REFLECTION PROFILING STUDIES OF THE 500-METER SHELF SOUTH OF OAHU: REEF DEVELOPMENT ON A MID-OCEANIC ISLAND

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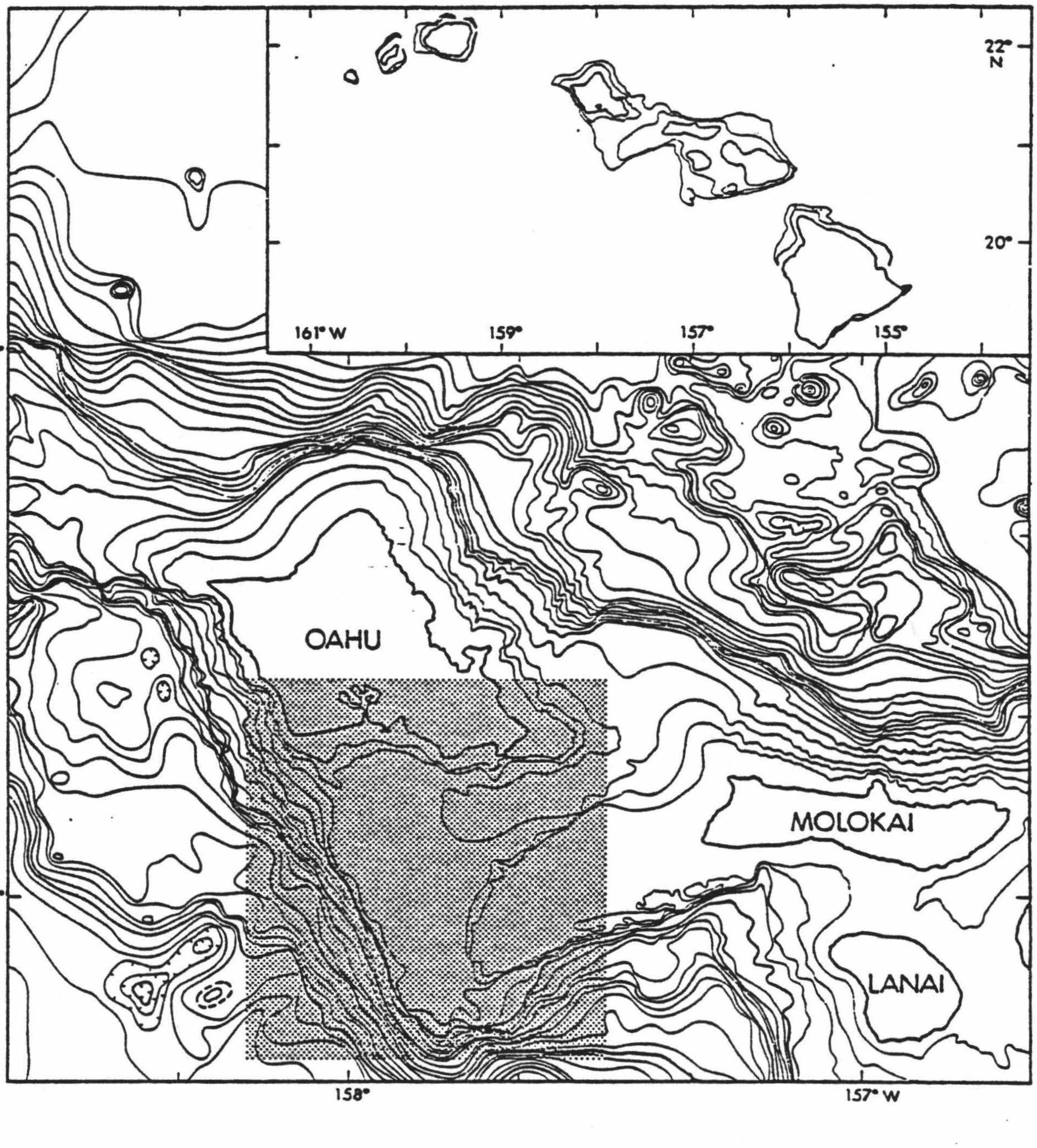
INTRODUCTION

The 500-meter shelf south of Oahu, Hawaii is shown in the generalized bathymetry in Figure 1. Similar broad, insular shelves are also marginal to the islands of Molokai, Lanai, and Maui (Fig. 1: inset). Some of these shelves have been correlated with a long stillstand when Lualualei and other deep valleys in the Waianae Range on Oahu were cut by streams (Stearns, 1935, 1974). South of Oahu, where the shelf stretches more than 50 km seaward, water depths, ranging between 400 and 700 meters, roughly average 500 meters; giving rise to the term 500-meter shelf (Kroenke and Woollard, 1966). Bounded on the north by Oahu, on the east by Penguin Bank, and on the south and west by the insular slope, the 500-meter shelf covers an area of 1850 km^2, which is greater than the exposed land area of Oahu (1650 km^2). The shelf has also been referred to as the Lualualei Shelf (Stearns, 1961; Ruhe *et al.*, 1965) from the valley cutting stage, named after the deepest valley, Lualualei, which was incised to at least 366 meters below sea level (Stearns, 1935).

Barrier reefs initially were observed in reflection profiles across the southern and western edge of the 500-meter shelf (Kroenke, 1965). Structures interpreted to be large patch or pinnacle reefs also were observed in those reflection profiles to interrupt lagoonal sediments landward of the barrier reefs. Shallow water reef fossils thought to be Miocene in age (Menard *et al.*, 1962) were dredged from the shelf about 10 km southwest of Honolulu. These fossils are now thought to be more likely Pliocene in age (personal communications from J. W. Durham and E. A. Allison to R. Moberly and J. F. Campbell, 1972).

Figure 1. Generalized bathymetry of the 500-meter shelf south of Oahu. Contour interval is 200 meters. The shaded rectangle designates the survey area. (Redrawn from Pararas-Carayannis, 1965.)

The shaded region in the inset shows areas within the depth range of the Lualualei Shelf around the Hawaiian Islands.


22°
N
20°
161° W
159°
157°
155°
22°
N
OAHU
MOLOKAI
LANAI
21°
158°
157° W

Penguin Bank contains numerous salients and reentrants, but the southeastern flank contains only one very large reentrant. Although the upper flank of Penguin Bank is very steep, averaging approximately 24°, the lower flank is less steep, apparently smoothed by a sedimentary apron. Likewise, the insular slope around the entire southern margin of the 500-meter shelf (south of 21°04'N) is relatively steep, averaging 16°. Locally, on the southern margin, slopes as steep as 40° are present, as inferred from the convergence of contours in Chart 1. To the northwest, however (north of 21°04'N), the insular slope is less steep, averaging 6°. On the north side of the 500-meter shelf, the submerged coastal slope of the island of Oahu is very gentle, about 1° to a depth of approximately 120 meters, where it becomes relatively steep, averaging approximately 12°, as it descends to merge with the surface of the 500-meter shelf.

Across most of the 500-meter shelf, the sea floor rises gently to the southwest at an inclination of approximately 0.5°. The broad, irregularly shaped, shallow areas (400 to 500 meters deep) near the western shelf margin in Chart 1, are the tops of the aforementioned barrier reefs, whereas the small elliptical-shaped areas on the shelf interior for the most part are the tops of the aforementioned patch or pinnacle reefs. Shelf margin reefs (Bubb and Hatleid, 1977) are also present, as will be discussed later. It is significant that the depths to the tops of all of the reefs are not only far below the Holocene limit of reef growth, but also far below the range of possible Pleistocene eustatic sea-level fluctuations. A few of the small circular-shaped shallow areas near Penguin Bank may be the tops of igneous piercements or sea stacks as will also be discussed later.

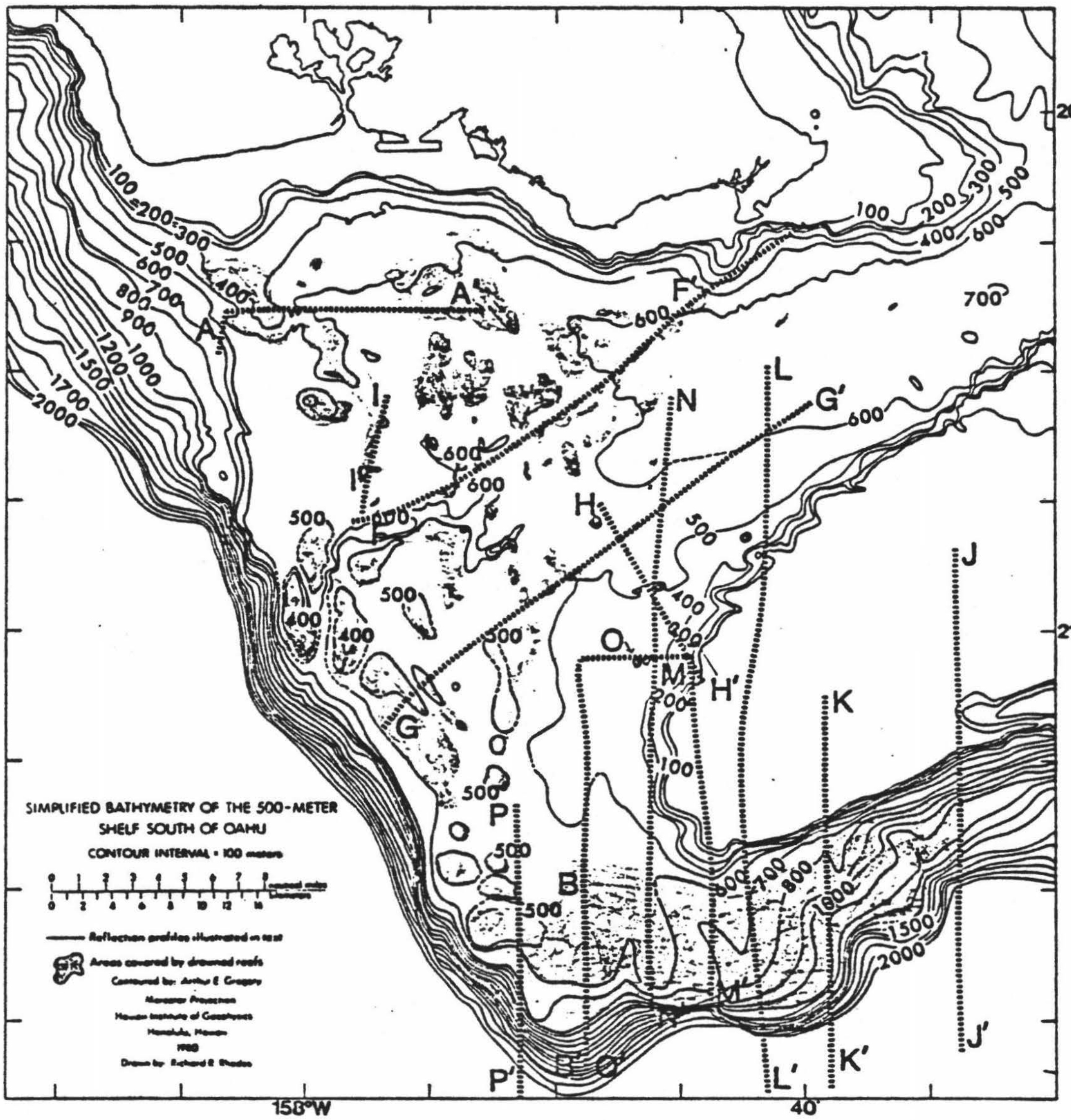
Since the initial sampling and profiling, additional samples of reef limestones have been dredged and additional patch reefs, some overlain by lagoonal sediment, have been revealed by subsequent reflection profiling. In late 1978, after compilation of the previously acquired data, the writer undertook a detailed reconnaissance survey of the patch reefs on the 500-meter shelf, using the R/V NOI'I. In addition, samples of the reef complex were dredged approximately 6.5 km landward of the shelf edge. Reef complex samples are described and identified in Appendix A.

The results of these surveys provide precise information on the location, configuration, and morphology of reefs on the 500-meter shelf. Newly constructed charts of bathymetry, basement topography, and buried reef topography reveal shelf morphology and structure, along with reef growth patterns and relationships with antecedent topography.

