PALEOENVIRONMENTS AT WAIMANALO, OAHU, HAWAII

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ABSTRACT

Eight boreholes, ranging from 15 m to 137 m in depth, were cored in the Waimanalo, Oahu, coastal plain in 1966 by the Hawaii Department of Land and Natural Resources to determine the practicability of utilizing deep wells for disposal of treated sewage effluents. The cores taken from these boreholes consist of mud and reef limestone facies deposited during the Pleistocene.

Paleomagnetic analysis of DH I showed that deposition of the stratigraphic section occurred in less than 1.7 my. The presence of three primary environments--initially a shallow lagoon, followed by a deep lagoon, and finally a reef--was recognized through lithological and paleontological analysis. Foraminiferal abundances were altered with each of seven recognized fluctuations of the sea and one specie, _Archaias angulatus_, did not survive to the present. Diagenesis, caused by meteoric phreatic conditions during regressive sea level transitions, altered the underlying sediments and reduced the foraminiferal abundances typical of the various environments. Magnetic polarity reversals determined in the longest core (DH I) were correlated with the standard time scale as follows:

135 m as the Olduvai termination, 104 m as the Jaramillo onset, 94 m as the Jaramillo termination, 84 m as the Brunhes/Matuyama boundary. The transgressive-regressive cycles recorded in DH I correlate more closely with deep sea records than with continental glacial records.

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I. INTRODUCTION

Eight boreholes were cored in the Waimanalo, Oahu, coastal plain in 1966 by the Hawaii Department of Land and Natural Resources to determine the practicability of utilizing deep wells for disposal of treated sewage effluents. Lithostratigraphy of the area based on these cores was presented by Lum and Stearns (1970) and the alternating facies of mud and reef limestone were related to eustatic changes in sea level in the Central Pacific Basin during Pleistocene time.

The nature of ancient depositional environments is very complex and can only be known through induction and inference. Several lines of independent evidence must be explored before any interpretations can be made. The evidence must be internally consistent and lead to the same conclusions. Sedimentary and biological paleoenvironments should correspond with their modern counterparts (Laporte, 1968).

This study proposes to determine the environments of deposition of the various sedimentary units cored using traditional paleontological and sedimentological means of

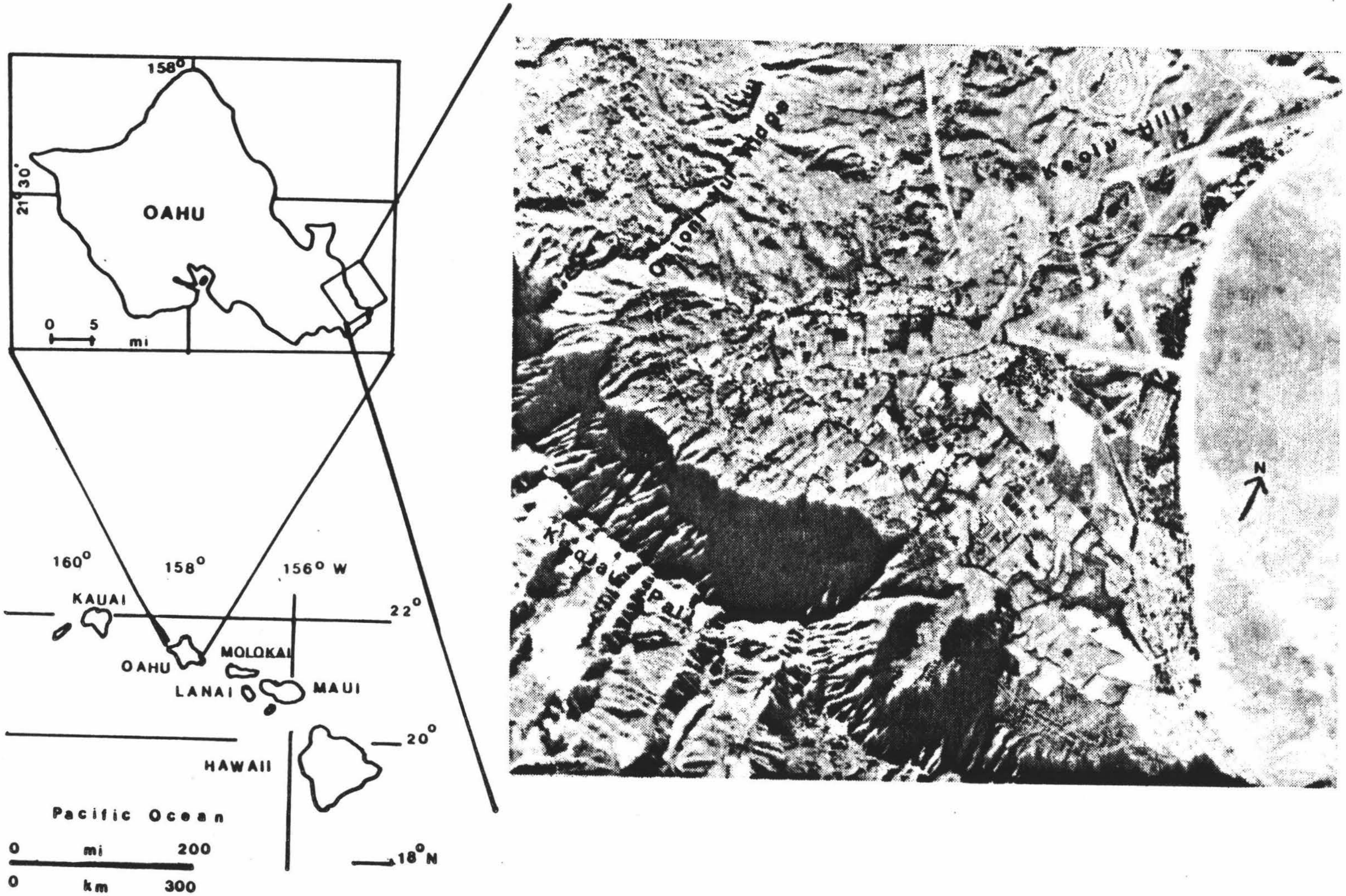


Figure 1. Location Map for Waimanalo, Oahu, Hawaii.

interpretation and to reconstruct a geologic history of the area based on analytical evidence. These interpretations are made within a magnetostratigraphic framework.

Regional Geology of Waimanalo

The Waimanalo plain, seen in Figure 1, is located on Oahu's southeastern shore in the Hawaiian archipelago. It is a triangular-shaped plain bounded on the northwest by the Onioni Nui Ridge and Keolu Hills (the southern boundary of the Koolau Volcano caldera), on the south by the steep escarpment of the volcanic Koolau Pali (cliff), and on the northeast by the Pacific Ocean .

The topography consists of a gently sloping alluvial upland and a low-lying sandy coastal plain fronting on broad Waimanalo Bay. In the shallow offshore waters, living coral reef and sandy bottom extend as far as 2.4 km seaward into a shallow bay. A slightly-arcuate beach of foraminiferal sand extends 5.5 km along the shore. Partially-cemented calcareous sand dunes less than 6 m high border the beach. A ridge of ancient, cemented, calcareous dune sand rises 6 to 49 m where the coastal plain terminates about 800 m inland.

The upland rises gently from behind the dunes to merge with talus slopes at the base of the Pali (Lum and Stearns, 1970). It consists of integrated fans of detritus produced as colluvium and alluvium by the weathering of the lava-flow banded cliffs. Intermittent streams have slightly dissected the area.

The scalloped Pali, formed by coalescence of a series of amphitheater-headed valleys, reaches heights of 790 m in Waimanalo (Macdonald et al., 1983). Prolonged periods of fluvial erosion and intermittent periods of marine erosion have sculpted the Pali and drowned the amphitheater-shaped valleys (Lum and Stearns, 1970).

Present-day land use of the Waimanalo plain is divided between housing, agricultural, military, and public interests. About sixty percent of Waimanalo beach lies within the boundary of Bellows Air Force Station to which the public is admitted on weekends. The ancient sand dunes are being quarried for cement; the rest of the coastal plain is devoted to public beaches and housing. The alluvial upland is one of the few areas on the island where moderate-sized agricultural endeavors are possible. Thus, dairies exist beside egg farms, horse ranches, tropical plant nursuries, and residences.

Previous Work

The sedimentary rocks of the Waimanalo cores consist of marine skeletal material (beach rock, dune deposits, and reef and related limestones), terrigenous material (silt, clay, and conglomerate) or combinations of each (marl) which were described in great detail by Lum and Stearns (1970). The lithologies reveal alternating periods of marine and subaerial conditions which suggest transgressive and regressive seas (Fig. 2). (See Appendix A for definitions of lithologic terms.)

The lithologies of deep cores taken from the Ewa, Oahu, coastal plain also indicate transgressive and regressive depositional sequences (Stearns and Chamberlain, 1967). The sedimentary history of this area, based on a micropaleontological study, was deciphered by Resig (1969). A shallow-water accumulation of Pleistocene age was indicated by the fossil assemblage. Hammond (1970) completed a magnetostratigraphic study of these cores. He suggested three possible correlations of the paleomagnetic stratigraphy of the Ewa I section between 618 and 1072 feet: between 1.62 and 3.32 Ma, between 1.79 and 3.92 Ma, or between 1.79 and 2 Ma. No other paleomagnetic investigation of sediments from the Hawaiian Islands has been undertaken.

Pleistocene reef environments of Oahu were studied by Pollock (1928) and by Hagstrom (1979). Neomorphism and cementation are the post-depositional processes which alter carbonate material in the fossil reefs. Longman (1980) described four primary diagenetic environments based on

Fossils
- □ Foraminifera (visible with hand lens)
- ○ Algae
- ○ Corals
- ⊂ Barnacles
- ╲ Roots
- △ Mollusk shell fragments

Lithology
- ▨ Clay
- ▩ Sand
- □ Dune
- ▩ Beach Rock
- ⊞ Reef and Related Limestones
- ☰ Marl
- ▦ Conglomerate

Other
- ✕ gradual transition
- ⋀ unconformity
- ○ sample
- X sample analyzed
- depth in core feet (meter)
- ⇨ paleomagnetic reversal

Figure 2. Legend for Core Log of Drill Hole I. (Figure 2a and 2b)

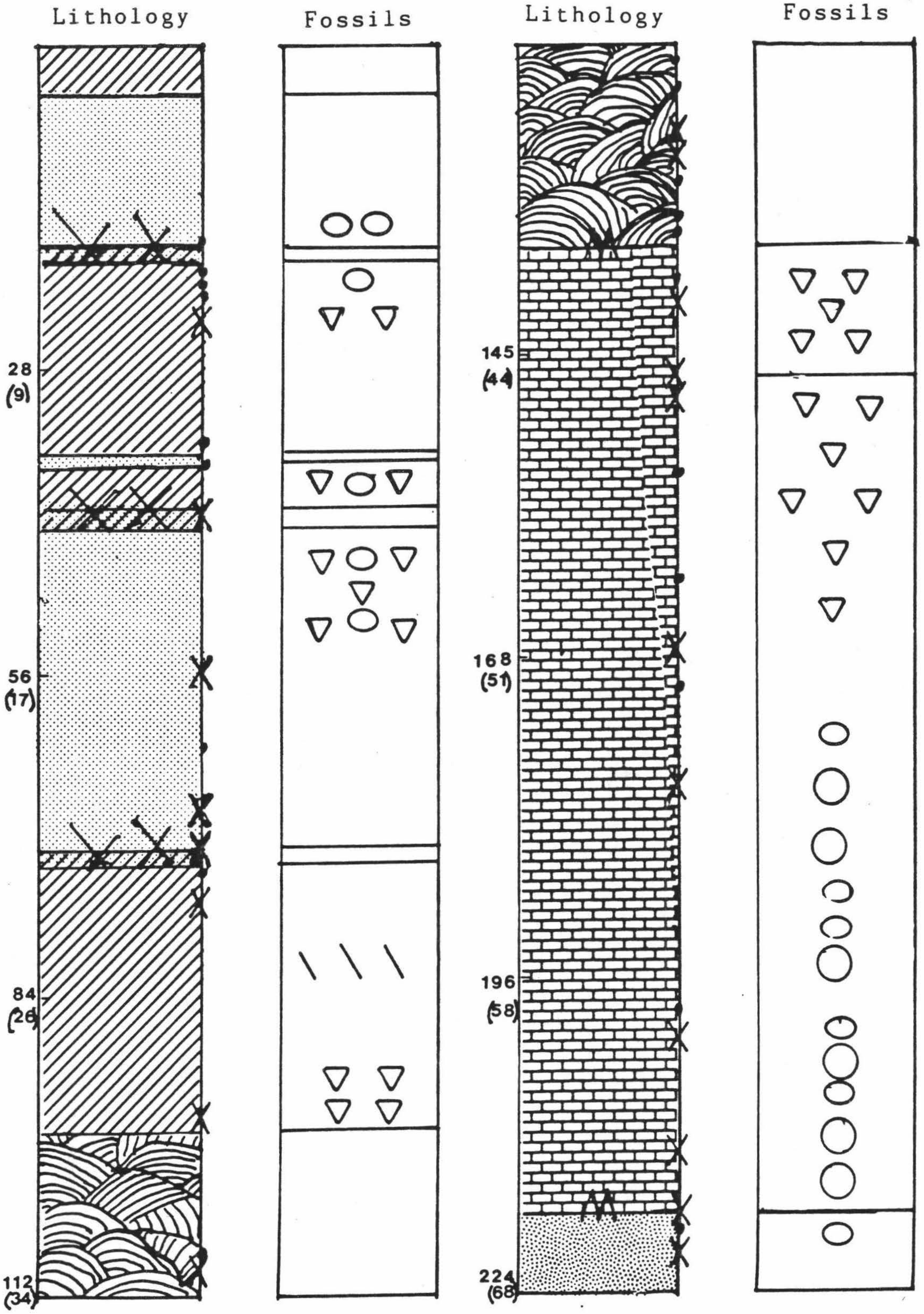


Figure 2a. Description of Drill Hole I (0 to 68 meters).

