch (Schreiber, 1968; 1969), contained undisturbed Eocene sediment beneath 3.7 m of reworked sediment containing Eocene, Miocene, Pliocene, and Recent fossils. South of this location near DSDP Site 43 (Fig.III-1), Ewing et al. (1968) also reported Eocene sediments in a piston core.

If, however, erosion of sea floor sediments occurs around the tip of the SE-advancing Hawaiian Ridge due to deflection of northward AABW flow by shallower sea floor, then it is difficult to explain the distribution pattern of the unconformity north of Oahu. The pattern indicates erosion increasing laterally outward from the Hawaiian Ridge, and little, if any, erosion in close to the Ridge. For a linear seamount or island chain advancing over its own compensating arch, one would expect that the sea floor over which the chain advances should also have experienced erosion by bottom current, before the products of later volcanism progressed upon it. Alleviation of this seeming discrepancy awaits proof of the age of the unconformity, accurate mapping ot its distribution, and a better understanding of AABW flow dynamics.

THE AGE OF VOLCANISM ON THE ARCH

Examination of the stratigraphic relationship between Reflector III and the sea floor lava flows in profiles ABCD and ZZ′ (proposed by Wallin and Frazer and shown in Fig.III-4) reveals that Reflector III is older. Reflector III lies 120 m below the upper surfaces of these lava flows (profile ZZ′), and therefore the flows must be younger. In addition, since 3.5-kHz echograms and seismic reflection records do not show any evidence (such as seismic onlap) that young sediment layers have infilled flanks or portions of the flows (Wallin and Frazer, 1982, submitted), the base of the lava flows is probably well above the level ot Reflector III.

If the erosion of Reflector III is concurrent with or subsequent to the formation of the Hawaiian Ridge 6-2 Ma, then the lava flows must be younger than 6-2 Ma. Because the construction of the Hawaiian Ridge is the only known volcanic and tectonic event during this time period (6-2 Ma to present) and in this area, these flows could then be expected to be genetically related to construction of the Hawaiian Ridge.