BATHYMETRY OF THE 500-METER SHELF

The area of interest is designated by the shaded region in Fingure 1. Detailed bathymetry of the 500-meter shelf, based on a compilation of all available bathymetric data, is shown in Chart 1 (in pocket). Instrumentation, survey methods and analytical techniques are described in Appendix B. The very large shallow bank on the eastern side of the shelf (right-hand side of Chart 1) is Penguin Bank, which appears to be devoid of any appreciable sediment accumulation (Kroenke and Woollard, 1966; Moberly _et_ _al_., 1975), and is thought to be a truncated subaerial volcanic rift (Malahoff and Woollard, 1965; Stearns, 1974). Within the survey area the northwestern flank of

Figure 2. Location of reflection profiles on the 500-meter shelf south of Oahu, which are illustrated in the text, showing their relationship to the drowned reefs (shaded areas). Contour interval is 100 meters.


SIMPLIFIED BATHYMETRY OF THE 500-METER SHELF SOUTH OF OAHU
CONTOUR INTERVAL = 100 meters
0 1 2 3 4 5 6 7 8
0 2 4 6 8 10 12 14
Reflection profiles illustrated in text
Areas covered by drowned reefs
Contoured by: Arthur E. Gregory
Hawaii Institute of Geophysics
Honolulu, Hawaii
Drawn by: Richard R. Rhodes
158°W
40'
21°N
20'
A
A'
B
B'
F
F'
G
G'
H
H'
I
I'
J
J'
K
K'
L
L'
M
M'
N
O
O'
P
P'
100
200
300
400
500
600
700
800
900
1000
1200
1500
1700
2000

REEF CLASSIFICATION AND ACOUSTIC STRATIGRAPHY

Reefs have been classified as fringing, shelf margin, barrier, and patch or pinnacle reefs. The criteria used to classify each individual reef in this report is given in Appendix C. The location of reflection profiles illustrated in the text and the location of reefs are shown superimposed on a simplified bathymetry chart in Figure 2. A typical profile across a barrier reef and patch reefs is shown in Figure 3. Primary and secondary seismic characteristics used to identify coral reefs and permit distinction between these and other features of clastic or igneous origins, as set forth by Bubb and Hatleid (1977), are observed in the reflection profile. The primary characteristics used to reveal directly the presence of reefs include boundary outline, onlap, and seismic facies change (white out). The secondary characteristics used to reveal indirectly the presence of reefs include drape, velocity anomalies, diffraction patterns, and basin architecture. Although reefs were first detected and later mapped by a combination of boundary outline, white out, and onlap, the interpretation is reinforced by the presence of velocity anomalies causing apparent "lift" of the basal reflector.

Seismic velocities of the barrier and shelf margin reefs have been determined from the ratios of water travel time at the point where the outcropping forereef slope intersects the outcropping basement slope, to reef travel time at the nearest point of maximum velocity lift (Fig. 4). Velocities calculated in this manner range from 2.0 to 2.4 km-sec^{-1}, averaging about 2.2 km-sec^{-1}, and agree well with reef

Figure 3. Profile A-A' showing both barrier and patch reefs. Note the boundary outline (a), velocity lift of the basal reflector (b), onlap (c), white out (d), and drape (e).

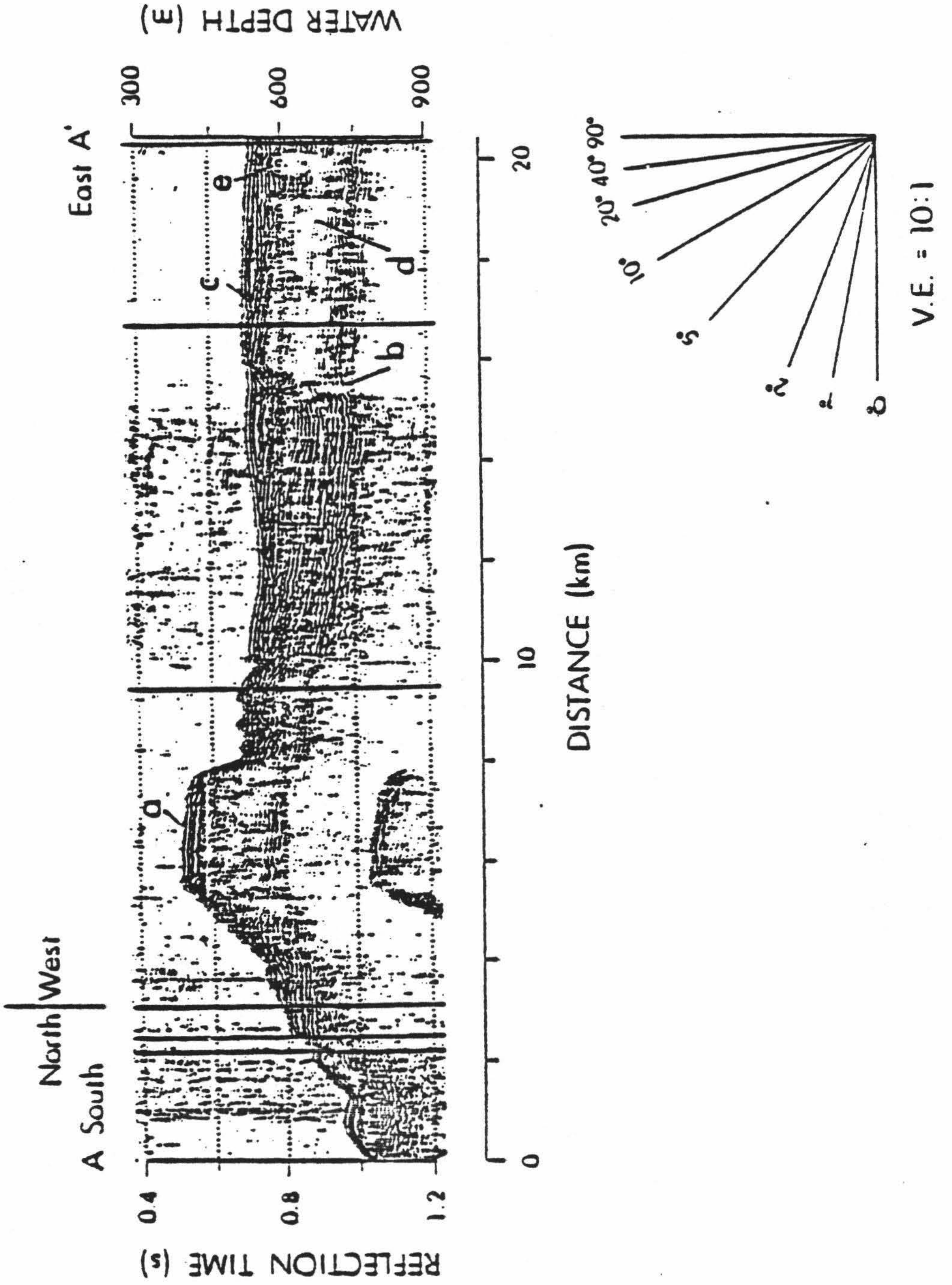
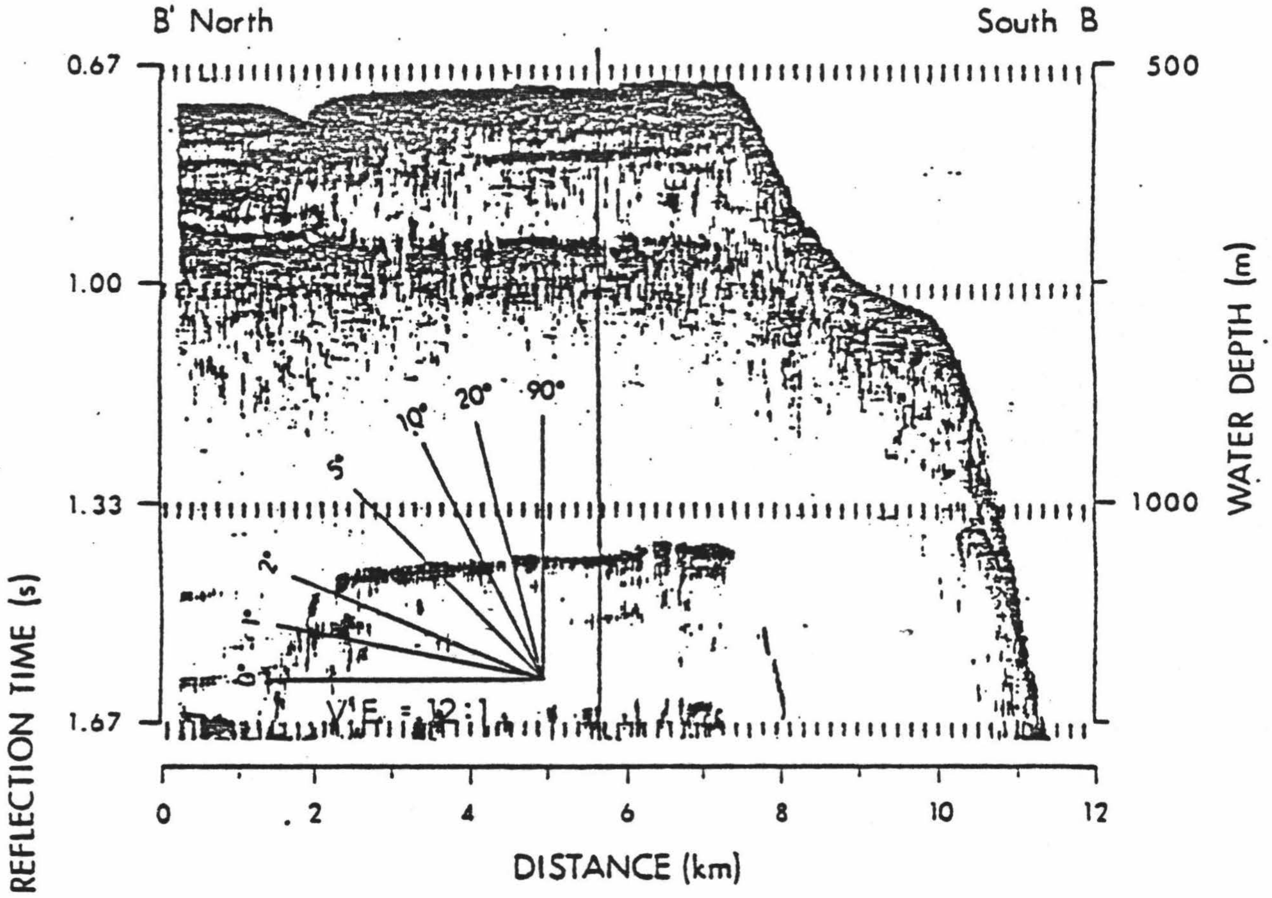
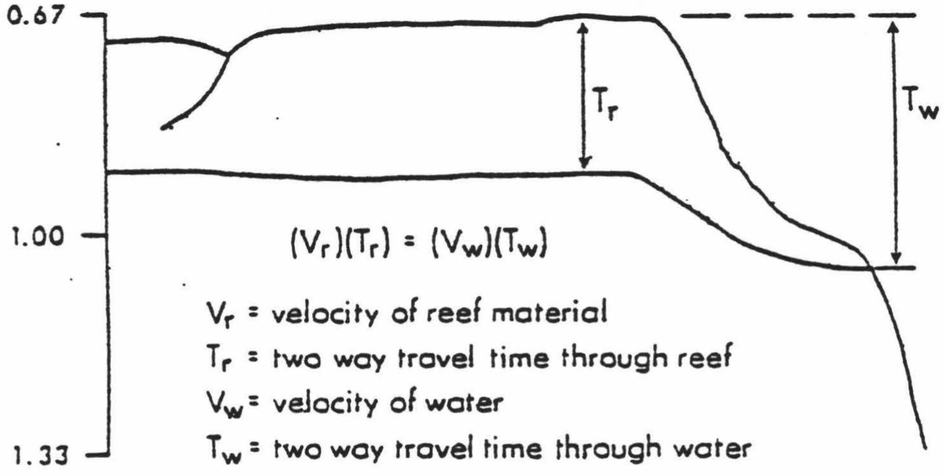

REFLECTION TIME (s)
0.4
0.8
1.2
WATER DEPTH (m)
300
600
900
A South
North
West
East A'
a
b
c
d
e
0
10
20
DISTANCE (km)
V.E. = 10:1
0°
1°
2°
5°
10°
20°
40°
90°

Figure 4. Profile B-B' used to determine reef velocity.





$$(V_r)(T_r) = (V_w)(T_w)$$

V_r = velocity of reef material

T_r = two way travel time through reef

V_w = velocity of water

T_w = two way travel time through water velocities cited in the literature (Press, 1966; Furumoto *et al.*, 1970). Moreover, when samples of coral reef material dredged from the shelf were subjected to simulated *in situ* shelf conditions (salt water saturation, temperatures of 6°C and pressures of 40 to 100 bars), similar results were also obtained (Table 1).