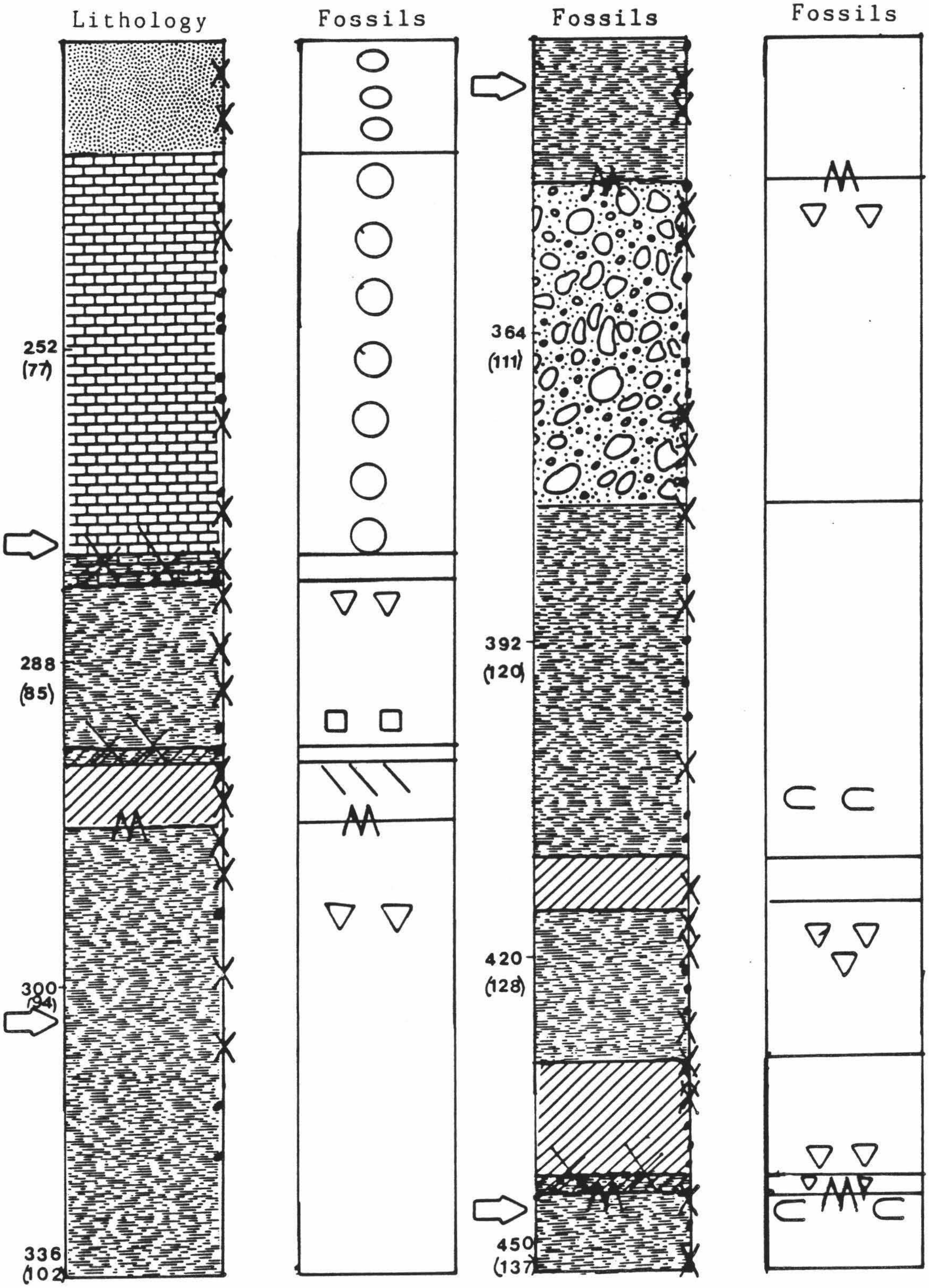


Figure 2b. Description of Drill Hole I (68 to 137 meters).

flow, CO_2 saturation and kind of pore water, and on water-air ratios in the pores.

Littoral sedimentary processes on the windward coasts of two Hawaiian islands have been studied. Inman et al. (1963) found that the highest concentration of terrigenous sediments occurs on the semi-arid lee side of Kauai. Coulbourn (1971) found that the ultimate source of the terrigenous fraction in Kahana Bay, east shore of Oahu, was the stream draining Kahana Valley. The sediments, structure, and depositional history of Kaneohe Bay, Oahu, a protected embayment or lagoon northwest of Waimanalo, were examined by Smith et al. (1964), Roy (1970) and Hollett (1977), whereas Bell (1976) studied the foraminifera.

Characteristics of the three primary environments described in this study were based on foraminiferal analysis. All species of foraminifera identified were reported from Recent Pacific collections (Barker, 1960; Cushman, 1910, 1924, 1932, 1937, 1939; Cushman et al., 1954; Phillips, 1977; Graham and Militante, 1959; Hayward and Brazier, 1980; Moore, 1974; Todd, 1957; Todd and Low, 1970). The description of reef facies found in this study follow the methods of interpretation of Flugel (1978), Ginsburg (1956, 1973), Reading (1978), Schlanger (1964), Scholle (1978) and Stieglitz (1972) who described near-shore sedimentary environments and facies based on the size and shape of constituent particles of the sediments.

Relative ages for various sedimentary formations of the Hawaiian Islands have been determined, but ascertaining the absolute ages has been very difficult (Stearns, 1978). Using the K/Ar dating method, Hawaiian basalts were dated. McDougall (1964) found that the subaerial part of the Koolau Volcano was built between 2.56 and 2.15 Ma, and Doell and Dalrymple (1973) reported that it erupted subaerially between 2.6 and 1.8 Ma. Ku et al. (1974) used the uranium series to date fossil corals from the +7 m Waimanalo shoreline (120,000 B.P.). Fossil corals from sediments older than 120,000 years are generally recrystallized and of little use in dating. The limestones of the Kaena shoreline (+30 m) were assigned an age of about 500,000 years because a basaltic dike which cuts them at Black Point, Oahu, has a K/Ar age of 410,000 years (Stearns and Dalrymple, 1978).

Since the maximum age of the Waimanalo cores is 2.6 Ma, no more then ten paleomagnetic transitions will be found (Mankinen and Dalrymple, 1979). The principal magnetic minerals found in Hawaiian soils are titanomaghemite and hematite, while the dominant magnetic mineral in Hawaiian basalts is titanomagnetite (Hammond, 1970). Lagoonal mudstone (marl) proved to be the best dating material. It is sufficiently indurated so that sample plugs were easily made and sufficiently fine-grained so that the magnetic moment was readily measured (Hammond, 1970).

Unconsolidated reef limestone and fragmented mudstone could not be sampled for obtaining oriented samples was precluded by their condition.

Age dating based on mollusks is now feasible using a technique based on the racimization of amino acids in their shells (Belknap and Wehmiller, 1980). This technique is applicable within the 0.12-2.0 my time interval in which deposition of the Waimanalo sediments probably occurred. However, this method did not prove to be of value for this study due to a thermal dependency problem described later.

II. SAMPLING AND LABORATORY METHODS

The drill holes, DH I to DH VIII, range in depth from 15 to 137 m with a total core recovery of 671 m, averaging 55% recovery in limestone and 75% in compacted marine clays (App. B). The sediments recovered are beach and reef limestones, and marine and terrigenous clays. Basal basalts from the Koolau Volcano were not cored. DH VIII's cores had been misplaced and were not sampled for this study.

The cores of DH I and III, having diameters of 5.5 cm, were sampled at intervals of one meter, except for parts of the section showing environmental transitions where samples were more concentrated (Fig. 2). Samples weighed between 30 and 500 gm depending on rock density. They are designated according to depth in core. Since the cores were originally labeled in the English system of feet and inches, this system is maintained for consistency. All other measurements are given in units of the metric system. Depth "down-hole" and depth "below sea level" were two measures recorded in the well logs. In several places, the lithologies as seen in the core boxes did not correspond with the descriptions of the well logs. The core boxes were assumed to be the standard in those instances.

The weight-percent calcium carbonate (%CO_3) was calculated by dissolving 2 to 3 gm of material, taken at 3 m intervals, in 2.3 N hydrochloric acid. The residue was filtered through preweighed Whatman No.2 filters, dried and reweighed. The weight-percent (wt %) of the sample soluble in acid was calculated using:

$$(b/a - 1)(-100) = \text{weight percent}$$

where a equals weight of original sample and b equals weight of residue. Soluble material is considered to be of marine origin and insoluble material of terrigenous origin.

Thin sections were made of consolidated reef material and dune and beach rock to define reef facies and to study the diagenetic processes. Faunal assemblages were identified and rock porosity was estimated. Component grains were analyzed for size, roundness, and degree of sorting. Evidence of solution, recrystalization, and cement formation was studied relative to the diagenetic interpretation presented by Longman (1980). Sections were made from the top and bottom of each bed and from seaward and landward portions of each unit.

The cathodluminescence feature of a Cambridge S4-10 scanning electron microscope (20kv at 20°) was employed to analyze the cement of carbon-coated thin sections of reef material. Scanning electron micrographs of gold/palladium coated rock fragments were taken on the same machine (20kv and 10°) to investigate the origin of sediment grains, cement formation and degree of diagenesis. The material was scanned for the presence of discoasters during this part of the study.

Microfossils were recovered from 10 gm samples of loose, friable to moderately compacted sediment. Where necessary, the material was broken to pea-sized pellets with a mortar and pestle. The sample was then disaggregated in 15% hydrogen peroxide solution, wet-sieved through a 63 micron screen to remove the silt-clay fraction and reweighed. The dried sample was poured into perchloroethylene to concentrate the microfossils further. Unbroken foraminiferal tests, which generally float on the dense liquid, were retained by pouring through Whatman No.2 filter paper. Both the concentrate and the residue were dried and reserved, for all the large and most of the replaced and filled foraminiferal tests, ostracodes and other microfossils failed to float. The material was divided with a microsplitter and studied microscopically.

Remarkably well-preserved shells of the mollusk genera Anomia and Pinna were recovered from sediments at the bottom of DH I and II. Since these shells were thought to be located in the time-stratigraphic "never-never land" (too old for C^{14} and too young for U^{238} or K-Ar dating methods), a dating technique utilizing the racimization of amino acids was undertaken by Dr. J.F. Wehmiller (University of Delware). The task involved measuring the

D/L (right/left) leucine ratios from peak heights produced by capillary column gas chromatography. The amino acid racimization technique is based on the fact that the D/L ratio of amino acids of modern organisms essentially equals 0. After death, the L-enantiomer for each amino acid is slowly racimized until an equilibrium mixture is attained and the D/L ratio equals 1. The increase in this ratio is used to obtain a measure of time that has elapsed since death. In the process of racimization, optically active stereoisomers are converted to a mixture of two optically inactive isomers. The results, however, are dependent upon temperature of the environment and of burial, pH, and other environmental variables (Bates and Jackson, 1980).

A paleomagnetic investigation was considered for this study only after careful deliberation since several of the core boxes had been dropped, and a few core pieces had been mis-oriented in the core boxes during previous sampling. Therefore, paleomagnetic studies were done on those samples with unambiguous orientations, i.e. those samples which fit perfectly between two other core segments. The cores were halved lengthwise and a 2.5 cm chuck was used to cut a plug perpendicular to the previous cut. The sample plugs were labeled according to the box and row numbers in DH I. Wai 104.0 is from box 10, row 4, first sample while Wai 091.1 is from box 9, row 1, sample 2 (App. C). These cores were not oriented during drilling so there was no azimuthal control. "Up" was duly marked on each plug.

A Schonstedt Spinner Magnetometer model DSM-1 was used to measure the NRM (Natural Remnant Magnetism) of the marine sediment samples. Progressive alternating field demagnetization experiments were carried out on all samples at intervals between 0 and 600 Oe in a shielded chamber.

III. RESULTS

Sedimentology

Sediment Analysis

The percent calcium carbonate values range from 0 to 100% (Fig. 3). The absence of calcium carbonate represents a regression of the sea, allowing terrigenous sediments (soil) to accumulate, whereas 100% calcium carbonate signifies a transgression of the shoreline towards the mountains accumulating marine sediments.

The light-colored marine fraction is composed of various sized (mostly fragmented) remains of the principal lime producers--green and red algae, mollusks, corals, and foraminifera (Table I). To a lesser extent, the remains of sponges, holothurians, ostracodes, and echinoids are also present. Most of the sediments containing marine fossils are deposited at or below sea level. However, dune rock composed of marine material is formed above sea level.

The dark terrigenous fraction consists of olivine, augite, plagioclase feldspar, basaltic rock grains, quartz crystals, volcanic glass, titanomaghemite, hematite, and clay minerals (Table II). These detrital grains are the result of terrestrial weathering of basalts, soils, and

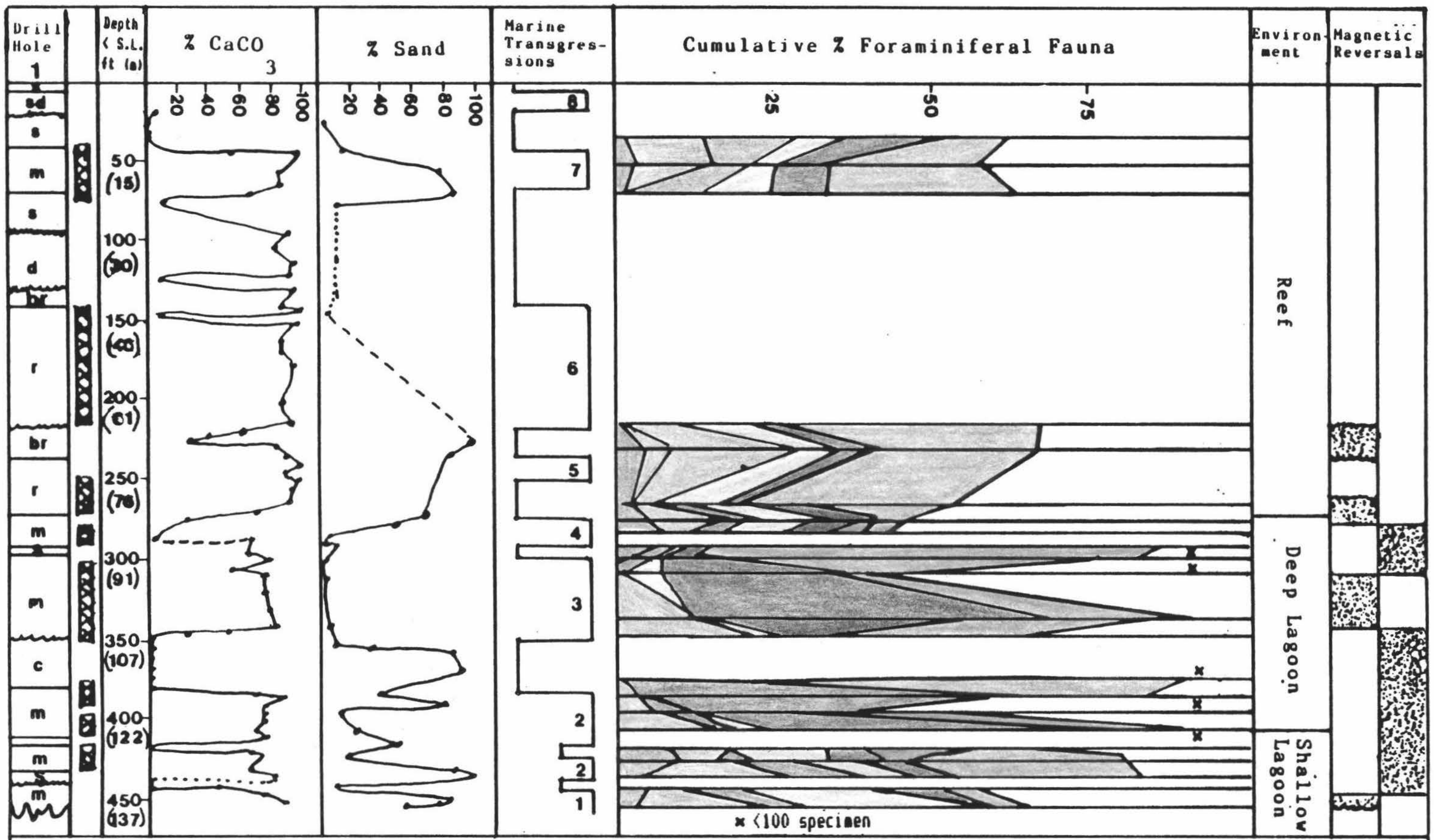


Figure 3. Waimanalo Depositional Analysis.