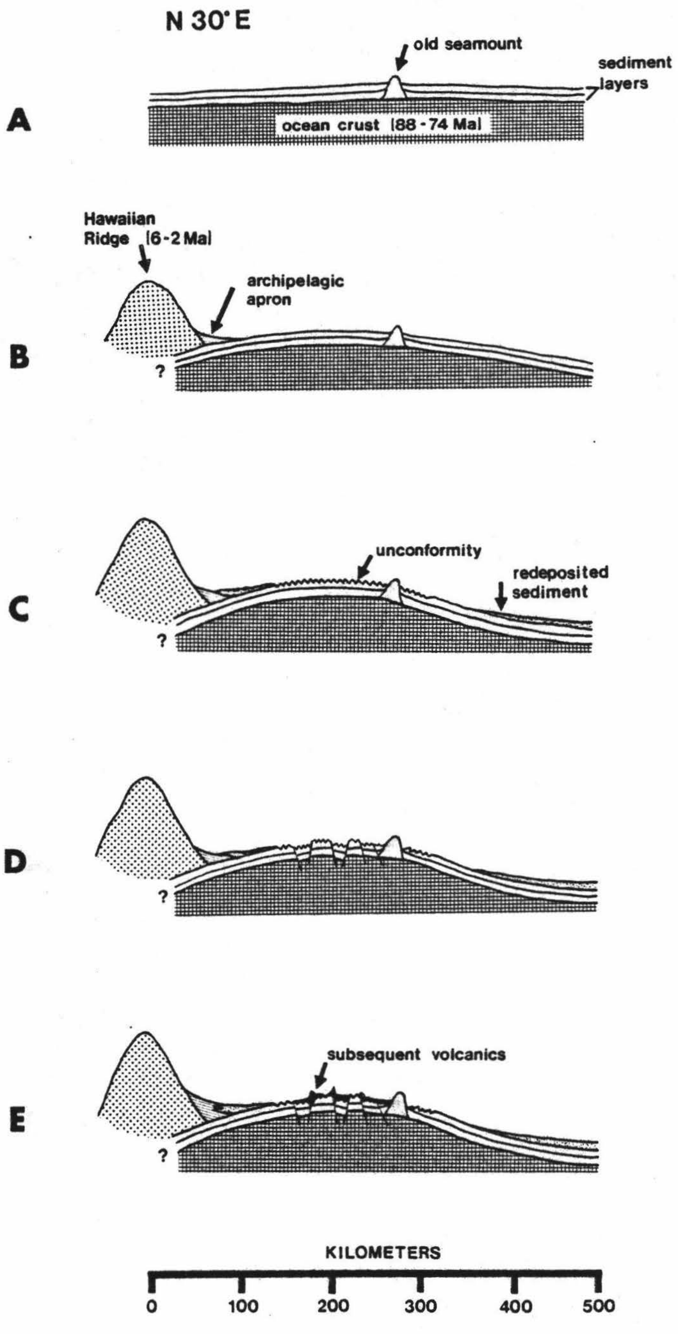
The buried lava flows of profile HH′ are probably much older than 6-2 Ma. As mentioned previously, we cannot be sure whether Reflector III or Reflector IV, or both, are above or below the feature interpreted to be a buried lava flow (chaotic reflector). However, since sedimentation rates are known to be very low in these areas (< 1 m/m.y.; Winterer et al., 1971; Hayes, 1975; Moore et al., 1978; Prince et al., 1980), we believe that deposition of the 95-m thick sediment cover above the flows must have taken place over a relatively long period of time. This suggests to us that the buried flows of profile HH′ are older than the sea floor flows of profiles ABCD and ZZ′. Since the slight bathymetric low in which these buried flows occur (on profile HH′) is enclosed on the NW and SE ends of the profile by long ENE-trending ridges (Fig.III-2), these ridges are likely eruptive sources for the flows. This suggests that the general and obvious ENE-trending structural grain of the northern Arch (Fig.III-2) is of old origin as well.

DISCUSSION AND CONCLUSIONS

The orderly deposition of sediment in this area since the formation of the crust 90-80 Ma has been interrupted by several possible volcanic, tectonic, and erosional episodes. We postulate the following sequential chronology of events: (1) Initial deposition of 100-200 m of sediment (composition unknown) on oceanic basement to beneath the level of Reflector IV, during which at least one major volcanic episode occurred, followed by (2) deposition of siliceous-rich sediments, sometime before the Eocene-Paleocene boundary (to eventually form the chert layers encountered at DSDP Site 67, which we correlate with Reflector IV). This is followed by (3) deposition of radiolarian brown clay atop the chert from Eocene-Paleocene time up to the time preceding the construction of the Hawaiian Ridge (6-2 Ma), during which time (4) a second volcanic event caused activity along minor eruptive centers and fissures, probably of general ENE-trend. This was followed by (5) propagation of the Hawaiian Swell across the south of the area causing erosional activity concentrated on the axis of the Arch, and culminating in (6) a third volcanic event coeval with, or subsequent to, the erosional episode, forming widespread lava flows and minor edifices.

Primary evidence for the first volcanic event are K/Ar age determinations of rocks from Kauluakalana and Paumakua Seamounts which give Late Cretaceous to early Tertiary ages. Indications of a second event, younger than Eocene-Paleocene boundary age, follow from the volcanic sandstones and mudstones recovered at DSDP Site 67 (probable Eocene age; Winterer et al., 1971). The buried flows interpreted in profile HH′ are most likely products of one of these first two episodes. Evidence for the third volcanic event (6-2 Ma) is more tenuous. There are features on the Arch, which we interpret as lava flows, that are relatively younger than an unconformity observed on seismic profiles (Reflector III). For reasons discussed in this paper, we believe the unconformity represents the surface of the sea floor prior to the construction of the Hawaiian Ridge 6-2 Ma. This, therefore, means that volcanism producing the flows occurred at a time after the unconformity, or after 6-2 Ma. Wallin and Frazer mapped areas of little or no sediment cover on the Arch (Fig.III-4). We believe that these are the areas covered by lava flows produced from a third volcanic episode. Figure III-14 summarizes our proposed geologic history for the time period from just before the development of the