The reef velocities thus determined were used to calculate velocities for the lagoonal facies sediments. Assuming the patch reefs have the same approximate velocity (2.2 km-sec^{-1}) as the barrier and shelf-margin reefs, then the velocities of the lagoonal facies sediments are determined by comparing the ratios of patch reef travel time, to sediment travel time (in similar fashion to that shown in Fig. 4). Velocities calculated in this manner range from 1.55 to 1.75 km-sec^{-1}, averaging 1.65 km-sec^{-1}. This range is almost the same as that of the seismic refraction velocities determined for the beaches and sandy bottoms in shallow water (Coulbourn *et al.*, 1974) and compares favorably with laboratory velocities measured on indurated sediments dredged from the shelf interior, again determined at simulated *in situ* conditions (Table 1).

Using these velocities, thicknesses of reefs and adjacent lagoonal sediments were calculated and depths to key reflecting horizons, including igneous basement, were determined and contoured. The depth to igneous basement is shown in Chart 2. The contours have been extended inland, showing depth below sea level of the basalt-sediment interface, based on the subsurface maps of Palmer (1927), Wentworth (1951), and on more recent deep well data (Stearns and Chamberlain, 1967). The fact that all indications of the presence of reefs have

Table 1. Velocity of reef rocks and induraced sediments under conditions of saltwater saturation, temperatures of 6° C, and variable pressure.

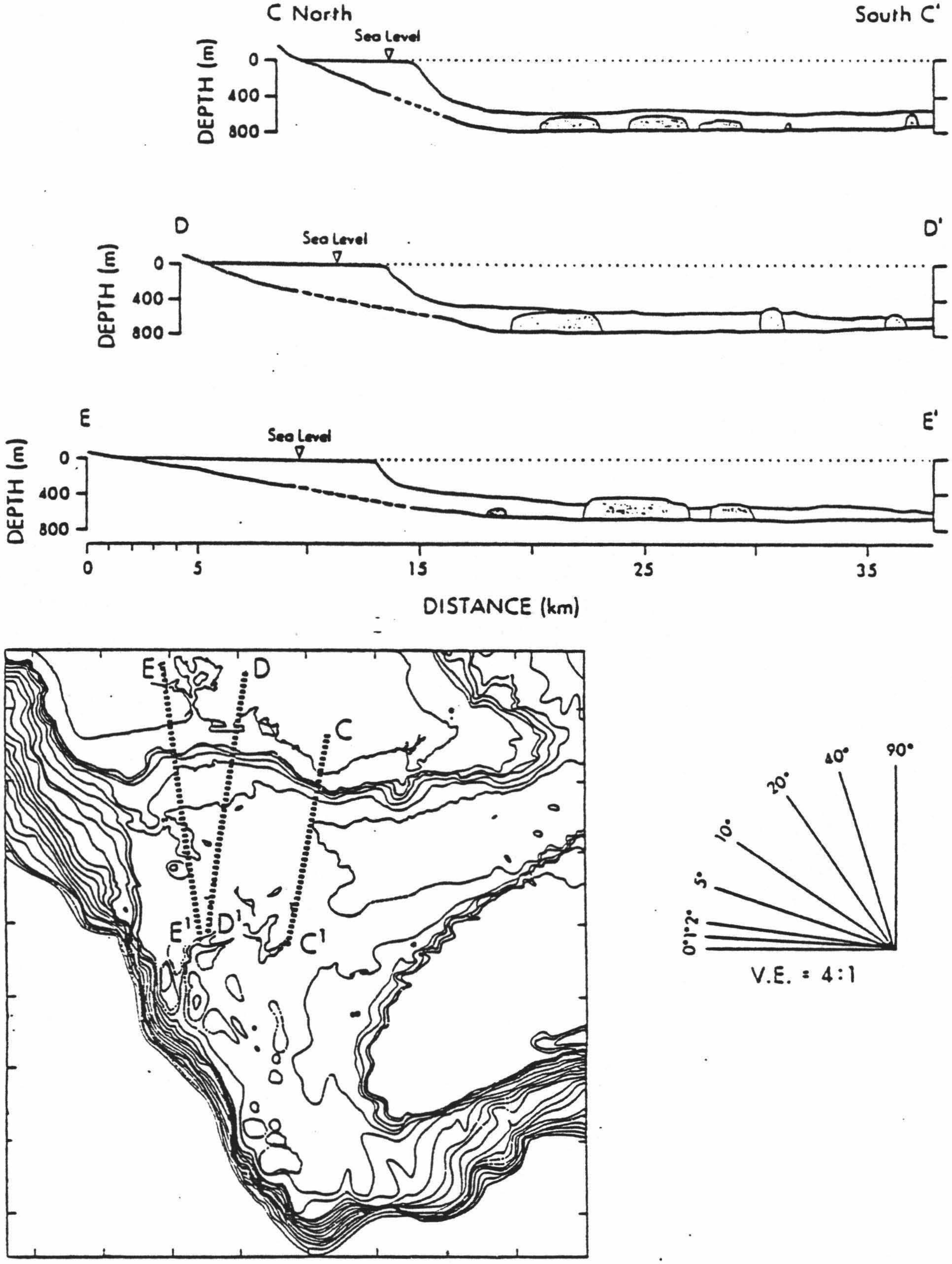
SAMPLE NO. :	1	2	5	6	7	8	
DRY DENSITY (g/cc) :	2.35	2.54	2.18	1.80	1.81	1.73	
ROCK DESCRIPTION :	calc. mud and Poritas	coral-algal-wackstone	calc. mud and coral	iron oxide mudstone	iron oxide mudstone	iron oxide mudstone	
PRESSURE (bars)			VELOCITY		(km-sec^{-1})		PRESSURE (bars)
3.4	2.146	2.180					3.4
5.5	2.153	2.182					5.5
6.9		2.198					6.9
8.3	2.449	2.200					8.3
10		2.204					10
11		2.208					11
12.4		2.209					12.4
20			2.193	1.346	1.331		20
40			2.201	1.433	1.417		40
60			2.225	1.478	1.461	1.438	60
80			2.237	1.492	1.475		80
100			2.242	1.524	1.506	1.461	100
200			2.292	1.559	1.542	1.493	200
300				1.578	1.560		300
400			2.324	1.592	1.574	1.537	400
4000						1.757	4000
300			2.315				300
90			2.264	1.530	1.512	1.649	90
70			2.262	1.521	1.504	1.642	70
50			2.250	1.498	1.463	1.605	50
30			2.224	1.452	1.435	1.573	30
10			2.219			1.559	10

been eliminated from the basement topography is evidence itself that the correct velocities were used for calculating thicknesses of both the reefs and sediments.

BASEMENT MORPHOLOGY AND REEF DISTRIBUTION

The depth to basement chart (Chart 2) reveals a broad basement platform ranging in depth between 600 and 850 meters below sea level with characteristics similar to that observed in the bathymetry (Chart 1). The perimeter of the platform, for the most part, is surrounded by steep insular basement slopes. The sediment-covered lower flanks of Penguin Bank like the sediment-free upper flanks, are steep (averaging 19°) and also appear to be incised by reentrants. It remains unclear whether or not a major fault exists at the base of Penguin Bank. South of 21°04'N, the insular basement slope is similar to that shown in the bathymetric chart. North of 21°04'N, however, there are relatively narrow ledges at and below the platform-insular slope break which are covered with sediment and are thus not apparent in the bathymetric chart. The south Oahu basement slope, at the north end of the platform, shallows to the north under the Oahu coastal plain with an average inclination of approximately 4°. Broad salients and reentrants characterize this slope. The three profiles shown in Figure 5, aligned approxiamtely north-south, illustrate some of the lateral and vertical variations in this slope. The difference between the south Oahu basement slope and the coastal plain is an indication of the depositional character of this coastal plain as discussed by Stearns and Chamberlain (1967) and Resig (1969).

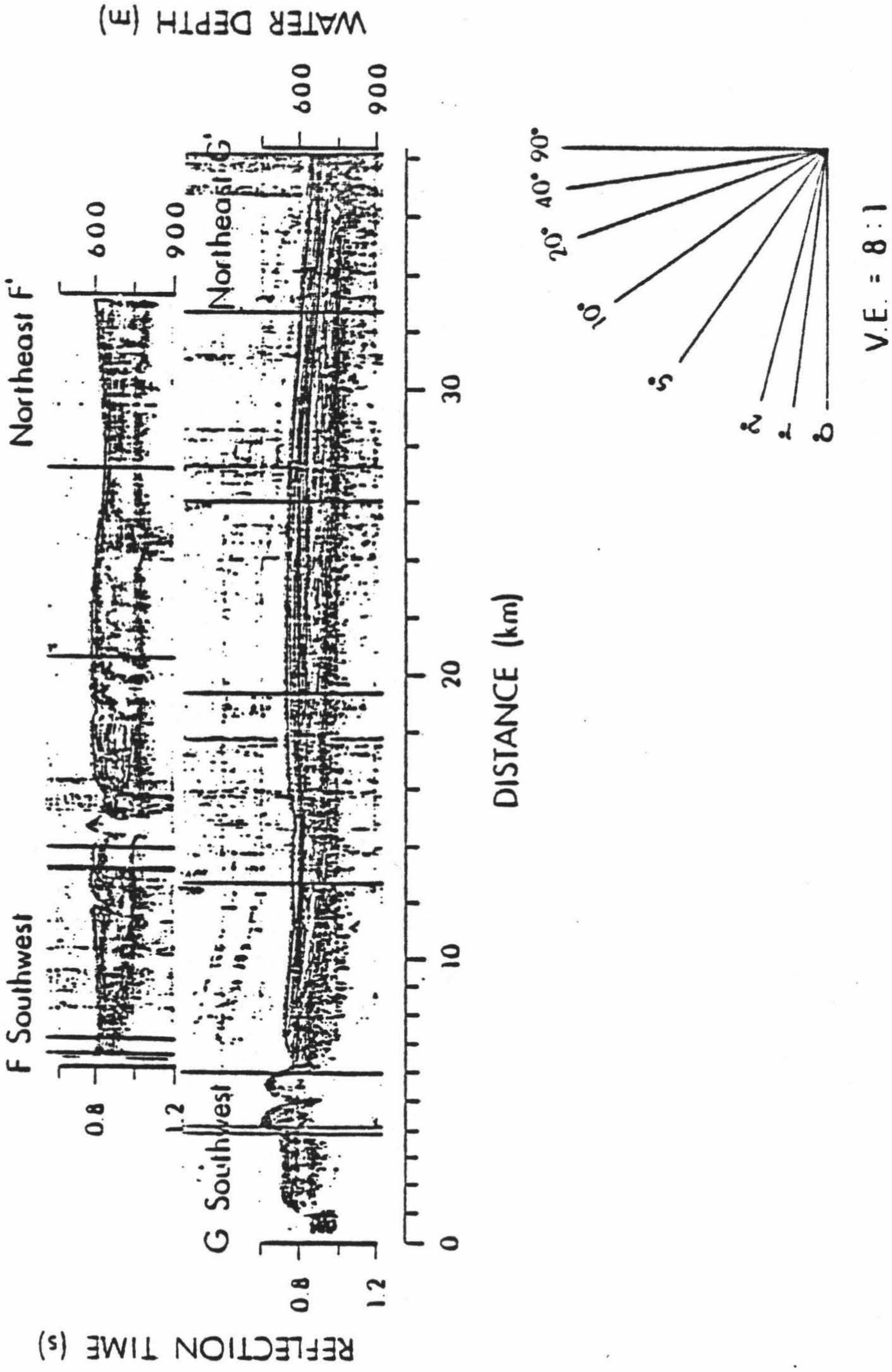
Figure 5. Profiles C-C', D-D', and E-E' across the Oahu coastal plain, submerged Oahu coastal slope, and the 500-meter shelf. Basement is dashed where there is no well or reflection profile control. Drowned reefs on the basement platform are illustrated in halftone.