Lithology c-conglomerate m-marl r-reef limestone br-beachrock s-silt/clay d-dune sandstone sd-sand

unconformity ☒ altered sediment

Biofacies ☐ Shallow Lagoon ▨ Brackish Water ☐ Deep Lagoon ☐ Quiet-Water Tropical ▨ Shallow-Water Tropical ▨ Reef ▨ Algae

TABLE II

Detrital Grains Found in DH I and DH III Samples.

GRAINS SAMPLES	Plagioclase Feldspar	Augite	Basaltic Rock Fragments	Crystalline Quartz	Volcanic Glass	Magnetic Minerals	Olivine	Clay Minerals
DH I								
25-4	X	X	X	X	X	X	X	X
43			X	X	X	X	X	X
55-10		X	X			X	X	X
70	X	X	X	X	X	X	X	X
74	X	X	X	X	X	X	X	X
145			X	X	X	X		X
220-41			X	X	X	X	X	X
225-48			X		X	X		X
270-12			X	X		X		X
270-52			X		X	X		X
280-35			X		X	X		X
288-67a								X
288-67b				X		X		X
300-8			X					X
310								X
340								X
340-39			X					X
350-47	X	X	X	X	X	X	X	X
350-60	X	X	X	X	X	X	X	X
369-27	X	X	X	X		X	X	X
380-39			X	X	X	X	X	X
380-101								X
390-44					X			X
400-81								X
412-39	X	X	X	X		X	X	X
420					X	X		X
430		X	X	X		X	X	X
430-16			X	X		X	X	X
430-34					X	X		X
440-39a			X		X	X	X	X
440-39b			X		X	X		X
450						X		?
DH III								
255-6	?	X	X	X	X	X	X	X
260-10	X	X	X	X	X	X	X	X
270-19			X		X	X	X	X
299			X			X	X	
299-57			X		X	X	X	
299-92		X			X	X	X	X
310					X	X		X
320-12								
330								

hydrothermally-altered material of the Koolau Volcano, and of pyroclastic activity (Moberly, 1963; Fan and Grunwald, 1971; Hollett, 1977).

The %CO_3 values of most of the cores are generally between 60 and 90%. This represents a mixture of grains from the two sources (Fig. 3).

The values for percent sand (%Sand), representing the separation of sand from silt/clay-size grains, tend to cluster below 20% and between 65 and 85% (Fig. 3). When %CO_3 is plotted against %Sand, four fields appear (Fig. 4): 1) fine-grained with low %CO_3, 2) fine-grained with moderate %CO_3, 3) coarse-grained with moderate %CO_3, 4) coarse-grained with high %CO_3.

Thin Section Analysis

A study of 27 thin sections of representative lithologies in DH I and III indicates the presence of the supralittoral environment--dune, the littoral environment--beach, and five sublittoral environments--tidal flat, lagoon, back reef, reef flat, and reef edge (Fig. 5). Each facies was defined according to fossil assemblage, grain-size and shape, degree of sorting, and the type and amount of original pore space, as follows:

The <u>tidal-flat</u> facies consisting of silt and mud was identified in sections I-147-5 and 180-2 (Plate I, Fig. 1). This environment occurs shoreward of a lagoon where

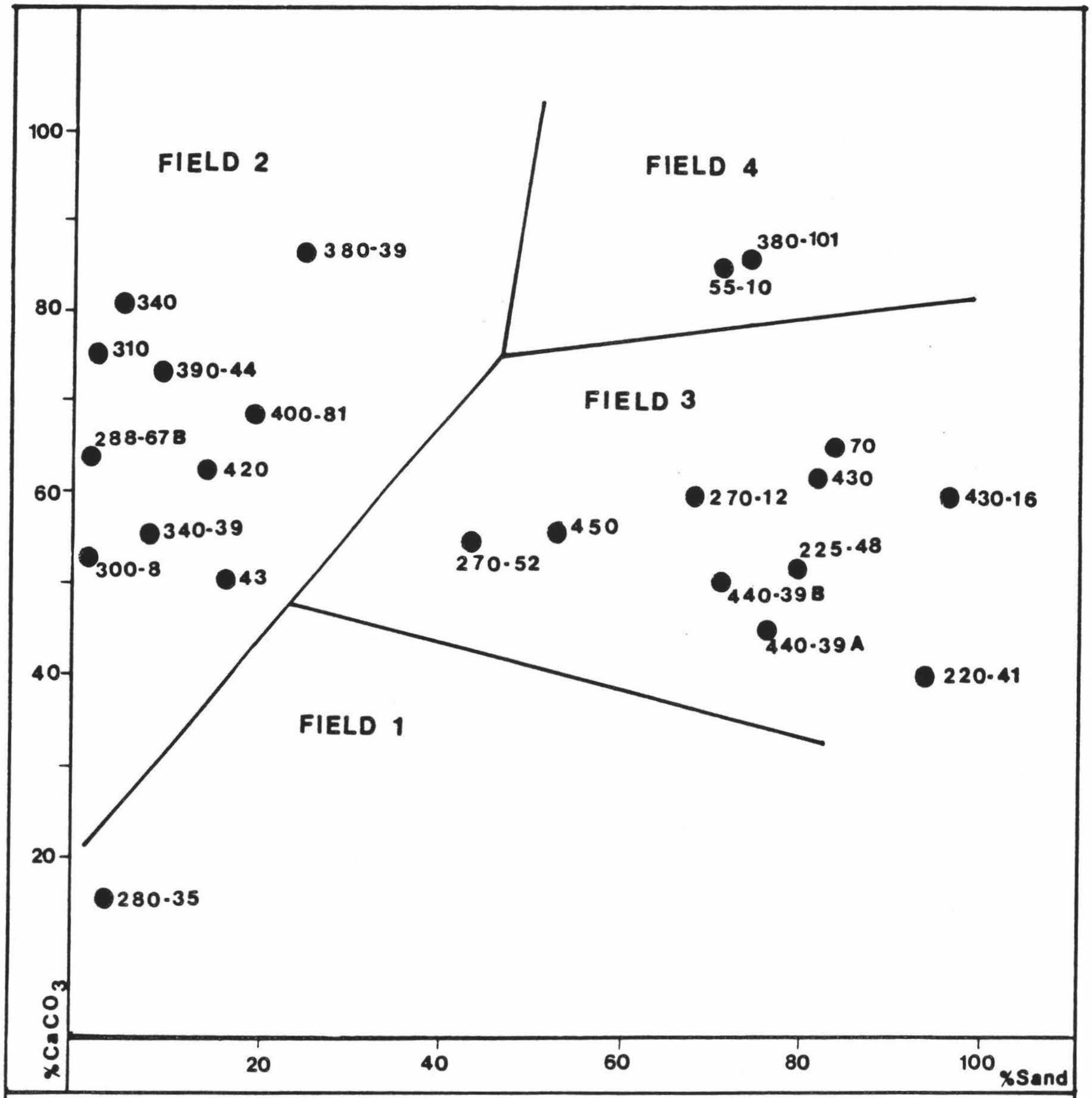


Figure 4. % $CaCO_3$ Versus % Sand (>63 microns). Four fields of values are indicated.

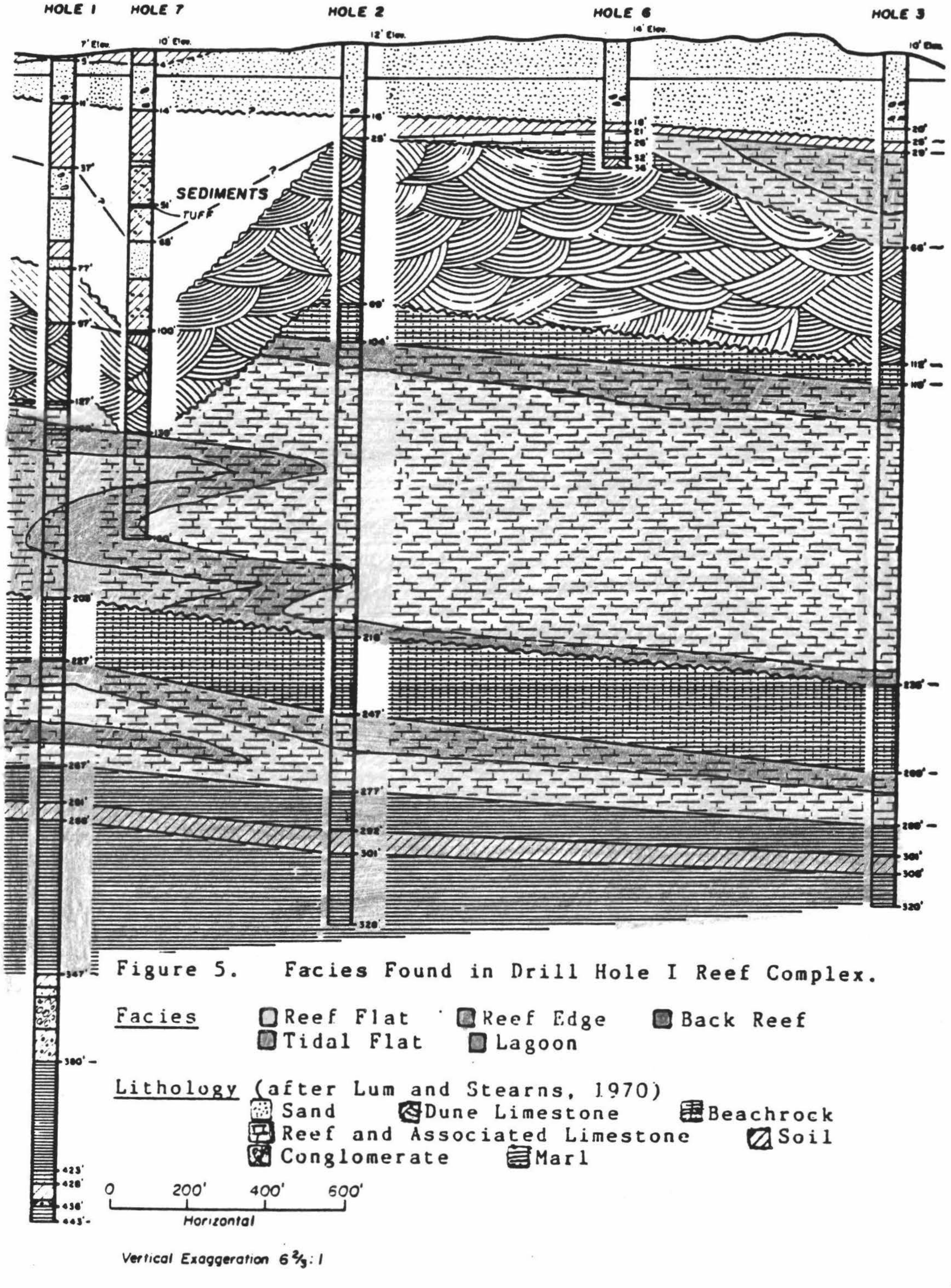


Figure 5. Facies Found in Drill Hole I Reef Complex.

Facies ▢ Reef Flat ▩ Reef Edge ■ Back Reef
▩ Tidal Flat ▩ Lagoon

Lithology (after Lum and Stearns, 1970)
▒ Sand ▨ Dune Limestone ▤ Beachrock
▦ Reef and Associated Limestone ▨ Soil
▩ Conglomerate ▤ Marl

currents and wave action are weak; consequently, the sediments are mostly fine-grained and porosity is low. Pellet-like features are the framework for fenestrae which are usually filled with microspar. Echinoids, pelecypods, foraminifera, ostracodes, and gastropods contribute skeletal material. Some elongated grains are parallel oriented.

The lagoonal facies, a low energy environment, is represented by sample I-280 (Plate I, Fig. 2). It is a speckled, compacted marl made up of terrigenous sand and marine fine-sand and silt fractions which form a micritic matrix of low porosity. Skeletons of reef dwellers are represented in this facies but in a broken and abraded condition which indicates postmortem transport. A foraminiferal assemblage consisting of the biserial form Bolivina and several small miliolid and rotaliid species occurs here along with various pelecypods.

The back reef facies represented by I-256 is another low energy, low porosity area (Plate I, Fig. 3). It consists of medium to fine sand with an average grain size of 0.2 to 0.4 mm. Grains are generally subrounded and material is fairly well sorted and packed. Grains are made up of skeletal debris derived from reef fauna and flora. Halimeda and articulated coralline algae are represented while the foraminiferal fauna consists of miliolids, *Amphistegina*, *Amphisorus* and *Marginopora*. Bryozoans, gastropods, ostracodes, and pelecypods are also present.

The *reef flat* facies is the region behind the reef edge across which the energy of the surf is dissipated. Consequently, the degree of sorting varies from poorly sorted directly behind the reef edge to fairly well-sorted in the back reef region. The average grain size is coarse to medium sand (0.5-1.5 mm) and grains tend to exhibit early stages of rounding. *Amphistegina*, *Amphisorus*, *Marginopora*, *Heterostegina*, miliolids, and smaller rotaliids are the primary foraminifera. *Halimeda*, articulated coralline algae, and encrusting algae as well as echinoids, mollusks, and ostracodes may also be present. This facies was identified from I-170, 240-12, 265-2 a/b, 265-15, and III-66-14, 119-32, 280 (Plate I, Fig. 4).

The *reef edge* facies is represented by sections III-56.5-7 a/b (Plate I, Fig. 5). This is the highest energy environment which receives the full force of the surf. Encrusting foraminifera and algae, *Halimeda*, *Amphisorus*, and *Marginopora* are the diagnostic fauna and flora. The material is poorly sorted (0.1-4 mm) without any visible orientation. The grains are angular and porosity is usually >40%.

The *beach* facies was identified from sections I-210-4, 215-10, 224-7, and III-114, 119-17, 240, 245-11, 255-6

PLATE I

MICROPHOTOGRAPHS OF DIFFERENT FACIES.

Figure

1. Tidal-flat facies of fine-grained sediments. A vug is visible in lower right corner. x62. I-180-2.

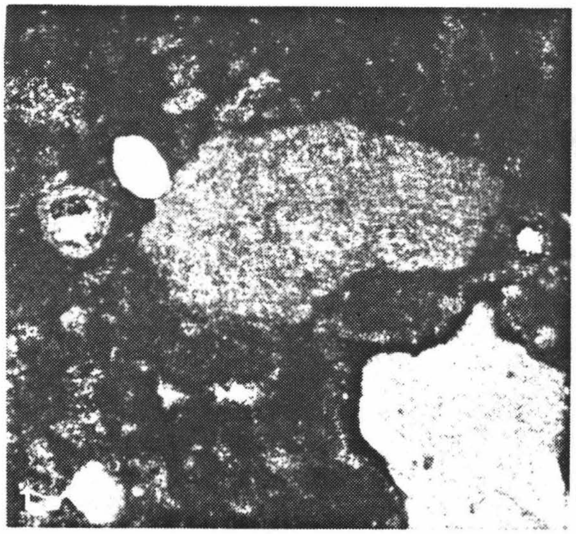
2. Lagoon facies in which the fine sediments act as a diagenetic seal protecting aragonitic material. x39. I-280.