FIGURE III-14: Schematic representation of formation of Hawaiian Deep and Arch north of Kauai and Oahu (modified after Normark and Shor, 1968). At a time immediately preceding the construction of the Hawaiian Ridge, sediment measuring about 250 to 360 m thick rests upon 86 to 74 m.y. old crust (A). Old seamounts of Late Cretaceous or Early Tertiary age are also present there (Paumakua and Kauluakalana are examples of these). Formation of the Hawaiian Ridge 6-2 Ma (B) causes the development of the Arch and Deep structures, and the creation of a small archipelagic apron, largely restricted to the Deep. This is followed by development of an unconformity (C), with deposition of eroded sediment in the Deep and outward from the Arch, perhaps concurrent with tensional faulting (D) on the Arch. Subsequent volcanic activity (E), with lava emanating from fault conduits, creates small seamounts and flows.


N 30°E
A
old seamount
sediment layers
ocean crust (88 - 74 Ma)
B
Hawaiian Ridge (6-2 Ma)
archipelagic apron
?
C
unconformity
redeposited sediment
?
D
?
E
subsequent volcanics
?
KILOMETERS
0
100
200
300
400
500

Hawaiian Ridge to the present.

We believe that Menard's hypothesis (later elaborated by Normark and Shor) of flexure and faulting of the Arch accompanied by volcanism is essentially correct. However, we differ in the following ways: (1) the Hawaiian archipelagic apron was restricted to the Deep in these areas and did not cover the Arch, (2) the major seamounts, and probably a large proportion of the volcanics on the Arch are the product of Eocene and older volcanism unrelated to the Hawaiian Ridge, and (3) an unconformity probably characterized the sea floor of the Arch at the time of construction of the Hawaiian Ridge.

Recent additional evidence that volcanism may be a common accessory to formation of a flexural Arch is provided in a study of the Hess Rise by Kroenke and Nemoto (in press, 1982). They cite evidence to show that volcanism accompanied the faulting of the Western Steps, an area on the western margin of the Hess Rise. The faulting and deformation of the Western Steps is thought to be a consequence of crustal flexure induced by lithospheric loading by seamounts of the Emperor Chain to the west.

We speculate that late Cenozoic volcanism on the Arch associated with the passage of the Hawaiian melting anomaly may result from a combination of lithospheric heating and flexural faulting of the Arch. A recent study of heat flow and bathymetry on the Hawaiian Swell (Von Herzen et al., 1982) suggests that the Swell is created by rapid heating of the lower part of the lithosphere over a relatively broad (500-1000 km) region (a 900 km wide zone symmetric about the Hawaiian

Ridge would include the entire northern Arch area). This thermal anomaly shifts the geothermal gradient of the lithosphere, which, with sufficient relief of pressure at depth by flexural faulting, may allow melting and the mobilization of magma.

The overall amount of volcanic activity on the Arch may be related to the degree or activity along the axis of the Hawaiian Ridge. The density of Arch volcanics increases southeastward through the study area. This seems to correlate with a southeastward increasing crustal load from islands of the Hawaiian Ridge. At another location, northwestward along the Hawaiian chain north of Gardner Pinnacles, a large apparent flexural Arch exists, which is populated by several seamounts. We do not know the origin of these seamounts, but since the load of the Hawaiian chain is here again relatively large, there may be an analogy between the two locations.