C North
South C'
Sea Level
DEPTH (m)
0
400
800
D
D'
Sea Level
DEPTH (m)
0
400
800
E
E'
Sea Level
DEPTH (m)
0
400
800
0
5
15
25
35
DISTANCE (km)
E
D
C
E1
D1
C1
90°
40°
20°
10°
5°
2°
1°
0°
V.E. = 4:1

The basement platform itself, like the 500-meter shelf, is also very gently inclined upward to the southwest (averaging about 0.5°), with the west-central part more than 200 meters shallower than the northeastern part. The extremely gentle inclination is best observed in profile F-F' (Fig. 6) aligned N52°E across the southern portion of the shelf, and in profile G-G' (also in Fig. 6) 10 km farther south, aligned N50°E. Locally, deep areas occur in the northern and central parts of the platform and along the southern part of the platform (Chart 2). South of Penguin Bank, the southernmost part of the platform progressively deepens in stepwise fashion to the east, reaching depths in excess of 1300 meters.

Although the relief of the basement platform shown in Chart 2 is slight, compared to the relief of the steep slopes bordering the platform, it is not without significance. Locations of reefs in the interior of the platform, for example, commonly coincide with elevated portions of the basement reflector. Excluding the southern margin of the platform, the shallowest areas of the basement platform are overlain by the thickest reefs. The topographic expression of the individual reefs is shown superimposed on the depth to basement in Chart 3. Fringing and shelf margin reefs on the deepest slopes south of Penguin Bank grade into and merge with the barrier reefs farther west. Barrier reefs up to 290 meters thick coincide with the shallowest basement along the western margin (less than 740 meters below sea level). Patch reefs of variable thickness, most commonly between 80 and 190 meters thick as exemplified in the right half of profile F-F' in Figure 6, coincide with intermediate basement depths farther east (740

Figure 6. Reflection profiles F-F' and G-G'. Note that basement is deepest at the northeast end of the profiles. In profile F-F', changes in basement slope are greatest near the southwest and northeast ends of the profile, whereas in profile G-G' the gentle northeast dip is continuous. Buried patch reefs are present in both profiles.


F Southwest
Northeast F'
G Southwest
Northeast G'
0.8
1.2
600
900
REFLECTION TIME (s)
WATER DEPTH (m)
DISTANCE (km)
0
10
20
30
0°
1°
2°
5°
10°
20°
40°
90°
V.E. = 8 : 1

to 780 meters below sea level). Patch reefs commonly less than 80 meters thick coincide with the deepest areas of basement platform north of Penguin Bank (greater than 780 meters below sea level).

The origin of the shallow circular features near Penguin Bank (indicated by the dash-dot contours in Chart 3) is ambiguous. A basement reflector is not observed to underlie these features, but it may be obscured by diffractions from the overlying steep slopes. Although the features, shown in profile H-H' in Figure 7 resemble igneous piercements they are not accompanied by a definitive magnetic signature that would indicate an igneous origin. Moreover, a reflector pattern indicating external centripetal dip, often found to be associated with igneous piercements (Kroenke, 1972), is not observed at the base of these features. Alternatively, the features could be interpreted as sea stacks, but the absence of current moating in the lower layers in contrast to the presence of current moating in the upper layers also argues against this interpretation.

In general, most of the reefs shown in Chart 3 appear to have been constructed directly on basement. Some of the patch reefs, however, appear to be underlain by a reflector which is shallower than basement, suggesting that these reefs were constructed on a sediment layer overlying basement. In almost every case, these reefs are adjacent to, or are part of, reefs directly underlain by basement (or a reflector which is indistinguishable from basement), such as shown in Figure 8. This type of reef is not distinguished in Chart 3 from reefs located directly on basement.

Figure 7. Profile H-H': Ambiguous structures northwest of Penguin Bank.

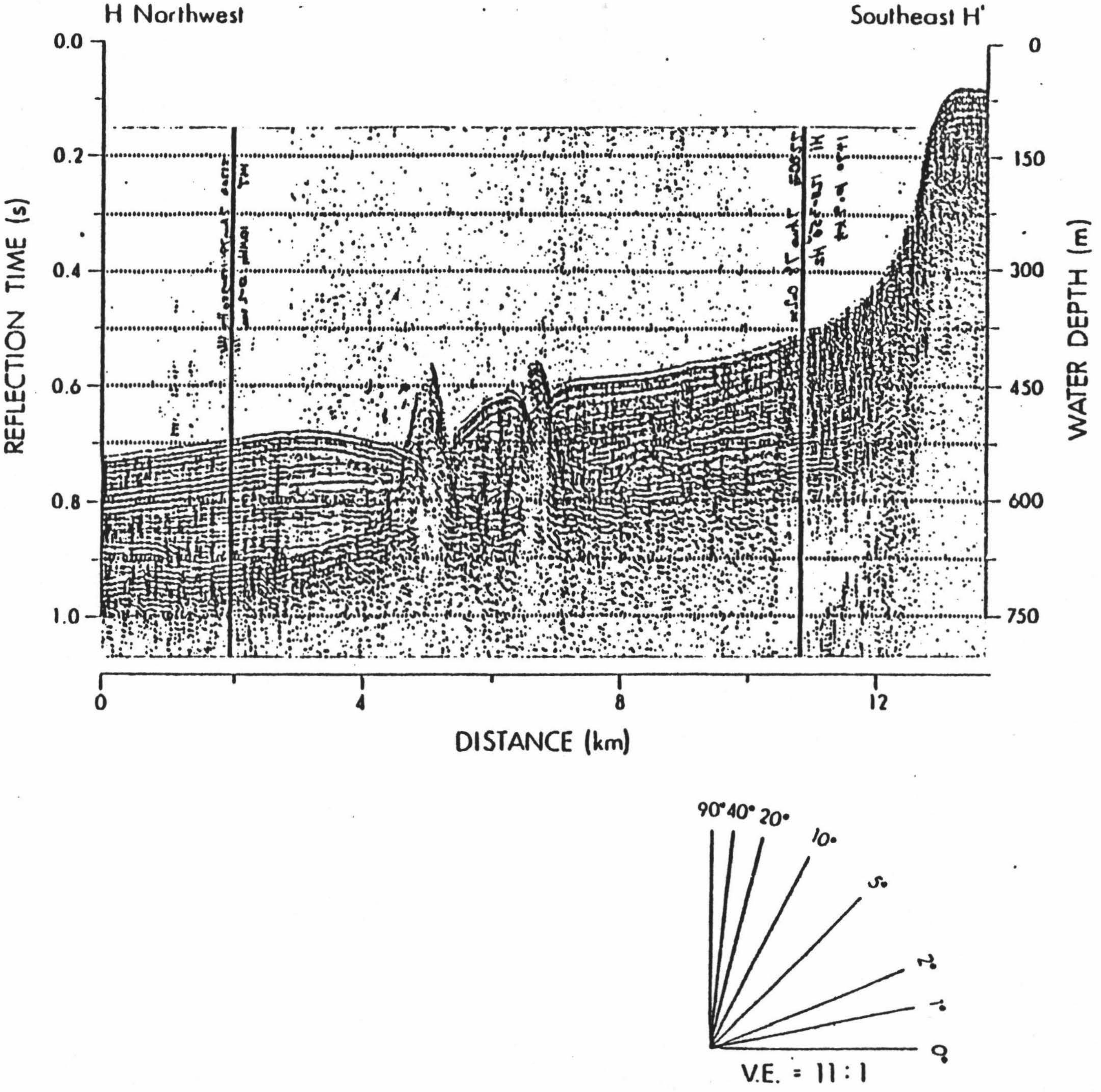
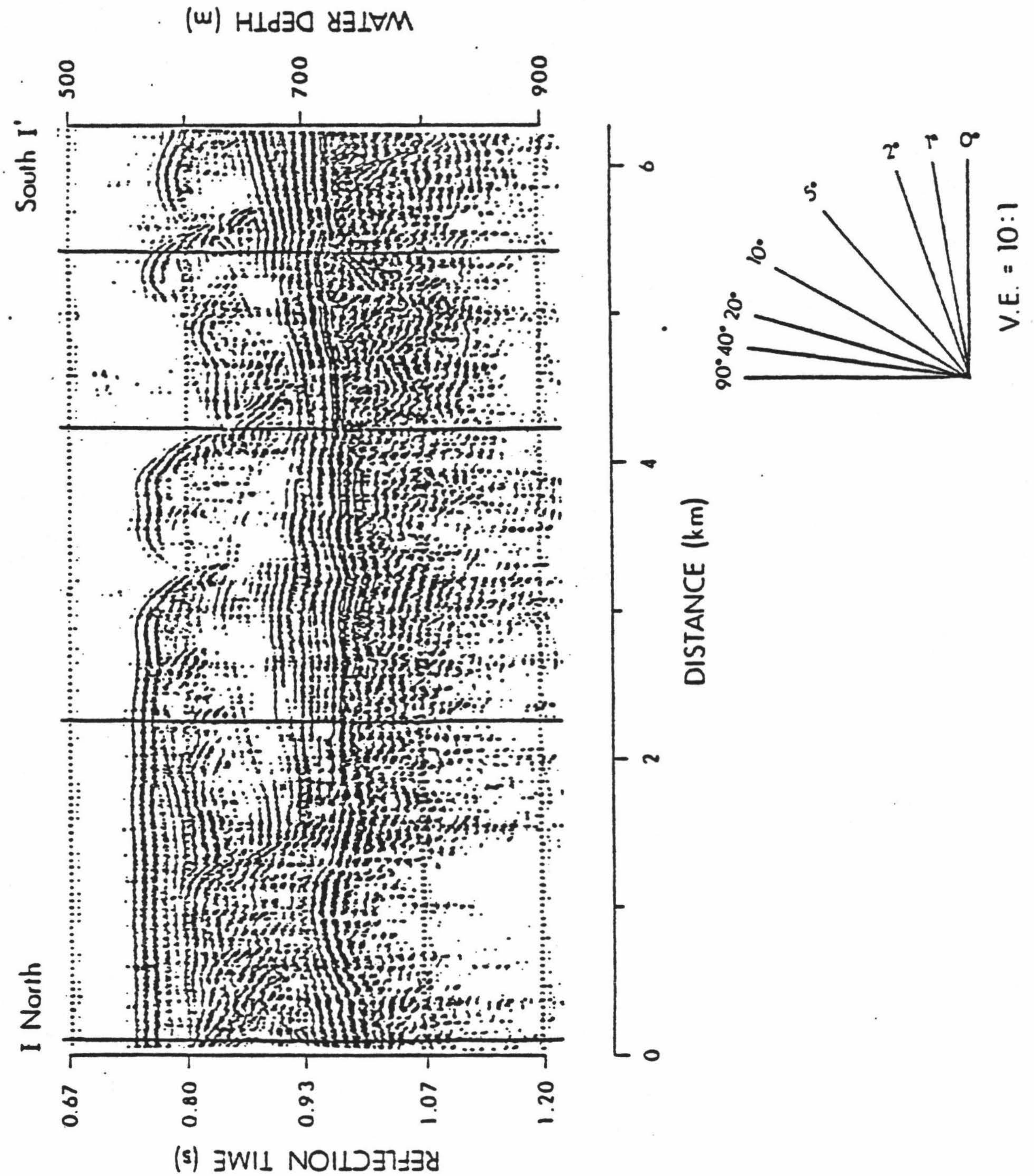

H Northwest
Southeast H'
REFLECTION TIME (s)
0.0
0.2
0.4
0.6
0.8
1.0
WATER DEPTH (m)
0
150
300
450
600
750
DISTANCE (km)
0
4
8
12
90° 40° 20°
10°
5°
2°
1°
0°
V.E. = 11 : 1

Figure 8. Profile I-I': Reef in the north part of the profile directly overlies basement, whereas reefs in the central and south part of the profile appear to overlie a sediment layer.