3. Back-reef facies consisting of fine sediments of biogenic and terrigenous origin. x50. I-256.

4. Reef-flat facies composed of large species of foraminifera: *Amphisorus* and *Amphistegina*. x39. I-240-12.

5. Reef-edge facies showing poorly sorted sediments and infilled shells. x39. III-56.5-7.

6. Beach facies composed of fairly well-sorted grains of biogenic and terrigenous origin. x39. III-114.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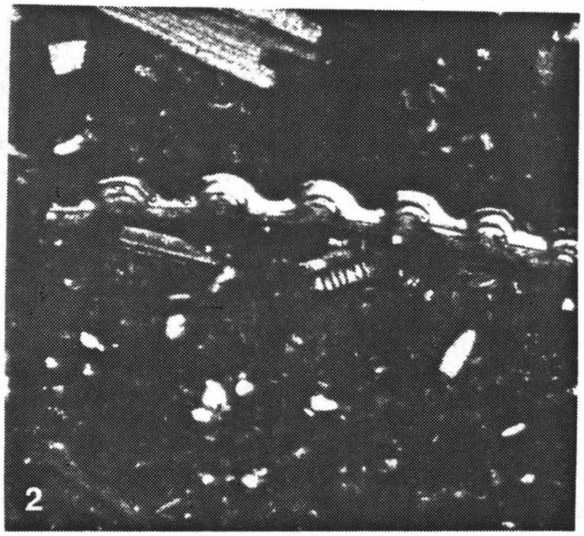
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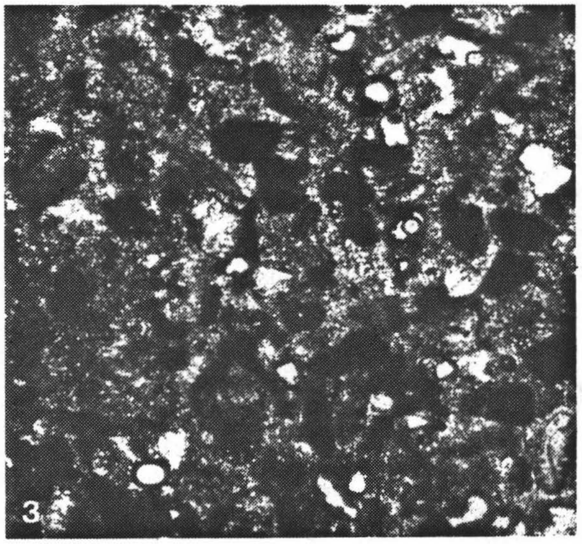
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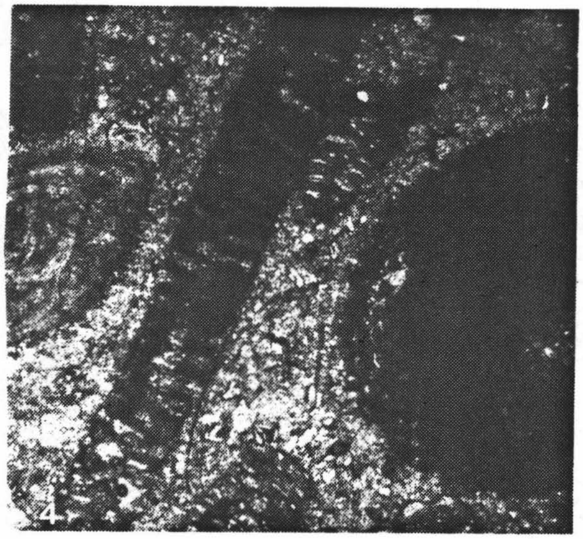
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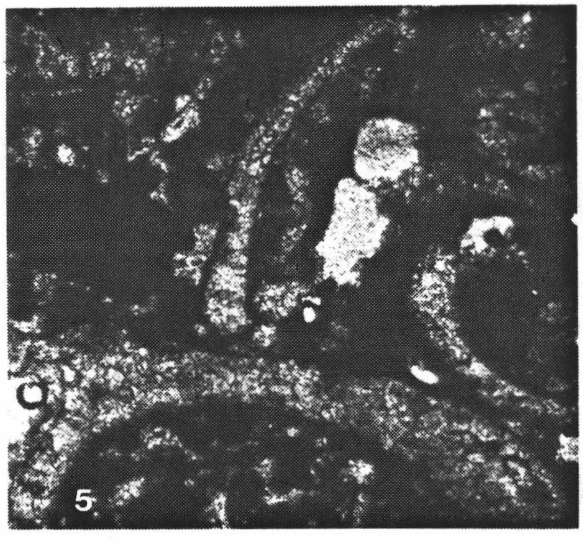
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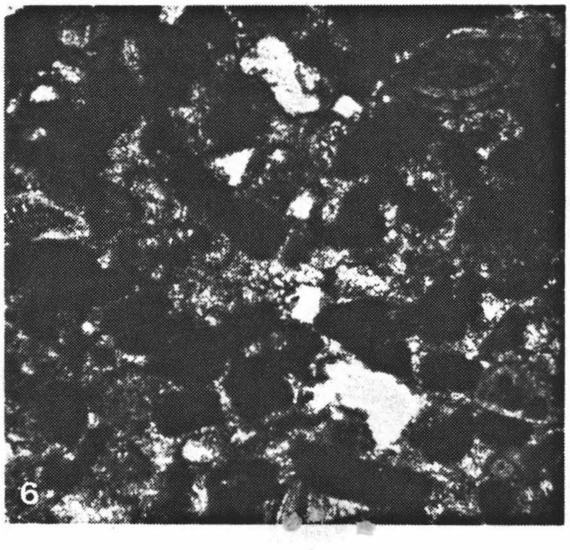
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PLATE II

DUNE FACIES AND DIAGENETIC FEATURES.

Figure

1. Dune facies showing rounded sediment grains derived from reef and altered isopachous cement fringes. x50. I-111-9.

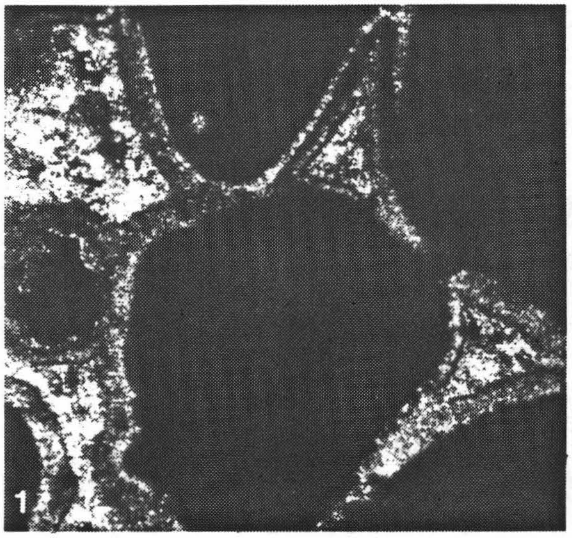
2. Closeup of isopachous fringe ghosts (above). x200. Crossed polars. I-111-9.

3. Three cement generations. x62. I-111-9.

4. Neomorphic pseudospar cement and poorly developed micritic envelopes. x157. III-101-17.

5. Mature micritic envelope development and moldic porosity. x39. III-119-32.

6. <u>Halimeda</u> plates in two different states of preservation. Plate on left shows the structures of internal cannels while plate on right shows no internal structures. x39. III-56.5-7.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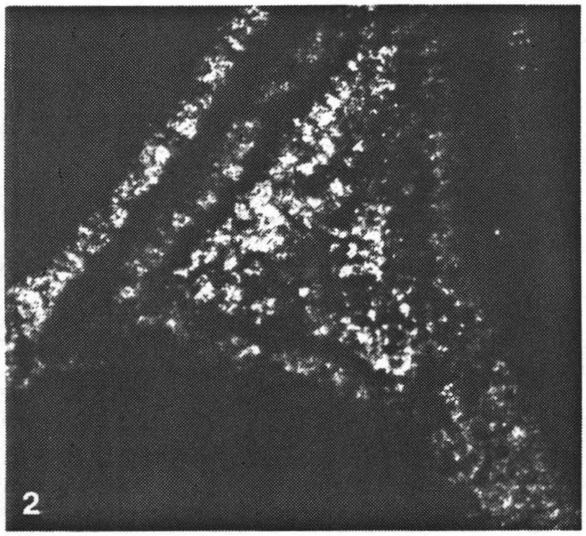
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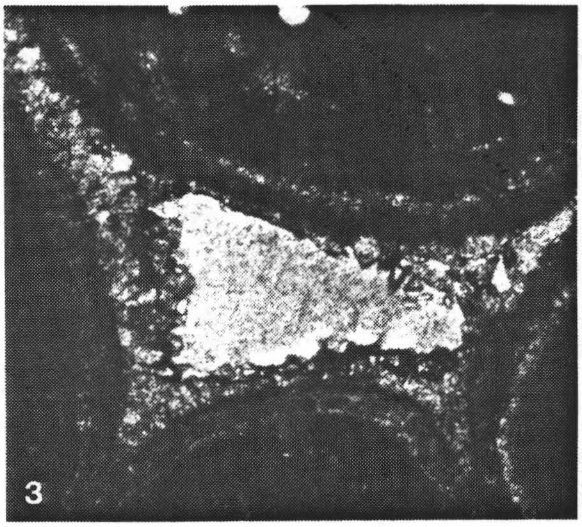
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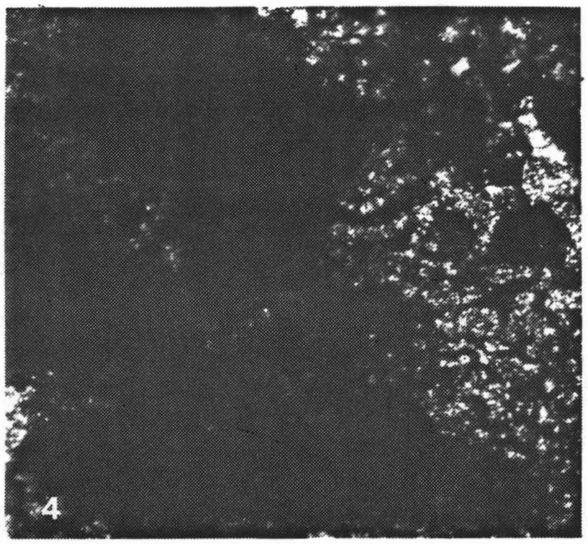
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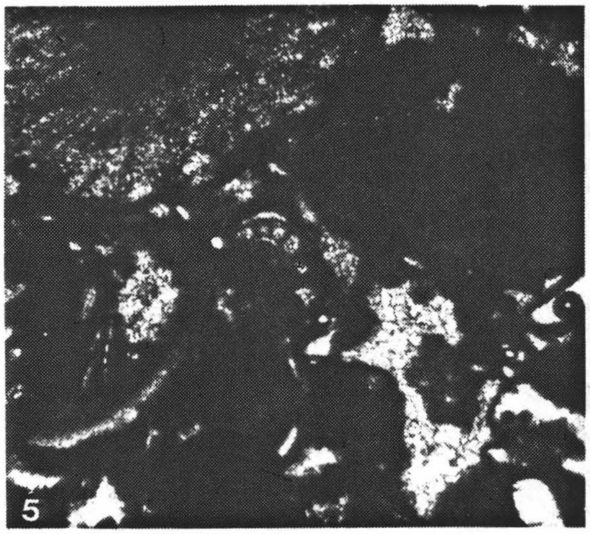
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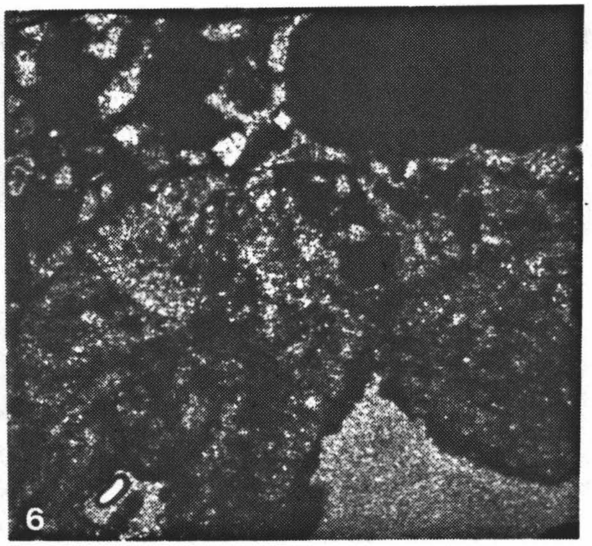
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PLATE III

DIAGENETIC FEATURES.

Figure

1. Scanning electron micrograph of endolithic algae, both filamentous and larger unicellular. x495. I-225-11.

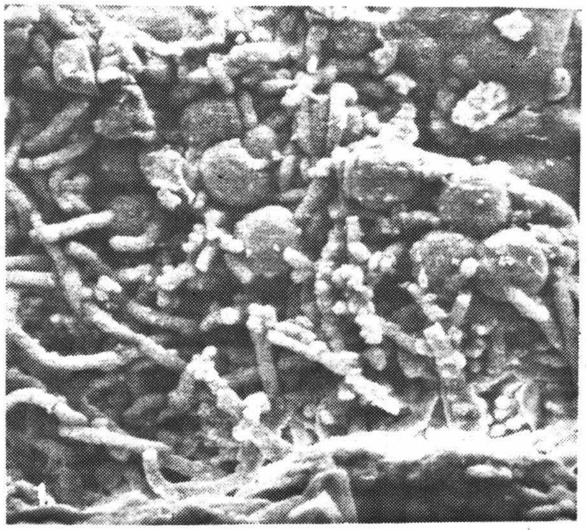
2. Enlargement of a section of Fig. 1 (above) showing endolithic algae coated with the clay mineral corrensite. x950. I-225-11.