CHAPTER IV

SUMMARY AND RECOMMENDATIONS FOR FUTURE WORK

Maps of 3.5-kHz echo character and sediment thickness have been prepared for the Hawaiian Deep and Arch north of the eastern Hawaiian Islands. Through correlation of available deep-sea core and drilling results and the comparison of echo character with seismic reflection character, a particular lithology or sea floor morphology has been assigned to each echo type. Sediment thickness on the Arch rarely exceeds 200 m and many areas there appear to have little or no sediment cover. Five prominent subbottom reflectors on reflection profiles have also been traced across the Hawaiian Deep and inner flank of the Arch. The nature and age of these reflectors is inferred based on reflection character, geometry of subbottom layering, and results of DSDP coring in the central Pacific. The principal findings of this study are as follows:

1). One kind of 3.5-kHz echo type is a rough, acousticallly reflective sea-floor lithology (Fig.II-18). This character is probably caused by the presence of sea-floor lava flows, the age of formation of which is unclear.

2). The almost certain existence of old volcanism (Eocene and older) on the Arch is recognized. Volcanic episodes of these ages are responsible for construction of the large seamounts on the Arch, and probably also the ENE-trending ridges (Fig.II-2).

3). The existence of an unconformity has been inferred on the basis of seismic reflection profiles. Because of its wide lateral distribution and the large amount of sediment which apparently been removed, this unconformity probably represents a significant erosional episode.

4). The size of the Hawaiian archipelagic apron in these areas is much smaller than previously thought, and does not extend beyond the crest of the Hawaiian Arch.

5). Possible extensions of regional structural elements across the northern Arch and Deep have been considered. Extensions of a nearby linear seamount trend and a major ridge (the Musicians NW-SE trend and Necker Ridge, respectively) have been ruled out.

Although this thesis gives my interpretation based on the evidence at hand, some points remain unclear. These include (1) the nature of material causing the 3.5-kHz opaque echo type, (2) the nature and age of volcanic products on the Arch, including the ENE-trending ridges obvious on bathymetry (Fig.II-2), (3) the age of the unconformity and time gap of the hiatus, and (4) the nature and age of Reflector IV. Future cruises to these areas have a good chance of solving some of these important questions, inexpensively, if they are carefully planned. My suggestions for addressing questions (1) through (4) follow.

In order to determine the nature of the 3.5-kHz opaque echo type (question 1) I suggest deploying several small cores, employing very heavy weights ("dart" cores), over the opaque echo type and near the transition areas southeast, east, and north of Kauluakalana Seamount. Additional gravity and free-fall coring using ordinary weights is not recommended; there has been no success to date in obtaining samples of this material using these cores. Two other relatively inexpensive techniques which might be used are bottom photography and sea floor dredging. Dragging a dredge anchored with a heavy weight across this rough sea floor terrain or its edge might yield rocks.

Determining the nature and age of volcanism (question 2) is best accomplished by comprehensively dredging the various morphological types of seamounts and ridges on the Arch (described in Chapter II). An immediate solution to the question of young volcanism might be gained by dredging the small seamounts east of Kauluakalana Seamount (shown in Fig.II-7) and radiometrically dating the rocks obtained.

Other evidence bearing on the stratigraphic age and character of Arch volcanism might be gained from additional reflection profiling. Historically, the interpretation of profiles from these areas has been hampered by long source wavelets. This is because profiling over thin sediment sections (200 m and less), which are characterized by numerous strong and discontinuous sea floor and subbottom reflectors, results in the superposition and interference of reflector patterns. Recent digital techniques of recording and processing seismic data should help improve the resolution of individual reflectors. Using sample rates of 1000 Hz or more, together with deconvolution processing, should provide resolution adequate to solving these geologic questions concerning the upper crustal structure. Again, the best area over which to concentrate a study of this type would be the transition areas near Kauluakalana Seamount (Fig.II-18).

Determining the age of the unconformity and Reflector IV (questions 3 and 4) would be most easily accomplished by drilling, since in most areas they are beyond the reach of long piston cores. However, because drilling of these targets is unlikely in the near future, the possibility exists that a long core deployed near the NW-end of profile EFG (Fig.III-2) might reach the unconformity, and possibly also Reflector IV. This is the shallowest certain occurrence of these features which we have noted on the profiles.

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