South I'
I North
WATER DEPTH (m)
500
700
900
REFLECTION TIME (s)
0.67
0.80
0.93
1.07
1.20
DISTANCE (km)
0
2
4
6
90°
40°
20°
10°
5°
2°
1°
0°
V.E. = 10:1

Volumes of selected reefs have been calculated in order to provide a comparison of the oceanic to the continental environment. Volumes were calculated by two methods: by approximating their dimensions using geometric shapes and by summing the volume of many small boxes. For any given reef, both methods yielded similar results. In the case of one of the larger well-delineated outcropping barrier reefs (the northwestern most reef in Chart 3), a minimum volume of 3 km^3 is estimated. If a reef of this volume had an average porosity of only 7%, it would be capable of containing over 1630 million barrels of fluid. The dredge samples, however, have much higher porosities, ranging from 10 to 35%, which are similar to porosity ranges of continental reef occurrences. In the case of the small, equidimensional pinnacle reefs, volumes of only 0.3 to 0.45 km^3 are estimated. Finally, in the case of the large buried patch reefs, volumes as high as 1.1 km^3 are estimated.

Lagoonal sediments surrounding the reefs are generally composed of reef derived carbonate sand and silt, foraminiferal tests, and mollusk fragments (Moberly and McCoy, 1966; Chave and Miller, 1978). Indurated shales as well also appear to overly some of the large patch reefs. The shale is composed of amorphous iron oxide bearing clays and silts derived from weathered basalts comprising Oahu and Penguin Bank (Appendix A). The shale has low permeability and could well serve as a caprock overlying the patch reefs. This is not to imply that there is petroleum potential on the shelves surrounding Oahu, but rather to suggest a scenario that could be applied to other volcanic island chains, provided that conditions of petroleum genesis and proximity to the reservoir are favorable at those locations.

ORIGIN OF THE PLATFORM MORPHOLOGY

A large isolated positive gravity anomaly is located west of Penguin Bank near the shelf margin centered at 21°01'N, 157°58'W (Watts and Talwani, 1975) and is considered to be a volcanic center (R. Moberly and J. F. Campbell, personal communication, 1980) which may have been the sources for some of the basalts which formed the basement beneath the 500-meter shelf. It may also mark the location of a seamount that existed prior to the formation of the Hawaiian Ridge (Moberly and Campbell, personal communication). In either case, the Waianae, Koolau, and Penguin Bank volcanoes are probably not the only eruptive centers to contribute to the constructional edifice from which the basement platform of the 500-meter shelf was carved.

During edifice formation, the additional crustal load of lavas superimposed on the lithosphere, and the removal of material from beneath the lithosphere (Moberly and McCoy, 1966; R. Moberly and E. Berg, personal communication, 1980) initially caused rapid subsidence of the edifice, perhaps facilitated by lithospheric fracture (Walcott, 1976). As the volcanoes passed through their caldera stage (Stearns, 1946; Macdonald and Abbott, 1970), a period of slow subsidence ensued. During that time, the basement platform was probably being cut by wave erosion, with truncation proceeding to the southwest as the island mass slowly subsided. At the same time, the slopes of the Waianae, Koolau, and Penguin Bank volcanoes eroded to form the broad salients and reentrants, interpreted to be stream valleys, characterizing the south Oahu and Penguin Bank basement slopes, shown in Chart 2.

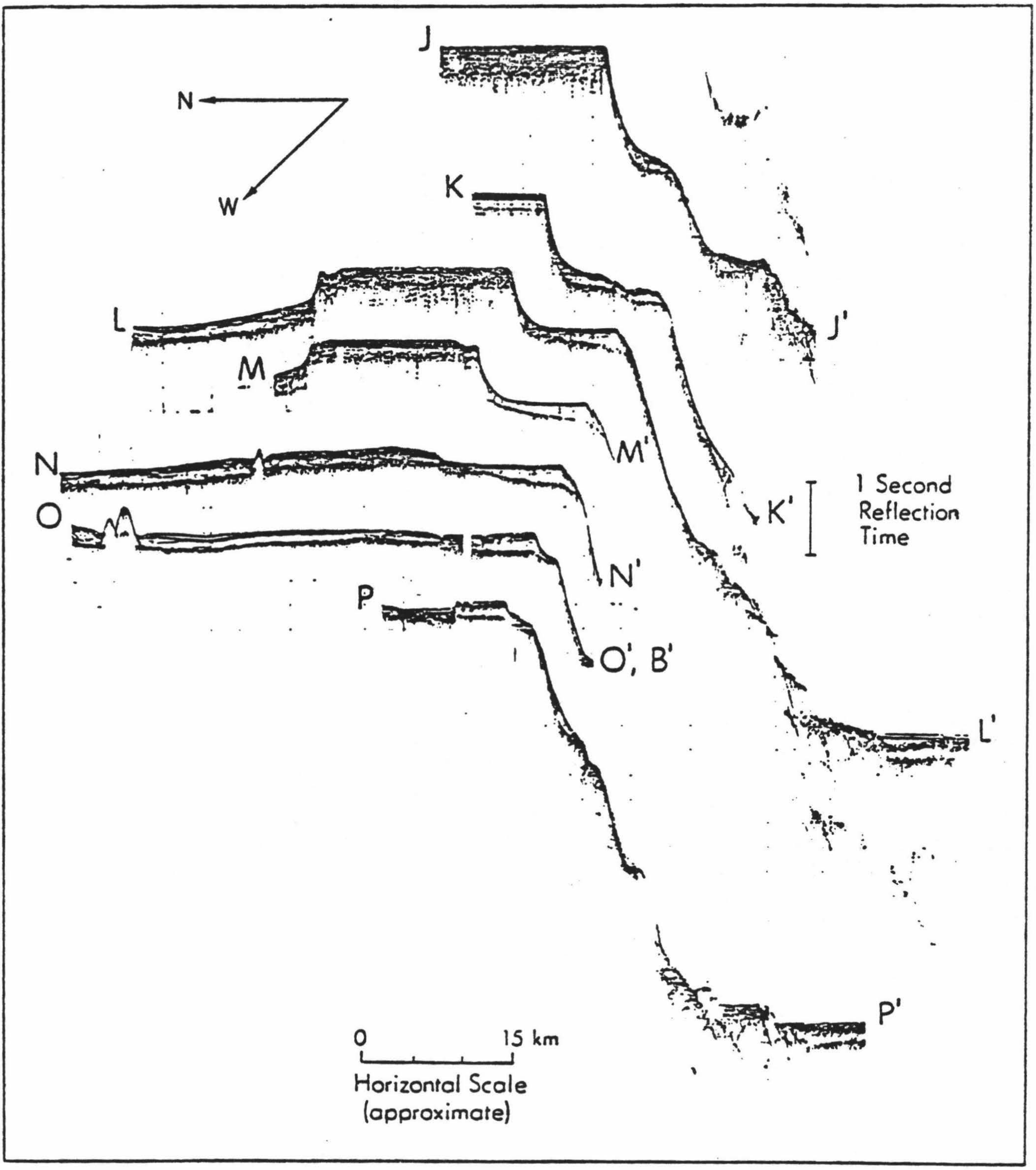
The slight dip of the surface of most of the basement platform 0.5° to the northeast) is in contrast with the much greater dip of the basalt flows (3 to 20°, Stearns, 1946) comprising the original constructional slope of the volcanic edifice and is strong evidence for a wave cut origin of the platform (Kroenke and Woollard, 1966). The dominant direction of wave erosion apparently was the same as the current direction predominating today (that of the northeast trades). Erosion also may have proceeded from the southwest margin to the northeast (to a much lesser extent, however) from waves driven by southwesterly "Kona" storms. Faulting appears to have controlled the shape of isolated deep areas in the north and central parts of the platform. Faulting may also have been partly responsible for the shape of the boundary between the basement platform and the Oahu coastal slope. In general, this pattern of faulting either parallels the south Oahu basement slope or is perpendicular to this trend, suggesting a rectilinear fault system. The discontinuous step-like morphology south of Penguin Bank is more suggestive of a faulted origin, rather than a wave cut origin, similar perhaps to the comparison made by Campbell and Erlandson (1980, in press) of the submarine Kohala terraces to the Hilina fault system along the southern slope of Kilauea volcano and also to that of the submarine extension of the southwest rift zone of Mauna Loa, Hawaii (Fornari *et al*., 1979). Apparently faulting has played an important role in reef formation, initially perhaps providing the prerequisite antecedant topography for the reefs to populate and finally perhaps causing their demise. On the one hand, the faulting could have taken place prior to reef growth, and the newly submerged, moderately sloped surfaces of the downdropped blocks simply would have been the earliest favorable sites for reef development. On the other hand, rapid dropping of the reefs to depths below the photic zone could have effectively drowned the reefs and would explain why the deepest reefs are relatively thin.

REEF GROWTH AND DEVELOPMENT

The great depth of the fringing and shelf-margin reefs south of Penguin Bank suggests that they are older than reefs located on the upper reaches of the basement platform. Initial reef growth seems to have begun as fringing reef on moderate slopes that are now greater than 1300 meters below sea level (Fig. 9, profile J-J').

The reefs grew vertically and migrated westward, becoming shelf margin reefs and ascending the moderate slopes to occupy successively shallower basement ledges in order to remain in the photic zone and keep pace with subsidence. As the reefs spread westward, the older areas of the reef to the east died off (perhaps during more rapid periods of subsidence) limiting thicknesses to less than 150 meters in eastern parts of the shelf margin (Fig. 9, profiles J-J', K-K'). By the time that shelf margin reefs in profiles L-L', M-M' and N-N' attained their maximum thickness, patch reefs probably had begun to grow on the northeastern interior of the basement platform. As subsidence continued, the reefs spread northward (from the southern margin) and southwestward (from the northeast portion of the platform), finally occupying the shallowest portions of the basement platform and forming the barrier reefs along the western margin (Chart 2). The largest area of living reef on the basement platform apparently existed

Figure 9. A composite of reflection profiles across Penguin Bank and the 500-meter shelf (from Kroenke and Woollard, 1966).


J
J'
K
K'
L
L'
M
M'
N
N'
O
O', B'
P
P'
N
W
1 Second Reflection Time
0
15 km
Horizontal Scale (approximate)

at that time, even though the reefs directly south of Penguin Bank, and the reefs on the deeper northeastern portion of the shelf were no longer growing. Although growth in the vertical direction was dominant (possibly in response to a more rapid rate of subsidence), at some locations reefs spread laterally, growing over adjacent lagoonal sediment. By the time reefs on the western portion of the platform had obtained thicknesses of approximately 100 meters, most of the reefs on the northeast and central parts of the platform had died. More rapid subsidence from faulting and tilting of the northeast and central parts of the platform is a possible reason that the reefs died. Another possibility is that a locally large sediment influx could have flooded the reefs, and still another is that unknown environmental conditions may have contributed to the termination of growth.

Barrier reefs continued to grow, attaining thicknesses up to 290 meters, after which reef growth ceased on the margins of the platform. With the exception of a few pinnacle reefs northwest of Penguin Bank, this also signaled the end of reef growth in the interior of the platform. Cessation of barrier reef growth may have been due to a resumption of a relatively rapid rate of subsidence, perhaps coincident with a rapid eustatic rise of sea level, dropping the reef tops below the photic zone--in effect drowning the reefs. One possible cause for this rapid subsidence is the load created by later volcanism in the vicinity of the platform, such as at West Molokai or Lanai, flexing the surrounding lithosphere and rapidly lowering the adjacent 500-meter shelf platform in a manner similar to that postulated by McNutt and Menard (1978) for late-stage tectonic uplift and subsidence of oceanic islands.

SEQUENCE OF EVENTS

Both during and following construction and merging of the Waianae, Koolau, and Penguin Bank volcanoes, possibly at the location of an older seamount, rotational block faulting appears to have occurred on the flanks of the edifice particularly along rift zones. The additional crustal load of lavas superimposed on the lithosphere, and the removal of material from beneath the lithosphere, initially caused rapid subsidence of the edifice, perhaps facilitated by lithospheric fracture. Rapid subsidence was followed by a period of slower subsidence, during which erosional processes began to significantly modify the terrain.

Wave erosion of some of the downfaulted blocks appears to have subsequently created benches and ledges along the southern and western portion of the edifice. The reefs grew vertically and migrated westward, becoming shelf margin reefs while ascending the moderate slopes of these ledges. In order to remain in the photic zone and keep pace with subsidence, the reefs occupied successively shallower basement ledges. As the reefs spread westward, the older areas to the east died off (perhaps during periods of more rapid subsidence).