3. Calcitization of a mollusk shell fragment. x157. III-56.5-7.

4. Microphotograph showing fibrous calcite after aragonite. x62. Crossed polar. I-180-2.

5. Geode-like encrustations showing several cementing episodes. x39. I-224-7.

6. Microphotograph showing various cement types. x39. I-170:
    1. drusy cement inside circular feature.
    2. blocky spar cement as pore filling.
    3. bladded cement rims.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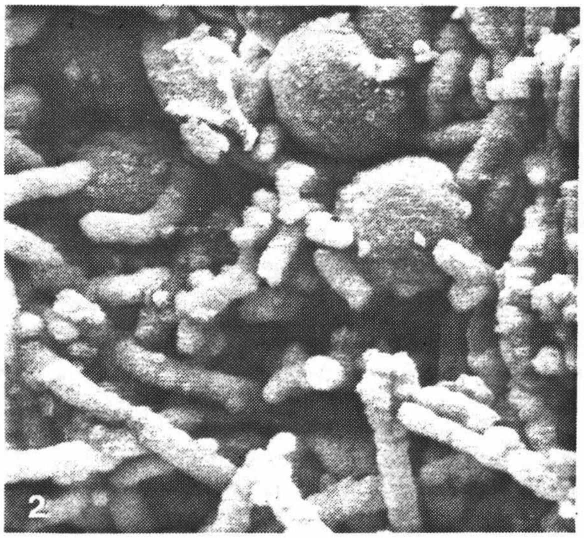
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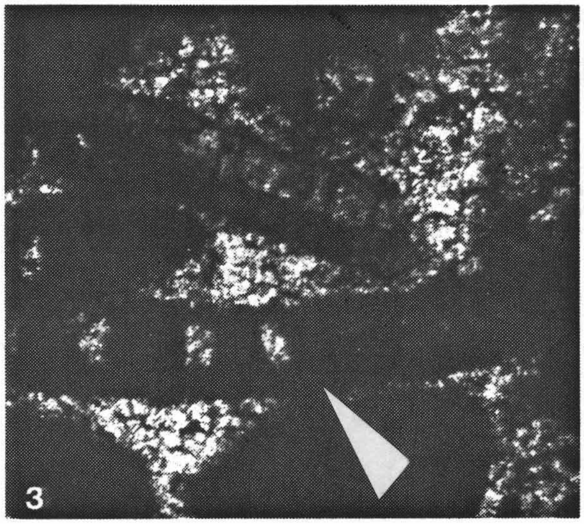
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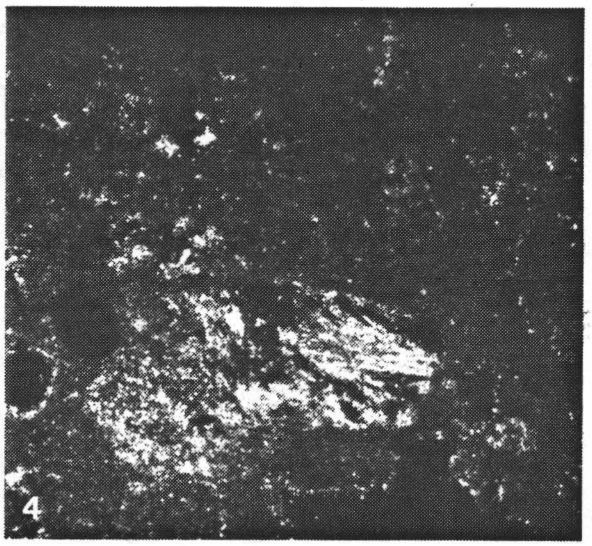
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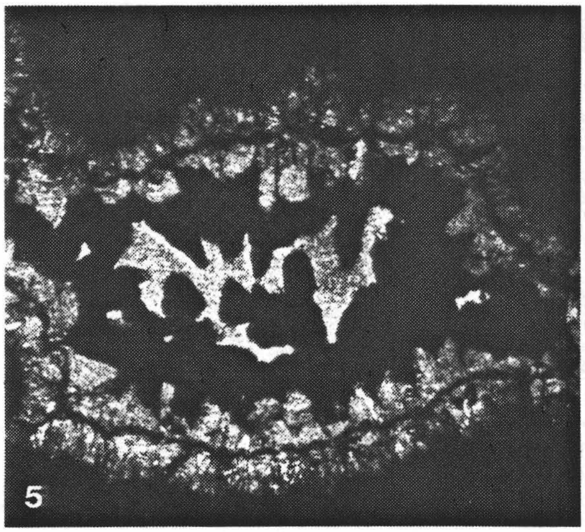
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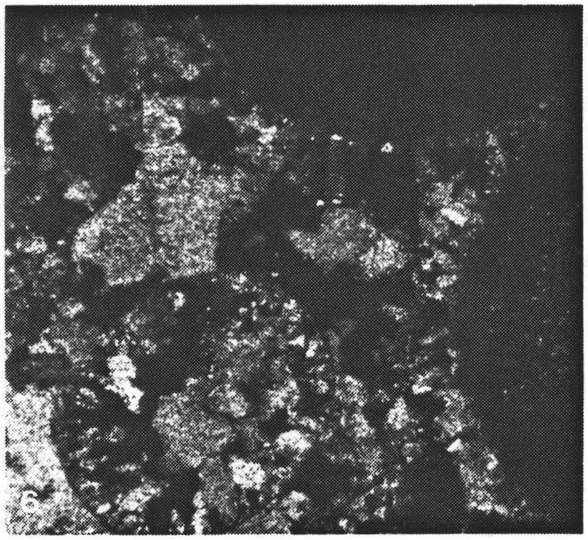
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PLATE IV

CATHODLUMINESCENCE, THE CLAY MINERAL-CORRENSITE, VARIOUS CEMENT CRYSTAL SHAPES.

Figure

1. Scanning electron micrograph of cement. x900. I-126.

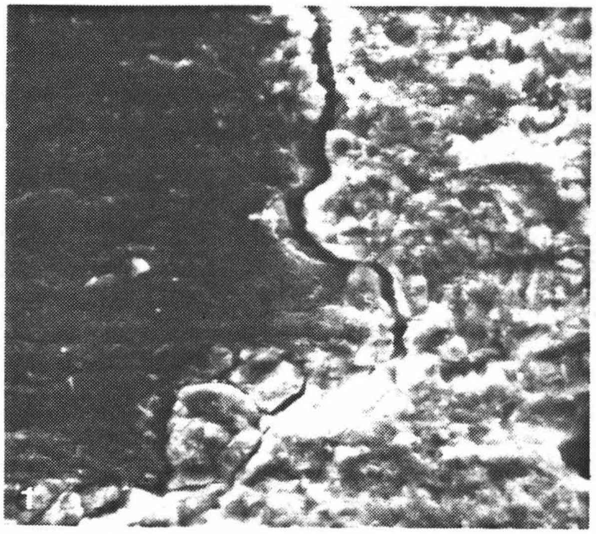
2. Scanning electron micrograph of cement viewed with the aid of cathodluminescence. One cementing episode is visible. x900. I-126.

3. Scanning electron micrograph of the clay mineral corrensite. x10K. I-224-7.

4. Scanning electron micrograph of dog-tooth spar cement crystals. x1K. I-225-11.

5. Scanning electron micrograph of crystals of blocky spar cement. x930. I-150-10.

6. Scanning electron micrograph of micritic crystals forming on a mollusk shell fragment. x1025. I-210-4.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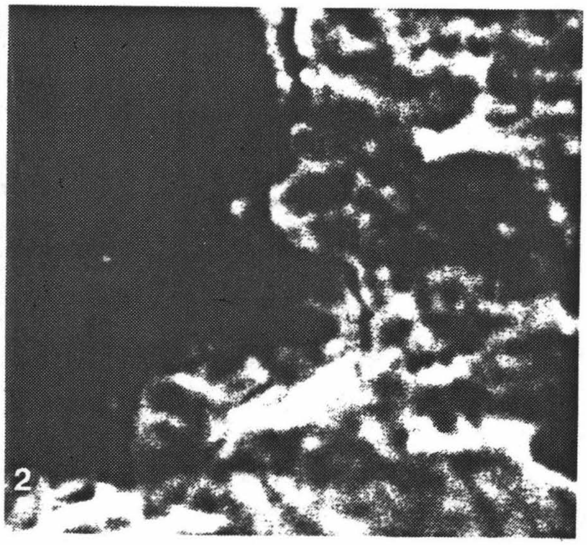
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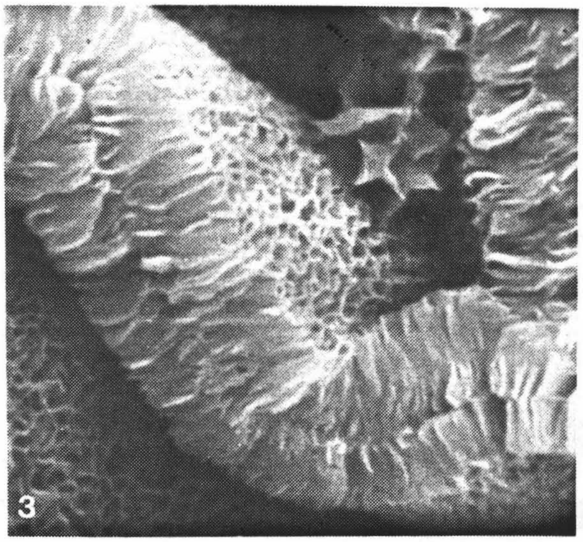
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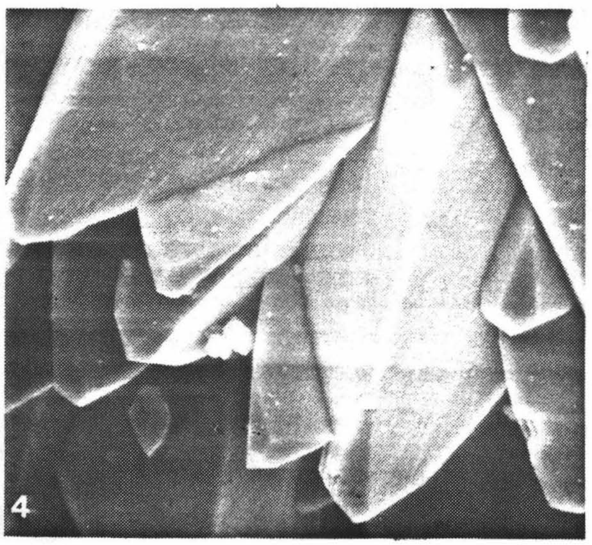
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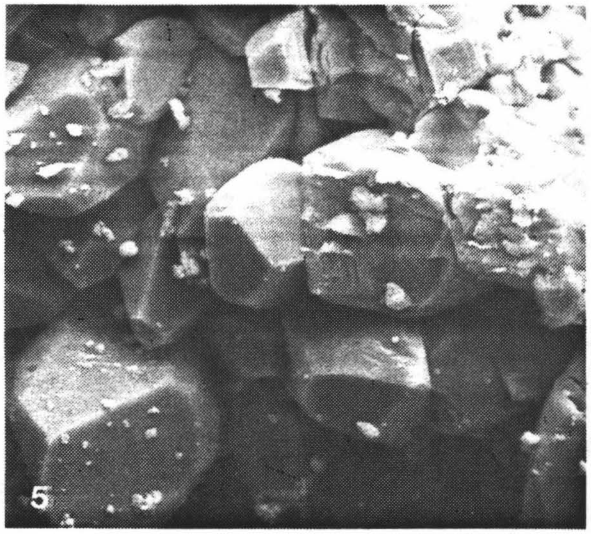
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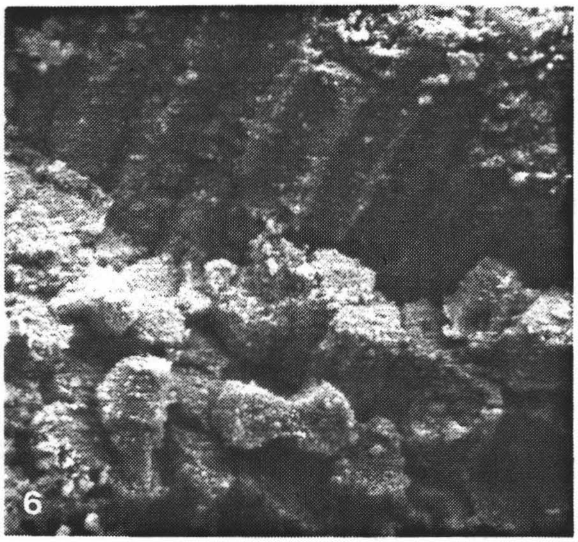
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Table III

Summary Diagram of the Diagenetic Processes and Products Showing Relative Importance with Depth. **

PROCESS AND/OR PRODUCT ** THIN SECTION	Isopachous rims	Sediment infilling	Micritic envelopes	Dissolved aragonite	Neomorphic spar cement	Equant cement rims	Calcitization	Aragonite neomorphism	Medium/coarse cement	Syntaxial overgrowths	Fractures	Clays	Primary porosity	Moldic porosity	Vugs	Vug infilling
DH III																
56-07		X	X	X			X	X					X	X		
66-14			X				X	X				X	?	X	X	X
76-09			X	X	X		X	X				X	X	X		
101-17			X	X	X			X				X	X	X		
114			X	X	X		X	X	X	X			?	X	X	X
119-17			X	X	X	X	X		*	X			X	X	X	X
119-32			*	X	X		?	X	X					*	-	
240				?	X			X				-		X		
245-11			X	X	X		?	-					X	X		
255-6			X	X	X		?		X		*	X		X	X	X
280			X	X	X	X	X		*	X				X	X	X
DH I																
111-09	*		X	X	X	X			X					X	X	X
124			X	X	X	X			-	X				X	X	X
126			X	X	X	X			-	X			?	X	X	-
147-05			X		X			X						X	-	
170	X		X	X	X	X			*				?	X	X	X
180-02				X	X		?	*	X					X		
210-04	X	X	-	X	X	X			*			X		X	X	X
215-10	-		X	X	X	X	X	?	X	X		X		X	X	X
224-07	X	X	X	X	X	X			*			X		X	X	X
240-12			X	X	X	X	X	X	X					X	X	X
256			X	X	X	X	X	?				X		X	X	
265-02			X	X	X	X	X	X	X					X	X	-
265-15			X	X	X	X	X	?	X	X				X	X	-
280			X	-	X		?					X		X	X	

**

rare -   common x   abundant *   questionable ?

(Plate I, Fig. 6). The grains are generally rounded and are either derived from the reef or have a terrigenous origin. Terrigenous grains of similar composition will often have two distinct shapes, rounded and angular, reflecting residence time in the marine environment. The degree of sorting and grain size are a function of the wave-energy level of the beach. Porosity is usually high. Laminations may be present. The biota are reef derived and primarily reflect the reef facies directly seaward of the beach.

Dunes, as identified by sections I-111-9, 124, 126, and III-76-9, 101-17, are well sorted deposits of rounded to subangular grains (Plate II, Fig. 1). Grain size is limited by the carrying capacity of the wind so no grains are larger than 2 mm in diameter (Pottratz, 1968). Porosity is high and some grains are aligned. As with the beach material, grains are derived from the same two sources.

Diagenesis

Many parts of the cores (Fig. 3) and all samples thin-sectioned contain evidence of post-depositional alteration. Neomorphism and cementation are the primary diagenetic features (Table III). Diagenesis has taken place under marine phreatic, meteoric phreatic, and possibly vadose conditions.

Marine diagenesis consists of submarine cementation, borings and internal sediment infilling. It has resulted in partial destruction of primary inter- and intraparticle porosity.

In most cases, isopachous fibrous aragonite and micritic Mg-calcite cements were originally formed. Intercrystal boundaries of isopachous cement fringe are still visible in a few places despite the alteration of aragonite to calcite (Plate II, Fig. 3). Micritic Mg-calcite cements were more common earlier in the diagenetic process as evidenced by the prevalence of microspar, the neomorph of micrite (Tucker, 1981; Plate II, Fig. 4).

The infilling of borings of many skeletal fragments by blue-green algae has formed dark micritic envelopes around the grains. Thin section III-119-32 contains grains with exceptionally well developed micritic envelopes (Plate II, Fig. 5). Aragonite appears to be preferentially attacked by the boring algae for these grains have mature envelopes while many of the calcite grains do not. Both filamentous and larger unicellular endolithic algae were identified, yet the borings were not seen (Margolis and Rex, 1971; Plate III, Fig. 1, 2).

Internal sediment infilling, possibly early post-depositional, is noticeable in the higher-energy environments, reef edge, and beach. The sediment consists of medium to fine-sized skeletal and terrigenous material (Plate I, Fig. 5).

Meteoric phreatic diagenesis has lead to preferential dissolution of aragonitic material, including cement, Halimeda plates, coral and mollusk debris, and to neomorphism. Calcitic blocky, drusy and dog-tooth spar cements were precipitated which occluded any remaining primary porosity.