Shortly thereafter, a period of relative stability, or more likely, very slow subsidence ensued, during which time wave erosion cut the basement platform. Truncation proceeded to the southwest, the waves being driven by the northeast trades, similar to the existing situation today. Erosion also may have proceeded from the southwestern margin to the northeast, to a much lesser extent, however, from waves being driven by "Kona" storms. Fault and stream drainage patterns may be partly responsible for the shape of the boundaries of the platform. Contemporaneous with, or shortly after truncation of the edifice slopes to form the platform, additional block faulting may have taken place, modifying the platform interior. Reefs became established on the elevated blocks, migrating from the northeast to the southwest and west following the pattern of truncation. The western area, the last to be truncated, became the site of an extensive barrier reef. While conditions were favorable for reef growth on the western margin of the platform, reefs were dying off on the eastern portion of the platform. One or more of several situations could have caused or contributed to the termination of reef growth: tilting and downfaulting of the north and northeastern portion of the platform; a locally large influx of sediment flooding the reef; and other fatal but yet unknown environmental conditions. Following the demise of the reef population on the interior of the platform and after the barrier reefs attained their maximum thickness, a very rapid, perhaps sudden, relative rise of sea level resulted in the catastrophic drowning of the last vestiges of the barrier reefs. Subsidence has resulted in inundation and burial of many of the reefs by terrestrial detritus and planktonic debris.

SUMMARY

Development of the 500-meter shelf south of Oahu, Hawaii, can be summarized as follows:

1. Construction and merging of the Waianae, Koolau, and Penguin Bank volcanoes, possibly at the location of an older seamount;

concurrent with and following volcanic construction, faulting occurred, particularly along rift zones and on the lower flanks of the edifice.

2. Rapid subsidence of the edifice, alternating with periods of slow subsidence accompanied by subaerial stream erosion and wave erosion controlled, in part, by faulting.
3. Formation of ledges or benches along the southern and western portion of the edifice by faulting, followed by truncation of the down faulted blocks by wave erosion.
4. Initiation of reef growth on the ledges along the southern portion of the edifice.
5. Migration of reef westward and northward, occupying successively shallower ledges as the edifice subsided.
6. A long period of very slow subsidence resulting in truncation of the entire basement platform. Truncation proceeded from the northeast to southwest followed by the growth of reefs over favorable portions of the platform. The western margin of the edifice was the last area to be truncated and populated with reef. While the barrier reefs were flourishing there, the patch reefs situated on the deeper portions of the subsiding platform were dying off.
7. Ultimately, a very rapid, perhaps sudden, relative rise of sea level resulted in the catastrophic drowning of the last vestiges of the barrier reef on the seaward margin of basement platform.
8. Continued subsidence, inundation, and burial of many of the reefs by terrestrial detritus and planktonic debris.

APPENDIX A

IDENTIFICATION AND DESCRIPTION OF REEF COMPLEX SAMPLES DREDGED FROM THE 500-METER SHELF AND VICINITY

Dredge stations on the broad shelves marginal to Oahu, Molokai, Lanai, and Maui are shown in Figure 10. The fore-reef slopes of shelf margin or barrier reefs were dredged at most stations, and coral-algal reef material was obtained at every station. In addition, basalt was recovered from station 15 and large slabs of indurated iron oxide mudstone were recovered from station 78-1.

Corals from several stations have been identified by J. W. Wells. These identifications are tentatively correlated by Wells with 4 of the 5 supposedly "new" species dredged from the shelf south of Oahu reported by Menard *et al.*, 1962 (Table 2). If this correlation is correct then it seems doubtful that the corals dredged by Menard *et al.* are Miocene in age, since the aforementioned corals are currently living in the northeast Pacific. Only one of Menard *et al.*'s genera, *Platygyra*, is not now found in the northeast Pacific.

A sample of reef rock from station 78-1 was scrubbed and broken open and foraminifera were removed from the interstices of coral. The foraminifera were analyzed by J. Resig, and her results follow:

> Planktonic foraminifera indicate Quaternary age. These may have infiltrated the reef rock after submergence. However, there was no evidence of older planktonics. Assemblage includes *Globorotalia truncatulinoides*, *G. tosaensis*?, *Sphaeroidinella dehiscens*, *Globigerinoides ruber*, *G. trilobus*, *G. sacculifer*, *Globorotalia Tumida*, *G. menardii*, and *Neogloboquadrina dutertrci*.
>
> Benthic foraminifera are dominated by species of *Amphistegina*, which live on algae or generally a shallow water substrate. The species represented are *A. lobifera*, *A. lessonii*, and *A. bicirculata*. *A. bicirculata* generally does not occur shallower than 30 meters (Muller, 1977) whereas the other two can occur in very shallow water such as in tidepools.

Figure 10. Location of dredge stations in the vicinity of the 500-meter shelf.

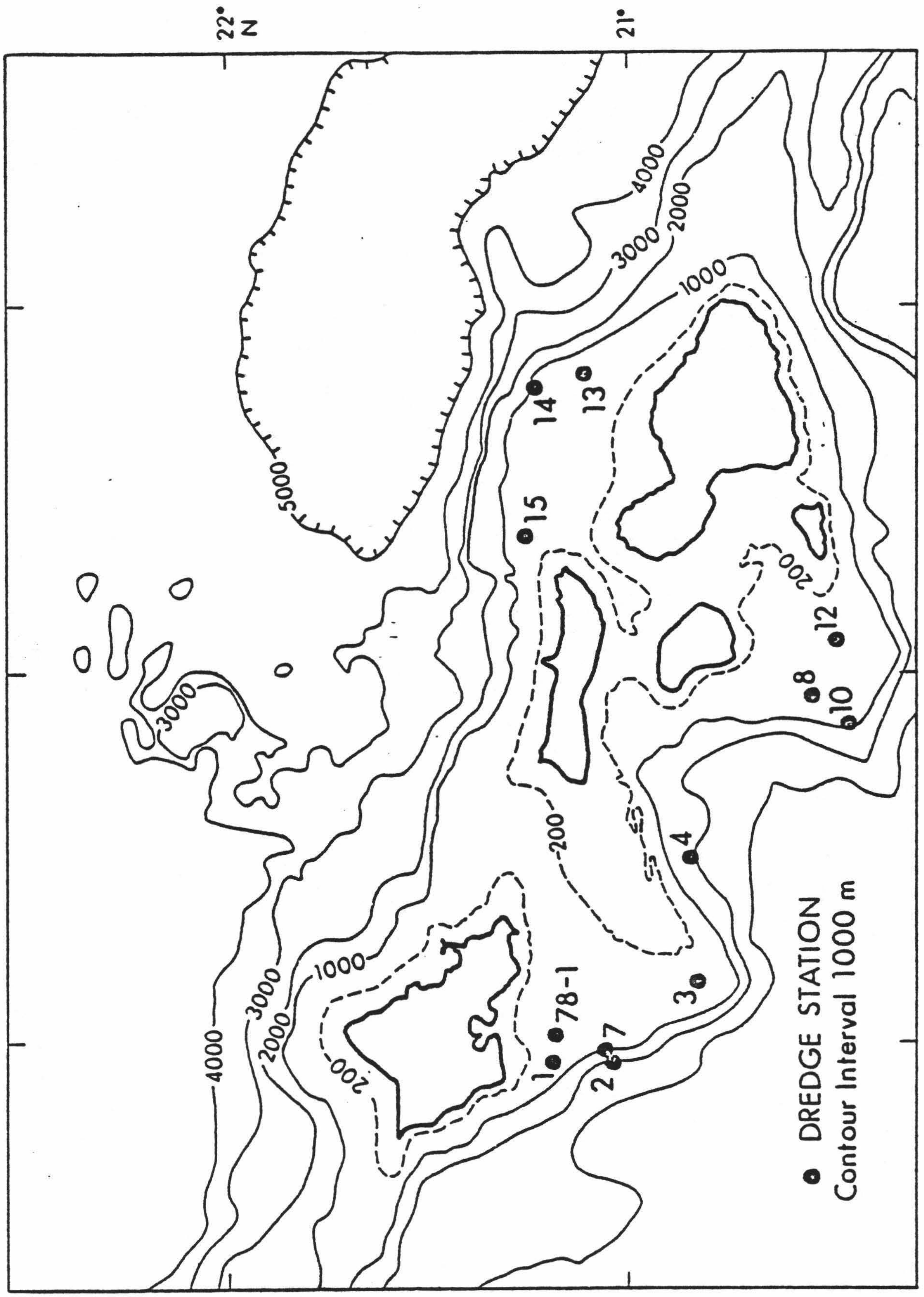

22° N
21°
156°
157°
158° W
5000
4000
3000
2000
1000
200
4000
3000
2000
1000
200
3000
200
1
78-1
2
7
3
4
15
14
13
12
8
10
DREDGE STATION
Contour Interval 1000 m

Table 2. Correlation of corals identified by J. W. Wells with those identified by Menard *et al*., 1962.

CORAL IDENTIFICATIONS By Menard *et al*., 1962	CORAL IDENTIFICATIONS BY WELLS	DREDGE STATION
Leptastrea n. sp. A	*Leptastrea sp. cf. L. Purpurea* Dana, 1846	8, 78-1
Leptastrea n. sp. B	*Leptastrea purpurea* Dana, 1846 (*Leptastrea transversa* Klunzinger) (*Favia hawaiiensis* Vaughan)	1, 78-1
Pavona n. sp. A, aff. *P. gigantea* Verrill	*Pavona duerdeni* Vaughan, 1907 (*Pavona clavus* Dana)	8, 78-1
Pavona n. sp. B, aff. *P. duerdeni* Vaughan	*Pavona duerdeni* Vaughan, 1907 (*Pavona clavus* Dana)	2, 8, 78-1
	Porites sp.	78-I
	Cyphastrea ocellina Dana	8
	Pocillopora sp. (different lithology from the rest)	78-1

A. lobifera - A. lessonii first appeared in the post-Miocene at Midway, probably in response to slight cooling of the water temperatures. Another suite of Amphistegina sp. characterizes Miocene strata, so that the benthic Amphistegina population of the reef rock indicates a post-Miocene age.

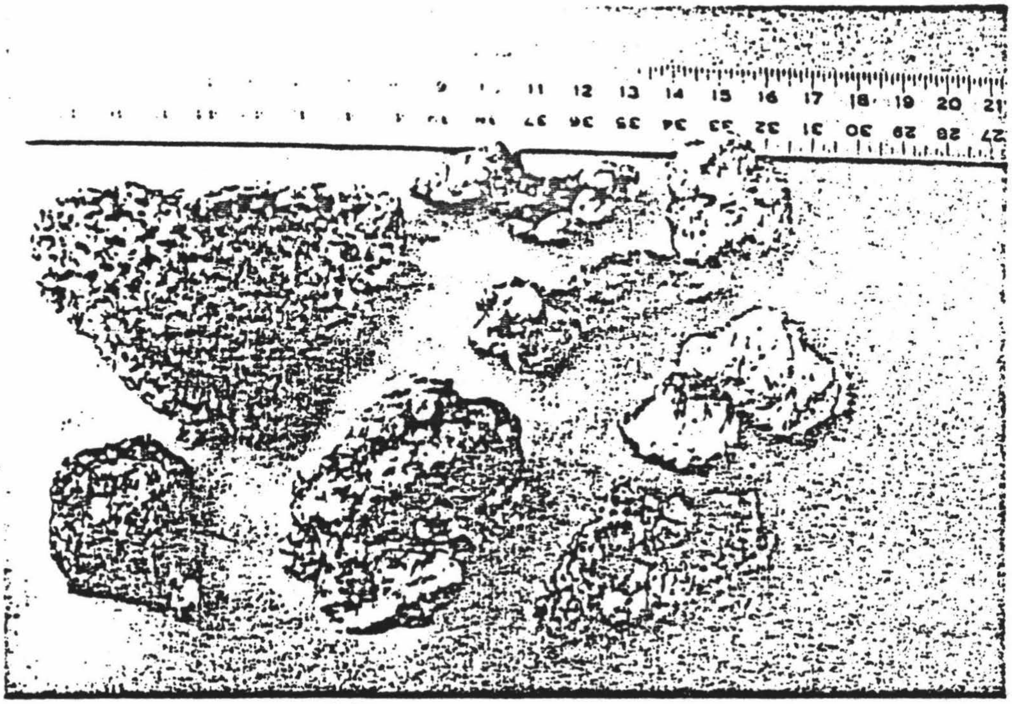
Other benthic foraminifera include Heterostegina Cymbaloporetta and Cibicides. These are shallow-dwelling forms, often attached to algae. The benthic population of the reef rock interstices is generally different from that of the loose surface material, where species of Cassidulina and Uvigerina dominate, although slight infiltration may have occurred.

The coral and foraminifera identities do not indicate a specific post-Miocene age. It seems likely that the dredge samples are Pliocene in age, but they may be as young as early Pleistocene.

Seven thin sections were prepared from samples obtained from dredge station 78-1 (Figs. 11 and 12). Six were prepared from four reef rock samples and one was prepared from a lithified iron oxide mudstone sample. Samples were cut perpendicular to the growth axis or to the bedding plane where possible. The samples were heated and coated with balsam after the first cut. From each sample, blocks were cut, impregnated with balsam, lapped smooth, and cemented to a petrographic slide. The mounts were cut and lapped smooth to an approximate thickness of 0.03 mm when possible.

Several of the reef rock samples are classified as foraminiferal-algal-wackstone (Dunham, 1962), such as that shown in Figures 13 and 14. Similar reef rock lithologies are shown in Figure 15. The reef rocks appear to be representative of a fore-reef or fore-reef transitional facies (Schlanger, 1964; Schlanger, personal communication, 1980). The corals have an aragonite, calcite, and magnesian calcite mineralogy;

Figure 11. Front side and back side views of ten reef rocks from dredge station 78-1. Scale units are inches.


11 12 13 14 15 16 17 18 19 20 21

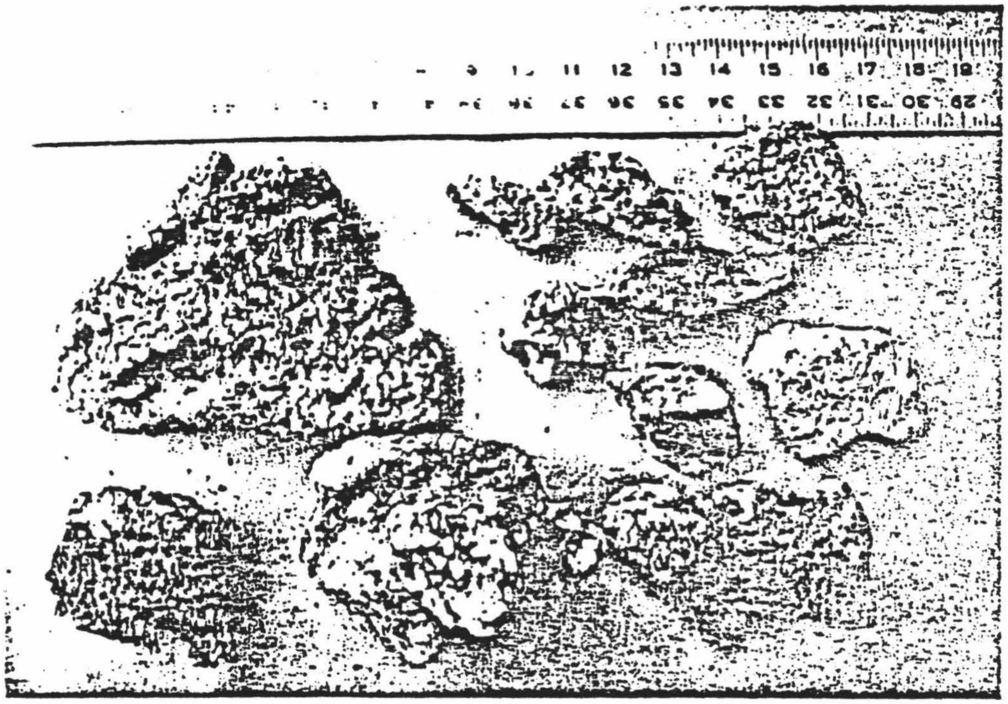
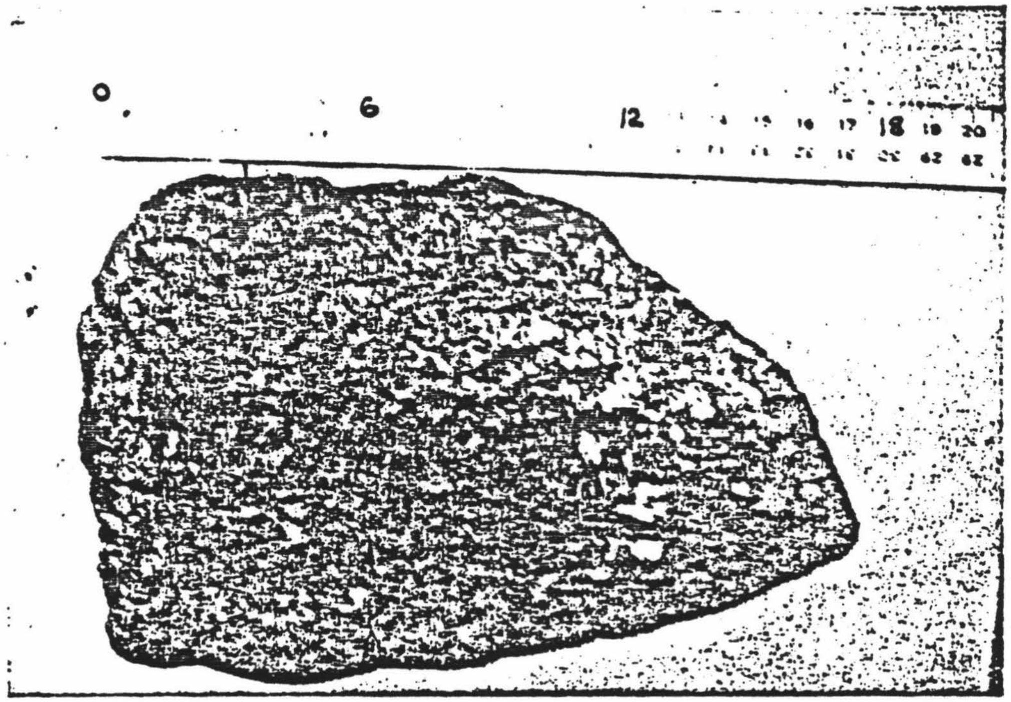
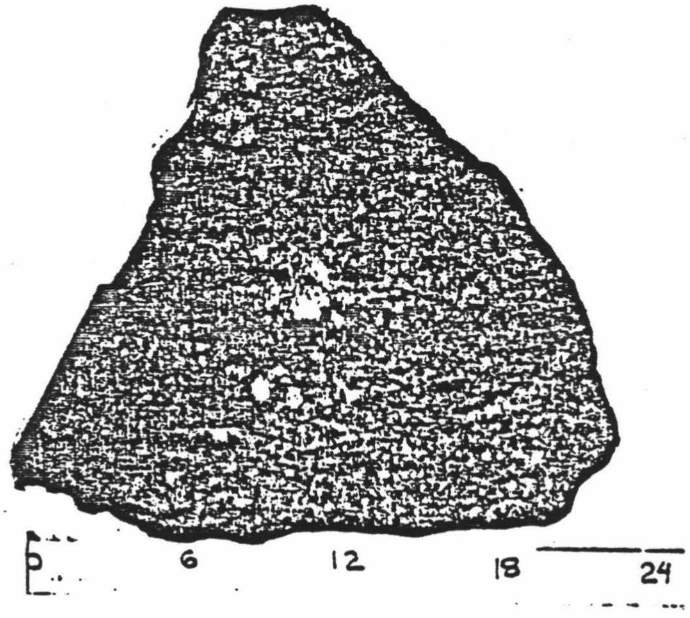

11 12 13 14 15 16 17 18 19

Figure 12. Top and side views of two mudstone slabs from dredge station 78-1. Scale units are inches.


0
6
12
18
20


0
6
12
18
24

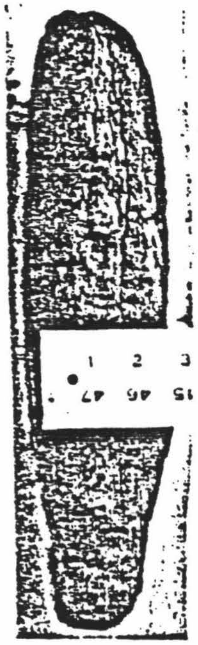

1
2
3

Figure 13. Foraminiferal-algal-wackstone from dredge station 78-1. Both photomicrographs have a magnification of 32X.

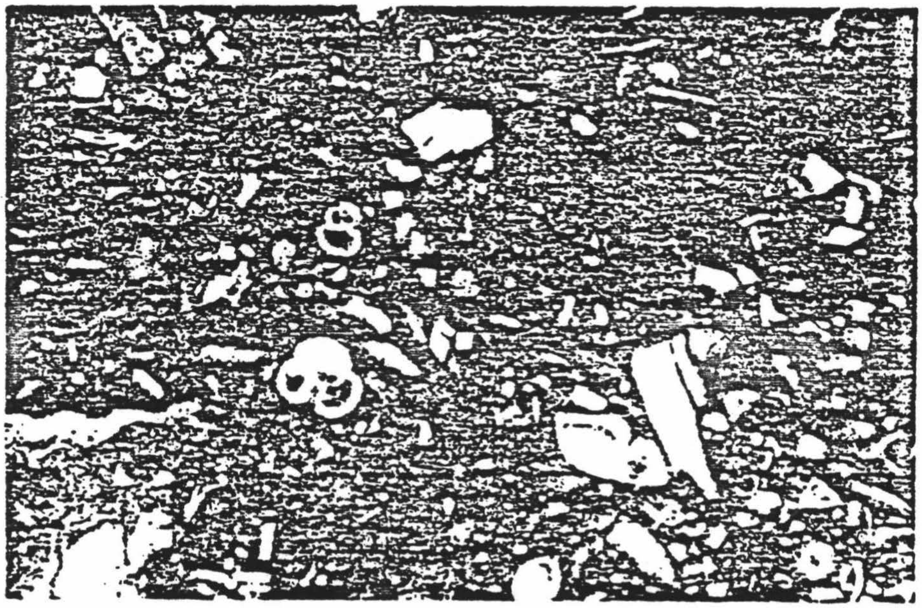
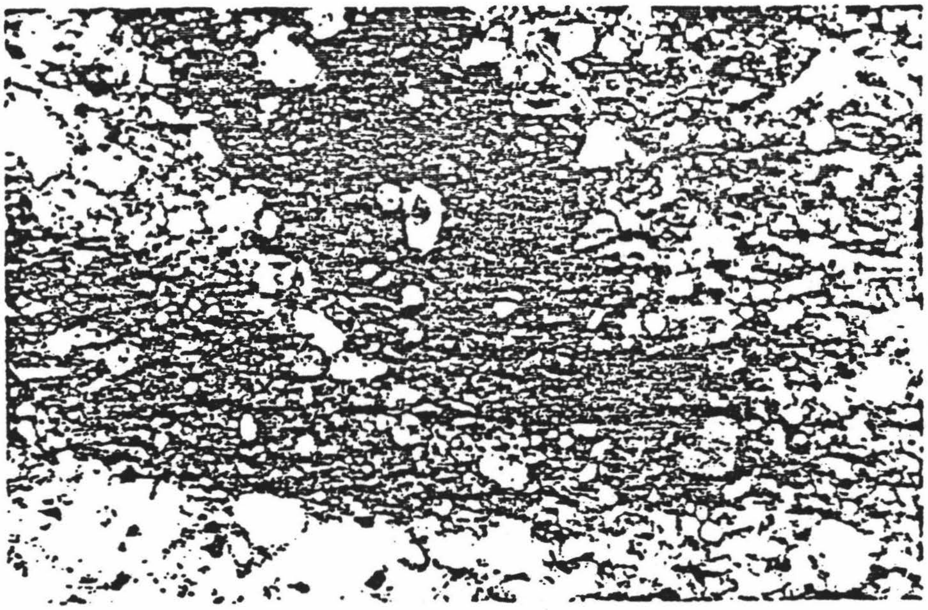
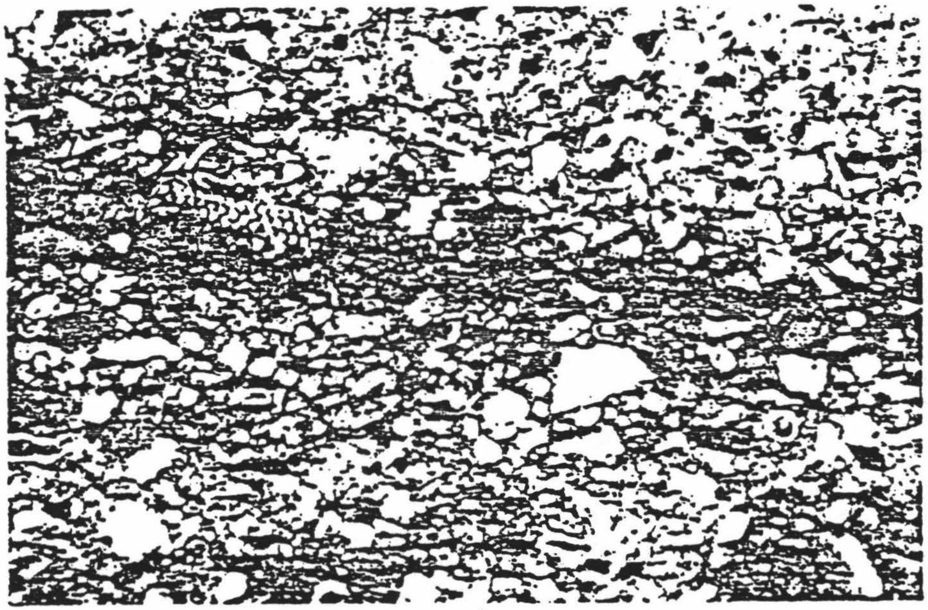