The multigeneration fringe cement of I-111-9 consists of two rim generations: an older cement rim which is translucent and thin, and a cloudy, thick, younger rim (Plate II, Fig. 2). The older rim, found on about 30% of the skeletal grains, has been recrystallized to blocky spar cement and appears to be meniscus-like in parts of the thin-section. The younger rim is found growing on the older rim, or more commonly, directly on skeletal grains. It appears to be at least twice as thick as the older rim. A third cement generation is present as blocky, interparticle spar. Grains with cement rims are most often found in dune and beach rock.

Formerly aragonitic Halimeda plates were found in various stages of preservation indirectly related to degree of envelope development. Internal canals and plate outlines were well defined where surrounded by a thick micritic envelope, whereas only the plate boundries were preserved where the envelope was thin. In several instances, well-preserved and poorly-preserved plates were found in the same sample (Plate II, Fig. 6).

Blocky spar-filled molds of coral and mollusk fragments were seen throughout the cores. No original coral material was found. However, altering fibrous aragonitic pelecypod shell fragments were still visible in the fine-grained sediments of I-256 and 280 (Plate I, Fig. 2). Fibrous pelecypod shell material is found in I-180-2; this is neomorphic calcite after aragonite--according to the evidence presented by Bathrust (1975) the entire section has been neomorphically altered (Plate III, Fig. 4). Calcitization of pelecypod shell fragments is seen throughout the material (Plate III, Fig. 3).

Precipitation of calcitic spar cement, as dog-tooth, blocky, or drusy cement, is evidence of exposure of the section to circulating meteoric pore water saturated with respect to $CaCO_3$. Crystal size is a function of space available for growth and rate of fluid flow through the pores (Bathrust, 1975; Tucker, 1981). Large crystals of dog-tooth spar cement are found in large, open areas while drusy and blocky cements are found in more confined spaces (Plate III, Fig. 6; Plate IV , Fig. 4-6). Thin section I-224-7 contains cavities that have been incompletely filled with geode-like encrustations (Plate III, Fig. 5).

Under transmitted light, several generations of cement are visible in many of the samples. Cathodluminescence analysis of the thin sections did not reveal any additional episodes of cementation (Plate IV , Fig. 1, 2).

All primary inter- and intraparticle porosity can be occluded by meteoric phreatic diagenesis. Micron-size intercrystal porosity most likely exists, but is very difficult to determine.

Meteoric waters in a solution zone, i.e. undersaturated with respect to $CaCO_3$, have selectively leached aragonitic grains developing secondary moldic porosity (Plate II, Fig. 5). Vuggy porosity is also present and is the result of solution enlargement of original interparticle and secondary moldic porosities. Whether this took place under vadose or phreatic conditions is open to conjecture. Longman (1980) suggests that evidence of neomorphic activity indicates meteroic phreatic conditions, while extensive leaching of aragonite suggests vadose conditions.

Paleontology

Foraminifera

One hundred and fifty-five species of foraminifera were identified in 34 samples: 9 were from DH III and 25 were from DH I (Table I). All species are reported from Recent Pacific collections.

The most common species found in 12 or more samples are: *Ammonia beccarii tepida*, *Amphistegina lessonii*, *Bolivina compacta*, *B. limbata*, *B. striatula*, *Cibicides lobatulus*, *Cymbaloporetta bradyi*, *C. squammosa*, *Fijiella simplex*, *Quinqueloculina polygona*, *Siphogenerina costata* and *Trifarina* sp. (new species). The original descriptions and authorship of the foraminiferal species are found in Ellis and Messina (1940 and supplements).

Two genera were found in more than 25% of the samples. These are the reef-dwelling genus *Amphistegina* which makes up 20% or more of 11 of the 22 samples in which it is found and the biserial genus *Bolivina* which comprises more than 20% of the population in 8 of the 31 samples in which it is found (Table I).

Two species of *Amphistegina* were identified. *A. lessonii* found in 21 samples is by far the most common. It generally lives attached to algae or other substrate in water between 5 and 20 meters deep (Muller, 1977). *Amphistegina lobifera*, found in 11 samples, has a thicker, more rounded test. It generally lives attached to algae in waters of 5 meters or less (Muller, 1977).

Eight species of *Bolivina* were found of which three, *B. limbata*, *B. striatula* and *B. compacta*, are abundant. This genus lives on muddy sediment.

TABLE IV
Percent OSTRACODE Species.

* SPECIES * * * SAMPLES *	Loxoconcha spp.	L. Longespina	Aurila sp.	Xestolebris sp.	Neocaudites sp.	Cyprideis beaconensis	Loxoconchella sp.	Urocytheresis sp.	Radimella sp.	Neonesidia sp.	Paracytheridea sp.	Hermanites sp.	Caudites	Callistcythere sp.	Bairdia sp.	Munseyella sp.	Cythera sp.	Paradoxistome sp.	Indeterminate genera	Number counted
DH I																				
25-4																				0
43										100										18
55-10	77										23									13
70	80					5					2	13								60
220-41																				0
225-48													100							32
270-12	3			32				41			1			20	1	3				79
270-52	30			65		x					3					2				296
280-35	5		11	62							8		18							202
288-67a																				0
*288-67b	100																			57
*300-8	71			18		11														17
310																				0
*340	97			3																79
*340-39	80			14													5			82
380-39					100															1
*380-101	7			87														5		40
390-44	38	24		31							7									29
400-81	100																			3
420	100																			128
430	100																			1
430-16						100														1
440-39a																				0
440-39b	90					10														42
450	37					63														1502
DH III																				
255-6	24								10										66	116
260-10	23							77												104
270-19	100																			2
299				50			50													10
299-57	27		4	69																55
*299-92						100														97
310	33		2	62	3															488
320-12	100																			24
330	100																			28

x < 1%   * complete carapaces recovered

Other Fossils

Ostracoda. Eighteen genera of ostracodes were identified (Holden, 1976; Table IV). The most common genera are *Loxoconcha* and *Xestolebris*. Hazel (in Resig, 1969) considered these genera to be indicative of brackish to normal marine environments. *Cyprideis beaconensis* (LeRoy), a brackish water species, is important only in samples I-450 and III-299-92.

Gastropoda. Twenty kinds of gastropods were identified in 11 shallower-water samples of DH I (Table VII). The shells were broken, recrystalized or badly abraded, making identification difficult. Pteropod shells were localized in the deeper lagoon sediments.

Miscellaneous Fossils. Remains of organisms of the phyla Porifera, Bryozoa, Echinodermata, Coelenterata, Mollusca, Arthropoda, and Vertebrata were found in the cores (Table I). Triradiate sponge spicules of two different sizes occurred in the shallow water samples. Bryozoans tended to follow the same distribution pattern as the sponge spicules. Multiradiate holothurian sclerites were found in sediments of all the different environments, as were echinoid spines; however, echinoid spines were found in twice as many samples. Coral fragments were seldom identified but occurred in both shallow and deeper water samples.

Pelecypod shell fragments, mostly too broken to be identified, were found in fine-grained sediments. Two species were identified: Anomia nobilis Linne' and Pinna muricata Reeve. P. muricata lives in soft, silty sand from tide-pool depth to 100 m (Kay, 1979). A. nobilis is a fouling organism that lives clustered and attached (Kay, 1979). These species were found between 127 and 130 m and at 134 m in DH I, and at 100 m in DH II.

Teeth of predatory fish were found in the deeper lagoon sediments. A terrigenous deposit at 88 m in DH I contained an unidentified tooth.

Barnacles occurred in association with pelecypod shell fragments at 125 and 134 m in the finer sediments. Resig (1969) reported a concentration of barnacles in Ewa I at 318 ft (97 m) in what was thought to be a coastal accumulation of debris.

Geochronology

Amino Acid Racimization

The D/L ratios for the Pinna (82-38) and Anomia (82-40) samples from the 125-128 m level of DH I are found in Table V along with the ratios for other pelecypods from Oahu. The ratios for the Waimanalo samples are nearly racemic, i.e. equal to one. Consequently, the results cannot be directly interpreted as age indicative without considering

Table V

D/L Values for the Amino Acid Leucine for Waimanalo Samples *

Sample Location	Genus	Sample Number	D/L leucine	Age (Ka)
Kaneohe Bay, Oahu	*Pinna muricata*	82-36	.04	0
I-420-63	same	82-38	.94	?
I-416-32	*Anomia nobilis*	82-40	.87	?
Nanakuli, Oahu	*Periglypta reticulata*	83-42	.69	120
Black Pt. Oahu	same	83-43	.27	114
Kaena Pt. Oahu	same	83-44	.20	600
Black Pt. beach	same	83-46	.00	0

* Analyses performed by J.F. Wehmiller in 1982, 1983.

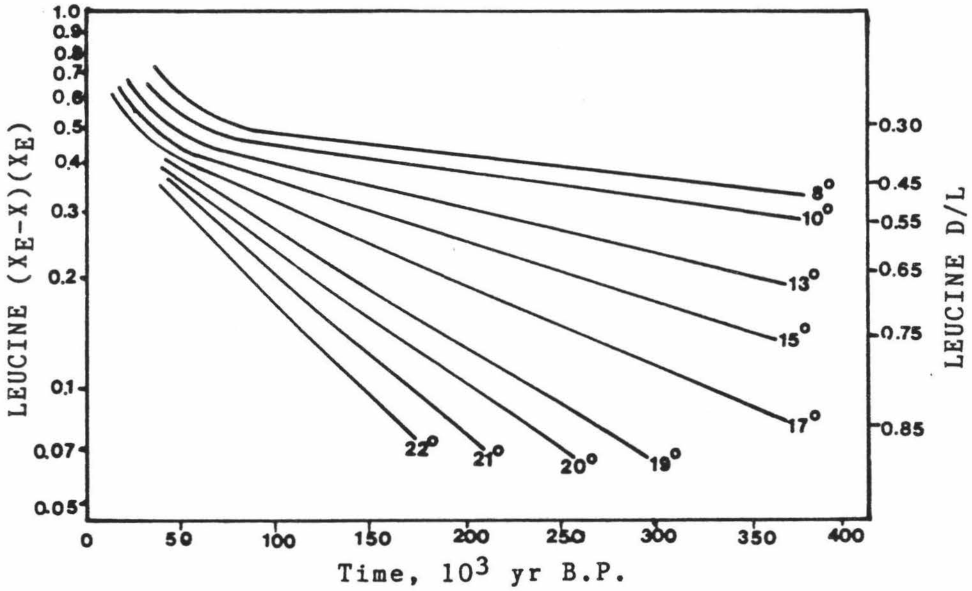


Figure 6. Nonlinear Leucine Kinetic Model modified slightly from that of Belknap (1979) as found in Wehmiller and Belknap (1982).

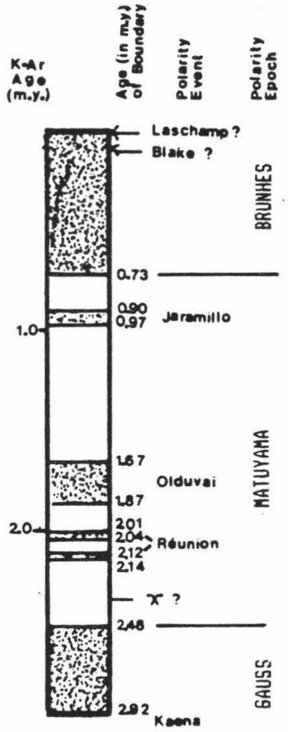


Figure 7. Late Cenozoic Polarity Time Scale. Stippled pattern indicates periods of normal polarity. Arrows indicate possible brief polarity events. (Mankinen and Dalrymple, 1979)

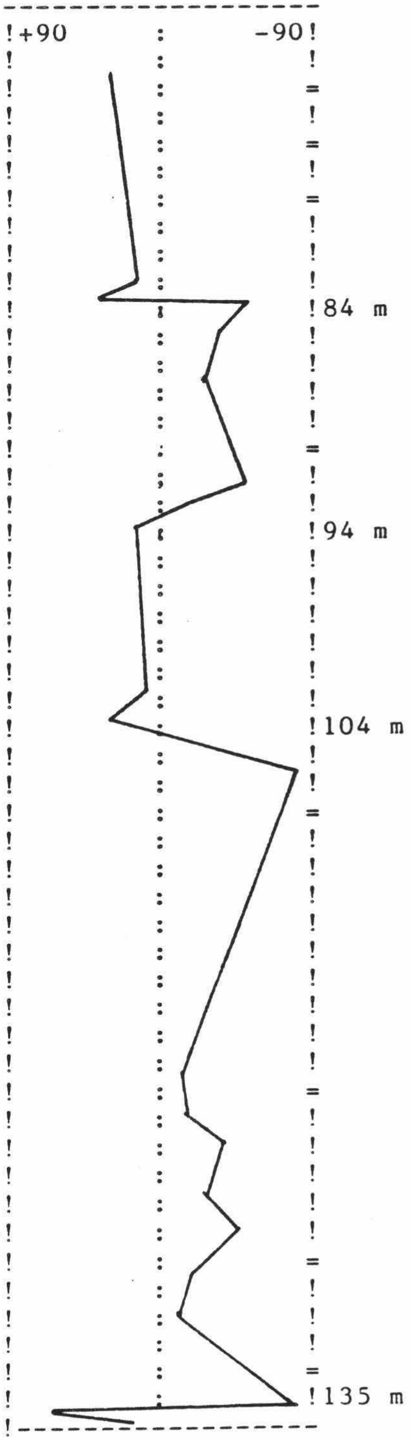


Figure 8. Paleomagnetic trace at 125 Oe in Drill Hole I.

the post shell-secretion thermal history to allow kinetic calculations to be made (Belknap and Wehmiller, 1980). An attempt to establish the thermal gradient for the region was made by determining the D/L ratios from samples of known age. Three mid-to-late Pleistocene Periglypta reticulata (Linne') samples were analyzed. The D/L values for two of the samples (Black Point 83-43 and Kaena Point 83-44) were unreasonably low (Table V). These samples come from the surface of outcrops that have been exposed for long periods of time. Only the Nanakuli Sea Cliff sample (83-42), which is from a recently exposed part of a emerged reef, gave reasonable D/L values. Sample 83-46 collected as beach rubble at Black Point, Oahu, was analyzed and found to be modern.

Dr. J.F. Wehmiller (personal communication) suggested a procedure in which age of formation and D/L value of sample 83-42 can be used to arrive at a thermal gradient. The D/L value of 0.69 of sample 83-42 fixed to an age of 120,000 years applied to the leucine kinetic model (Fig. 6) establishes an effective kinetic pathway for the region. Providing the other samples have a similar rate of racimization and similar thermal histories, extrapolation of this kinetic pathway to the greater D/L values of samples 82-40 and 82-38 allows age estimates to be made. These calculations suggest an age of no younger than 200,000 years for material at the 128 m level of DH I.

Paleomagnetism

Paleomagnetic results obtained from the cores are presented in Fig. 8 in which the inclination of 26 samples demagnetized to 125 Oe (AF 125) is recorded. The top of the section is normally magnetized. The paleomagnetic trace is concise, with reversals of the earth's magnetic field at 84, 94, 104 and 135 meters in DH I. The optimal level of demagnetization is considered to be 125 Oe, for most of these samples appear to have magnetically stabilized at this point.