Figure 14. Foraminiferal-algal-wackstone from dredge station 78-1. Magnification of the top photomicrograph is 32X, and that of the bottom photomicrograph is 128X.

Figure 15. Fragmented algal-foraminiferal wackstone (darker layers) grading into packstone in the upper right-hand corners of the photomicrographs (lighter layers). Samples are from dredge station 78-1. Both photomicrographs have a magnification of 32X.





no dolomite was detected. A pure aragonite branch of Porites sp. from station 79-1 underwent atomic absorption analysis for Sr/Ca ratios (Smith et al., 1977). The results indicate that the coral grew in waters averaging 24.5° (R. Redalje, personal communication, 1979).

The mudstone is made up of very fine sand (10%), silt (45%), and clay (45%) composed of amorphous iron oxides; very little Mg, Mn, or Ca is present. The iron oxides are probably derived from weathered island basalts (Moberly, 1963).

APPENDIX B

INSTRUMENTATION, SURVEY METHODS, AND ANALYTICAL TECHNIQUES

Pararas-Carayannis (1965) has summarized the history and methodology of collection of bathymetric data around Oahu (and other Hawaiian Islands) prior to 1965. The nearshore bathymetry, within 5 to 15 km of Oahu's coastline, is largely based on his charts. Bathymetry of portions of the 500-meter shelf farther seaward is based largely on HIG surveys during 1965-1966 and 1971-1979 and soundings from large scale NOAA nautical charts published prior to 1978.

In order to allow a margin of safety for navigation, the mean lower low water datum was used exclusively for all hydrographic surveys in the Pacific. Most of the topographic and geological surveys on land, however, are based on mean sea level. This was also deemed the most appropriate reference datum for work done by the University of Hawaii in the Hawaiian Islands area (Pararas-Carayannis, 1965) and it is the sea level datum on which the work described herein is based. Mean sea level is defined as the average height of the surface of the sea for all stages of the tide for a 19 year period. In the case of the Hawaiian Islands, the difference between mean sea level and lower low water is approximately 0.32 meters. For the deep water bathymetry which includes the 500-meter shelf of our survey this difference lies within the limits of error and thus it is not significant whether low water or mean sea level is used.

Echo sounding and reflection profiling equipment that was used in the 1971-1979 surveys is similar to that used on board the R. V. TERITU during the 1965-1966 surveys described by Kroenke and Woollard (1966). Instrumentation employed during the 1971-1979 surveys include: a 3.5 kHz echo sounding system consisting of Edo transceivers, programmers, Alpine wet-paper Precision Echo Sounding Recorders (PESR), and a hull-mounted 3.5 kHz transducer. On the R. V. KANA KEOKI, the transducer is mounted near the keep approximately 3 meters below the Plimsoll line. Thus the depth of the transducer below the waterline fluctuates with the balasting of the vessel, but nevertheless, is within the desired range of accuracy.

The development of the reflection profiling system currently in use on HIG vessels has been discussed by Kroenke (1972). The seismic reflection profiling system currently in use consists of a 4500 joule E. G. & G. sparker, a SECO hydrophone array (eel), assorted amplifiers and filters, and an Alpine wet-paper PESR. Seismic reflection signals were filtered between 50 and 60 hertz. Reflection profiles were recorded most commonly on 2, 4, or 5 second sweeps; 3.5 kHz bathymetric data were recorded most commonly on a 1 second sweep. Reflection and bathymetric records were annotated each half hour and at the time of events such as changes in course or speed.

Whereas LORAN and piloting were the methods of navigation for the R. V. TERITU, satellite navigation or piloting or both were the methods of navigation for the R. V. KANA KEOKI. A Del Norte Technology, Inc. Trisponder was used to determine the position of the R. V. NOI'I during the 1978 surveys. The trisponder is a line of sight distance measuring system that uses microwave RF signals to measure distances to a resolution of 015 metres and an accuracy of 3 metres (Campbell and Erlandson, 1979). The system's master unit, carried on the ship, measured the distance to two remote transponders located 29.16 km apart on the roof of the Makakilo fire station hose tower

(21°22.44'N 158°05.14'W) and on the roof of the building at 3019 Kalakaua Avenue (21°15.74'N 158°49.50'W). Ship position at any moment is calculated by simple triangulation.

Methodology

Bathymetry obtained along ships tracks positioned by the Del Norte Trisponder closely corresponds at track intersections to that obtained along ships tracks positioned by satellite navigation in conjunction with land sightings. These data also closely correspond to NOAA nautical chart bathymetry. Small adjustments of tracks controlled by both satellite navigation and lang sightings were made by matching bathymetric and subbottom reflection data at track intersections, always holding the R. V. NOI'I trisponder tracks and reliable satellite positioned tracks fixed. Track positions based on land sightings or satellite navigation were then adjusted in similar fashion to that stated above, holding the more reliably positioned tracks stationary, and also by comparison with nautical charts. Many ship track locations based on satellite navigation alone appear to be very poorly positioned, mislocated, at places, between 2 and 6 km from correlative breaks in slope, and pier locations. Poorly positioned tracks, along which reflection records were not obtained, did not warrant track adjustment and thus have not been included in the bathymetric data set.

There is no significant seasonal variation of sound velocity in the Hawaiian Islands (Pararas-Carayannis, 1965). The vertical variations of salinity and temperature in the upper 400 metres are so large that the velocities may be in error by as much as 2%, whereas at greater depths they are usually correct to within 0.2% (Matthews, 1939). South of Oahu, the fluctuations in salinity and temperature from location to location seem to be greatest in the upper 100 to 200 metres (Chave and Miller, 1978). On the one hand, the lateral variations in sound velocity due to shallow water salinity and temperature variations, seem to be extreme. On the other hand, shallow-water variations may, in fact, not be so extreme in the survey area, since water quality characteristics there are more typical of open ocean rather than coastal conditions (Chave and Miller, 1978).

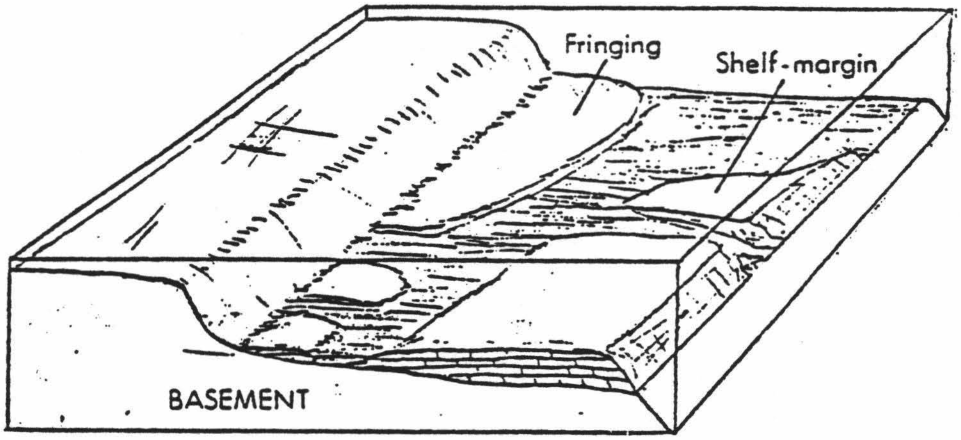
The echo sounder recorders are calibrated for a constant velocity of sound, either 1500 meters/second or 800 fathoms/second. All HIG shipboard bathymetric data have been tabulated in metres and corrected to the nearest metre for variation in the velocity of sound utilizing Matthews Tables. The standard sound corrections for water depths less than 1800 metres are less than 4 metres and most often less than 2 metres. The depth-correction interpolated from Matthews tables for any particular uncorrected depth was added to or subtracted from that particular uncorrected depth to yield the corrected depth. The corrected depth was then rounded off to the nearest whole metre.

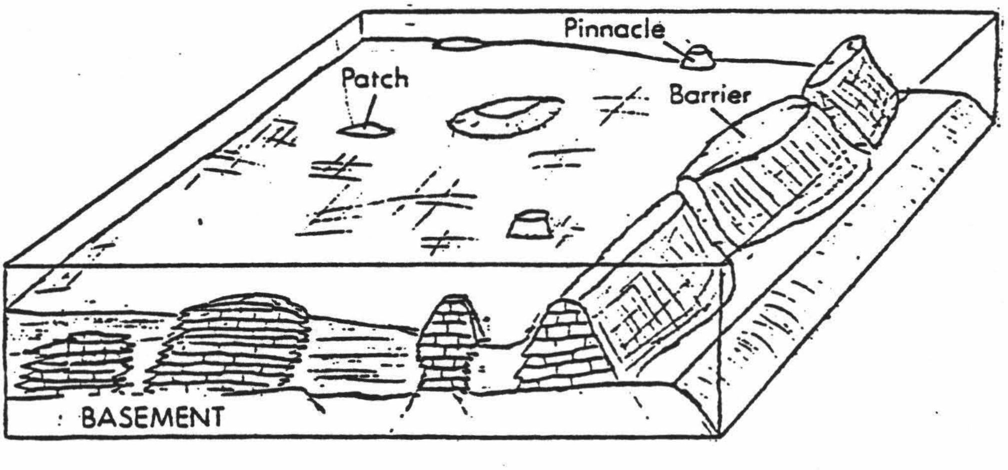
APPENDIX C

CRITERIA FOR CLASSIFICATION OF REEFS

Reefs have been classified according to the criteria of Bubb and Hatleid (1977) (Figure 16). Barrier buildups are linear, with relatively deep water on both sides during deposition (Fig. 3, profile A-A'). Pinnacle buildups are roughly equidimensional and are surrounded by deep water during deposition (Fig. 7, profile H-H'). Shelf margin buildups are linear, with deep water on one side and shallow water on the other (Fig. 9, profiles L-L', M-M', and N-N'). Patch buildups form in shallow water, either in close proximity to shelf margins, or over broad, shallow seas (Fig. 6, profiles F-F' and G-G'). The term fringing reef, as applied by Darwin (1839) and subsequently used by Edmondson (1946), Stearns (1946), and others, is reserved for reefs which border the shoreline or are located along a former shoreline (Fig. 9, profiles J-J' and K-K'). The transition from fringing to shelf margin to barrier reef is gradational or overlapping, for instance, south of Penguin Bank (Fig. 9).

Figure 16. Types of reefs recognized from seismic interpretation (after Bubb and Hatleid, 1977).


Fringing
Shelf-margin
BASEMENT


Pinnacle
Patch
Barrier
BASEMENT

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