IV. DISCUSSION

Criteria for Evaluating Paleoenvironments

An environment is a geographically restricted complex. It is characterized by physical, chemical and biological conditions, influences, or forces (Bates and Jackson, 1980).

Sediments

In general, the energy level at the site of deposition determines the grain-size of the sediment with wave base as the paramount factor (Pettijohn, 1975). Sand-sized and larger sediments (65-85% fraction of Fig. 3) are deposited above wave base in a turbulent environment while silt/clay -sized sediments (<20%) indicate deposition below wave base in a relatively quiet or still water environment.

Based on this fact, that energy level at the site of deposition determines the grain-size of the sediment, and according to sediment patterns prevalent on the windward side of a subtropical island (Inman et al., 1963; Coulbourn, 1971), each of the fields in Fig. 4 can be assigned to a facies. The first field of fine sediment, with a low $CaCO_3$ content, describes an area in a lagoon that is close to a stream mouth. Quiet waters of a lagoon or back-reef area are suggested by the second field of fine sediment and a moderate $CaCO_3$ content. A moderate energy reef-flat is appropriate for the third field of coarse sediment also a moderate $CaCO_3$ content, and a higher energy environment such as a beach is a likely explanation for the fourth field of coarse sediment which has a high $CaCO_3$ content.

An interpretation of the depositional environments of the reef is presented in Fig. 5, in which assumed facies have been indicated between core sites. The back-reef facies preceds both beach facies. If beach is to be deposited on top of reef as depicted, a slight regression depositing back-reef over reef-flat sediments is required. Then the shoreline slowly transgresses depositing beach sediments over back-reef. Back-reef deposits are also shown separating tidal-flats from reef-flats. This is reasonable when the energy dissipation necessary to create a tidal-flat is considered.

The basaltic beach rock found between 62 and 69 m in DH I is a combination of a gray to black basaltic sand sandwiched between cream to light brown calcareous sand in the mid 3 m of the deposit. Basaltic beach rock is also reported in Ewa I hole at -197 ft (60 m) (Stearns and Chamberlain, 1967). Inman et al. (1963) reported the dominance of terrigenous sediments on the semi-arid lee side of Kauai. An extended period of arid weather conditions is a likely explanation for deposition of such a widespread stratigraphic horizon.

Cementation and neomorphism are end-members of a spectrum of processes which produce sediment lithification. The dissolution-precipitation which accompanies cementation differs only in degree (amount of space available for reaction) from that which accompanies the growth of neomorphic spar. Both processes are simultaneously active in meteoric phreatic environments. This may be the case for marine phreatic environments as well (Bathrust, 1975).

Neomorphism and calcitization are found throughout the cores but appear to be the primary lithification processes at work in the upper part of the cores. Spar cementation becomes important only below 30 m (Table III).

Fine-grained sediments show little evidence of submarine cementation unless they are located directly below a regressive deposit or within the reef itself. These sediments tend to act as a diagenetic seal. In either case, exposure to meteoric waters have selectively dissolved aragonitic material and subsequently deposited calcitic spar cements. Or, as in the case of I-180-2, neomorphism has been the primary lithification agent producing neomorphic calcite and pseudospar (Plate III, Fig. 4).

Primary porosity is mostly found above 34 m while moldic porosity is found throughout the cores. Vuggy porosity tends to begin where primary porosity ceases and is evidence of both calcitic and aragonitic solution when sediments were flushed by meteoric water as the sea withdrew.

A dusting of rust- and brown-colored clays is found within some of the cements and pore spaces which suggests a detrital origin. It is very close in appearance to the chlorit-smectite mixed-clay corrensite (Welton, 1984; Plate IV , Fig. 3). EDX analysis was not available for this study.

The lithologies suggest many sea level transitions which should be visible in thin section. However, Bathrust (1975) points out that once the rock has stabilized, i.e., consists of porous calcite, and if it is to become more fully cemented, then a further allochthonous source of $CaCO_3$ cement must exist.

Fossils

Bell (1976) used the measurable environmental parameters of substrate, salinity, temperature, dissolved O_2 phosphate concentration, and water depth to explain the population distribution and abundances of foraminifera in Kaneohe Bay, Oahu. He determined that the single most important environmental influence that controls distribution in that shallow embayment was that of sediment type (substrate). This is followed in importance by salinity and phosphate concentration--the remaining parameters were of little consequence for this area.

Several approaches can be taken to interpret paleoenvironments based on a comparison of fossil assemblages with modern ones. Murray (1973) developed techniques which generally involve analysis at the suborder or genus level, while Resig (1969) interpreted the fossil assemblages in light of the modern distribution of their species.

When the three suborders Textulariina, Miliolina and Rotaliina were plotted by Murray (1973) on a triangular diagram, strong groupings of the suborder ratios appeared according to the salinity of the environment. Data from fringing and barrier reefs and lagoons of Kaneohe Bay, Oahu (Bell, 1976) show a normal marine to slightly hypersaline regime. Data from a fossil reef at Nanakuli, Oahu, (Hagstrom, 1979), generally plots in the same manner as Murray's data for normal marine lagoons. The ratios for the Waimanalo samples fit well within the field for normal marine lagoons and hypersaline lagoons. The ratios of all four studies are compared in Fig. 9.

The Fisher Alpha Index, a function of the number of species (s in Fig. 10) versus the number of individuals, is another indicator for salinity in an environment (Murray,

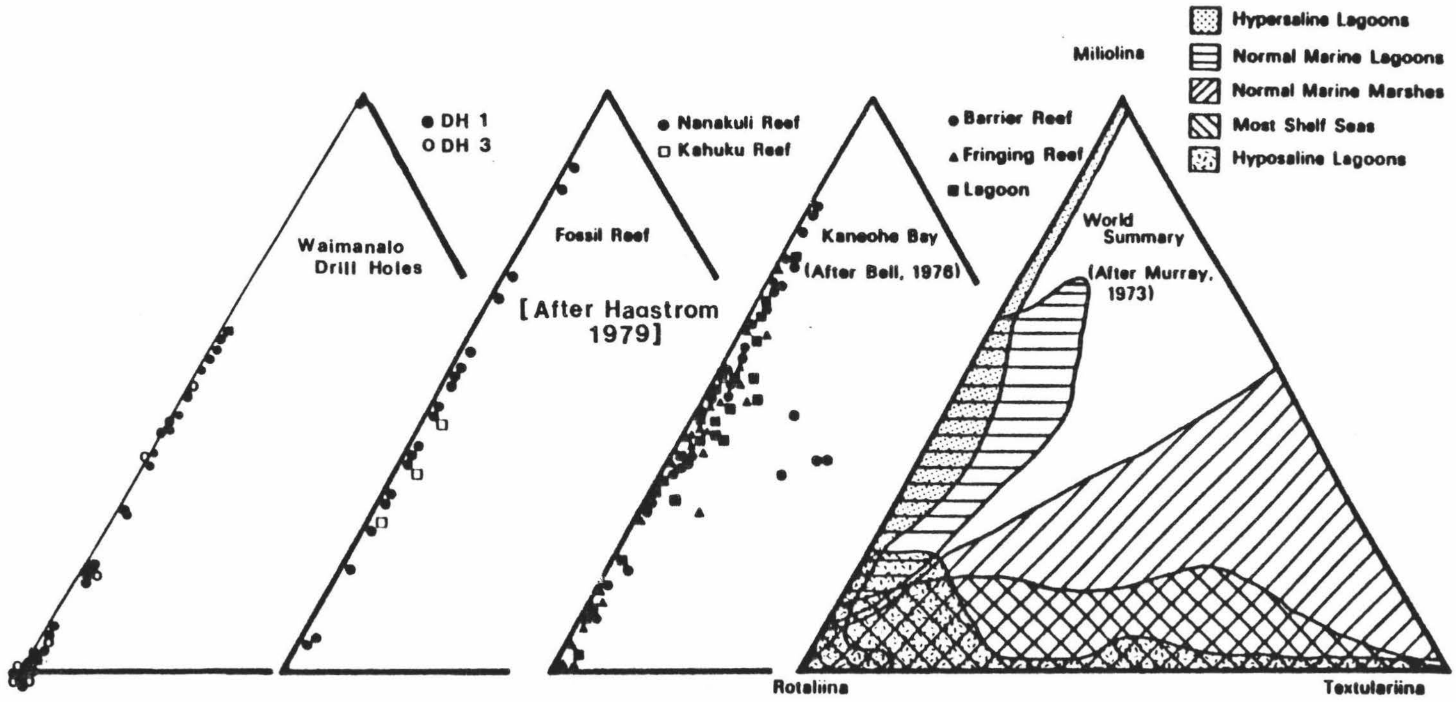


Figure 9. Triangular plots for sub-order ratios of Foraminifera.

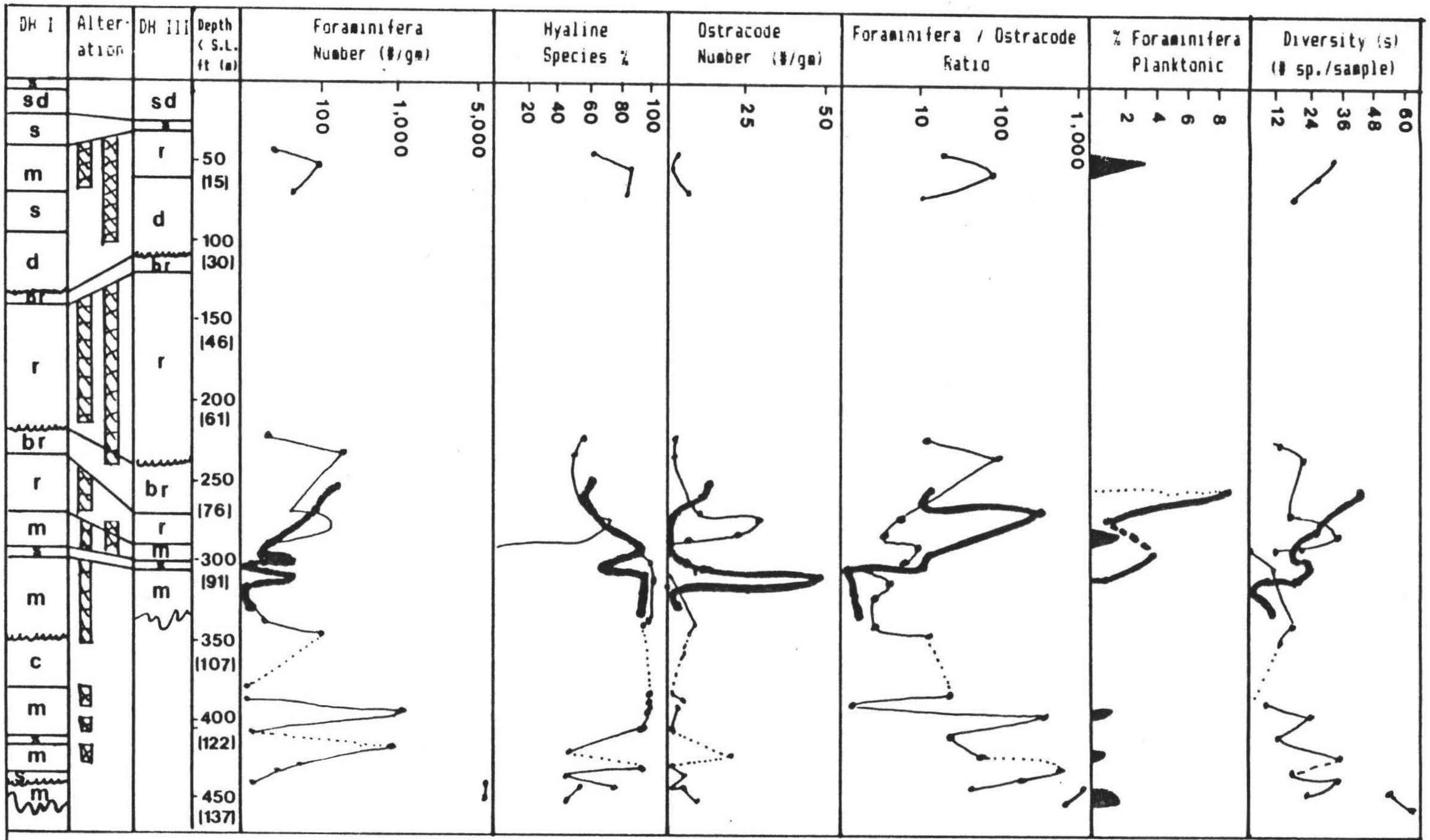


Figure 10. Waimanalo depositional analysis based on fauna.
Lithology m-marl, sd-sand, br-beachrock, s-soil,
c-conglomerate, d-dune sandstone, r-reef limestone.
▨ altered sediment ∿ unconformity — DH I — DH III

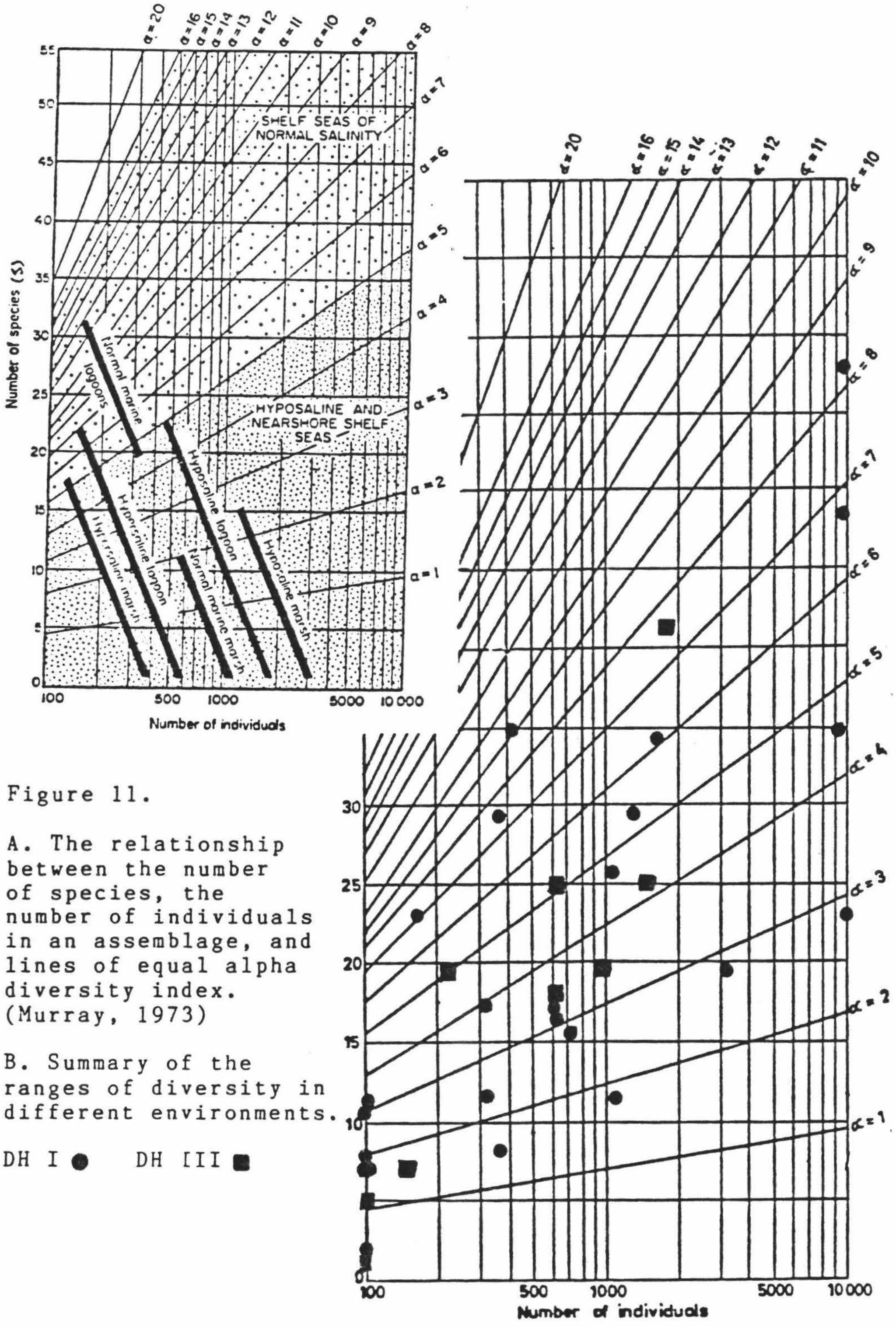


Figure 11.

A. The relationship between the number of species, the number of individuals in an assemblage, and lines of equal alpha diversity index. (Murray, 1973)

B. Summary of the ranges of diversity in different environments.

DH I ● DH III ■

1973). Assemblages from hypo- or hypersaline waters have alpha values less than five indicating low species diversity, while the values for normal marine waters are greater then five (Fig. 11). According to this system, 10 of 34 samples from the Waimanalo cores plot as normal marine while 24 samples indicate hypo- or hypersalinity environments. The conflicting interpretations derived from the two means of analysis may be due to the fact that only a fraction of the living assemblage is preserved in a fossil assemblage. This loss (due to predation or decompostion at the time of death or to solution, recrystalization, and possibly erosion at a later time) is obvious in altered sediments as evidenced by low abundance, the presence of fossil molds and casts, and the leached condition of many of the foraminiferal tests. This is a fossil assemblage that has been greatly affected by diagenesis. This demonstrates that the sensitivity of the three suborders technique is preserved in spite of post depositional alteration and is a more accurate tool in estimating the salinity of an ancient environment.

Foraminiferal abundance is usually given by foraminiferal number, the number of tests per gram of sediment (Fig. 10). Bell (1976) found that there was a tendency for abundance to be lower where bulk density of the sediment was high. Consequently, it was possible to distinguish between certain environments on the basis of abundance data. Coulbourn (1971) recognized abundance to be a function of grain size with fine-grain material having high abundance values (500-800) and coarse grain sediments having low values (<100). Hagstrom (1979) noted that abundance varied between different reef facies with the low energy reef-flat having values >70 and the higher energy reef-front and reef-edge having values <30. Low foraminiferal abundance (<50) in much of the Waimanalo section occurs in diagenetically altered deposits that are below regressive, terrigenous deposits. This suggests that diagenesis has modified the foraminiferal abundance typical of the various environments.

Three fields appear in the Waimanalo samples when abundance is plotted versus grain-size (%Sand) (Fig. 12). Fifteen of 23 samples plot within a low abundance field (<100), 4 samples fall into an intermediate field (100-400) and 4 more plot in a high abundance field (>950).

All three regions contain samples composed of both coarse and fine-grained material. One explanation for this pattern may be that the grain-size distinction at 63 microns is of little consequence. A better grain-size distinction would be between coarse, medium, and fine sand; then fine sands that should have higher foraminiferal abundance values would be separated from coarse sediments which should have lower values (Coulbourn, 1971).

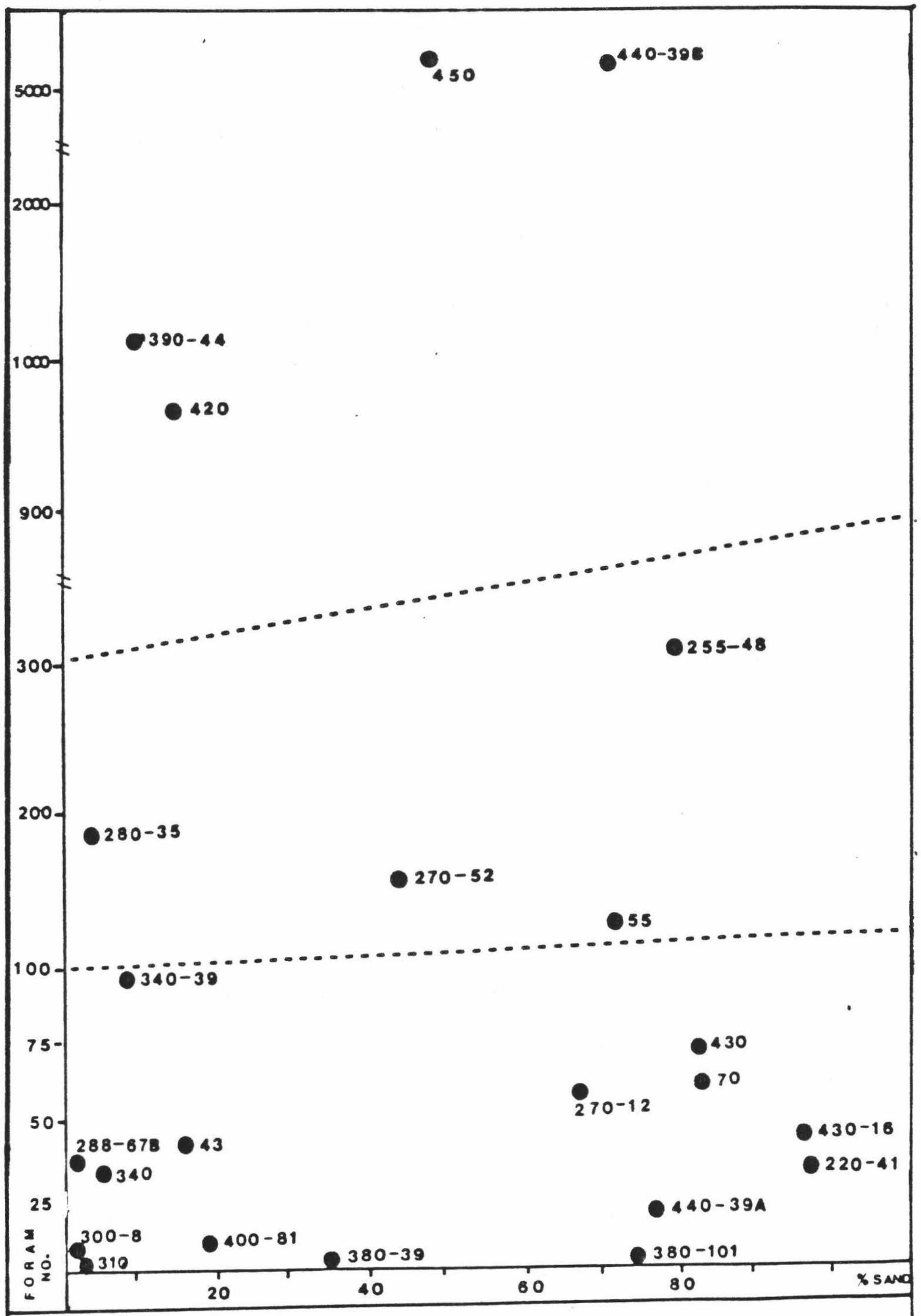


Figure 12. Foraminifera Number versus % Sand.

Diagnostic Species and Faunal Assemblages

A species is diagnostic of a particular province if it is restricted to that province and occurs in all samples within that province (Bell, 1976). This definition presents a problem when working with fossil assemblages. Diagenesis may destroy diagnostic species. The test construction of the species may be delicate and easily dissolved, or a particular section of the sediment pile may have experienced a more vigorous form of diagenesis destroying all fossils. In spite of these problems, certain species or combinations of species are important ecological markers. For the purpose of this study, a diagnostic foraminiferal assemblage is one in which the species selected are most characteristic of the total population of each facies.

Planktonic Foraminifera

The reef generally acts as an effective barrier inhibiting the movement of planktonic foraminifera towards shore. However, a few gain access to the area behind the reef through reef channels. Resig (1969) found this to be the case in near-shore sediments of Oahu where planktonic foraminifera composed 10-15% of the Recent fore-reef material sampled, whereas no planktonic foraminifera were found in samples taken from protected embayments. Since the planktonic foraminifera amounted to no more than 5% in any core sample from the Ewa plain, the presence of a barrier was implied.

In the Waimanalo cores, planktonic foraminifera were found in 10 samples (Table I). Sample III-255-6, a beach sediment, contained 9% planktonic foraminifera which implies the absence of a barrier or enlargement of a channel through the barrier. The remaining samples, containing <1% to 3% planktonic foraminifera, were deposited under lagoon conditions. When the percent frequency values are greater than 1%, as in I-43 and III-299, improved open-ocean circulation through channel development is suggested (Resig, 1969).

Benthonic Foraminifera

Ammonia beccarii tepida. This species is a euryhaline species usually found locally in association with *Elphidium* spp.. In Kaneohe Bay, it prefers fine sediment close to shore (Resig, 1969). It is found at all stream mouths, on the fringing reefs, and near springs in Kahana and Kaneohe Bays (Coulbourn, 1971; Bell, 1976). *Ammonia*, in high percentages, is considered diagnostic of brackish water. It is found in significant numbers in both drill holes at the reef/marl interface where it presumably signifies brackish shoaling water. It is found in fewer numbers below 125 m where it probably occurred in brackish water.

Table VI

Principal Species Representing the Various Biofacies from Five Studies on Oahu.

Resig, 1969 Ewa, Oahu	Coulbourn, 1971 Kahana Bay, Oahu	Bell, 1976 Kaneohe Bay, Oahu	Muller, 1977 Oahu beaches	This study, 1984 Waimanalo, Oahu
Reef *Heterostegine suborbicularis*, *Amphistegina madagascariensis*. Shallow Lagoon *Hauerina pacifica*, *Q. bosciana*, *Q. distorqueata*, *Spiroloculina communis*, *A. beccarii tepida*, *Q. poeyana*, *Hopkinsina pacifica*, *Bolivina striatula*, *Buliminella elegantissima*, *Tubinella funalis*. Brackish-Water *Cyprideis beaconensis* Shallow-Water Tropical *Bolivina limbata*, *Anomalina glabrata*, *Cymbaloporatte bradyi*, *Rosalina floridana*. Deep Lagoon *Cassidella schreibersiana*, *Bolivina compacta*, *B. spinescens*, *Reusella*.	Reef-Dwelling *Cymbaloporetta bradyi*, *Fijiella simplex*, *Marginopera vertebralis*, *Peneroplis pertusus*, *Quinqueloculina curta*, *Q. parkeri*, *Siphoninoides echinata*, *S. arietina*, *A. madagascariensis*, *Spiroloculina corrugata*. Brackish-Water *A. beccarii tepida*, *Elphidium* sp.. Sand Channel *Bolivina rhomboidalis*, *Cibicides lobatulus*, *Elphidium hyalocostus*, *Rosalina vilardebouana*, *Pateoris australis*.	Fringing Reef *Ammonia beccarii tepida*, *Elphidium advenum*, *E. simplex*, *Q. poeyana*. Patch & Shallow Barrier Reef *S. arietina*, *P. pertusus*, *M. vertebralis*, *Q. curts*, *Triloculina linneiana*. Deep Barrier Reef *A. madagascariensis*, *F. simplex*, *H. suborbicularis*, *Discorbis orientalis*. Northern Lagoon *Tretomphalus planus*, *Flintina bradyana*, *Triloculina trigonula*. Southern Lagoon *Bulimina marginata*, *Hopkinsina pacifica*, *Cassidella schreibersiana*, *Lagena striata*, *Cassidulina minuta*.	Exposed Reef Flat *Spirolina arietina*, *M. vertebralis*. < 30 Meters *A. lobifera*, *A. lessonii*, *P. pertusus*, *H. depressa*, *S. arietina*, *M. vertebralis*. > 30 Meters *O. ammonoides*, *A. bicirculata*.	Reef *Amphistegina lessonii*, *A. lobifera*, *M. vertebralis*, *Amphisorus hemprichii*, *H. suborbicularis*, *Operculina ammonoides*. Shallow-Water Tropical *Cymbaloporetta* spp., *Tretomphalus* spp., *Rosalina* spp.. Shallow Lagoon *Q. tropicalis*, *B. limbata*, *Q. polygona*, *Siphogenerina costata*, *Triloculina* spp.. Deep Lagoon *Cassidella schreibersiana*, *Fijiella simplex*, *Reussella* sp., *Bolivina compacta*, *B. striatula*. Quiet-Water Tropical *Trifarina* sp., *Glabratella patelliformis*, *Miliolinella* spp., *Hauerina* spp., *Spirillina* spp., *Bolivina* spp.. Brackish Water *Ammonia beccarii tepida* *Elphidium* spp.. Algae *Cibicides lobatulus*, *Discorbis* spp..

Hopkinsina pacifica. This species prefers lagoonal sediments with high organic content (Resig, 1969). It is found in DH I between 81 and 92 m. Sea level was beginning to retreat and land-derived organic detritus was transported seaward toward the lagoon. This species was not found in other samples deposited under similar conditions.

Cassidella schreibersiana. This species, when found in association with *Bolivina compacta*, *Fijiella simplex*, and *Reussella* sp., is indicative of water depth between 15 and 30 m (Resig, 1969). This assemblage is first found in marl at 128 m and persists to 120 m. Sea level withdrew to deposit 10 m of terrigenous basalt conglomerate between 116 and 106 meters. It reappears above the conglomerate for two additional meters indicating a transgressive sea and a return to deep lagoon conditions.

Amphistegina lobifera and *A. lessonii*. These species live attached to algae or the coralline surface of Recent reefs in water between 2 and 20 meters deep (Muller, 1977). They are a prime constituent of beach sand due to post-mortem transport in the turbulent environment (Resig, 1969). Thus it is reasonable to find *Amphistegina* in all facies in the proximity of the reef. The number of individuals should also increase with proximity to the reef. This is generally the case as confirmed by the data of Table I. *A.*

lessonii is found in percentages greater than 20% close to reef sections in shallow water deposits. *A*. *lobifera* is found in significant numbers only at 131 m (I-430) where its presence indicates shallow water.

Sample I-380-39 contains only *Amphistegina* spp.. The tests of these species are the sturdiest of all those found in the cores. It is presumed that the tests of other species have been destroyed by abrasion and recrystallization.

Marginopora *vertebralis*. This species occurs with *Spirolina* *arietina* and has been identified in all three studies of Recent assemblages as a resident of the exposed reef (Table VI). Neither of these species is reported in the Ewa cores (Resig, 1969). *M*. *vertebralis* is always reef associated in the Waimanalo cores.

Heterostegina *suborbicularis* (*H*. *depressa* of Muller, 1977). This species has been found in recent sands of the outer Honolulu reef at depths of 20 - 80 m (Rottger, 1976). It is also found in beach sand with the peripheral regions of the chambers worn away (Resig, 1969). Bell (1976) placed it in the deep barrier-reef assemblage. In this study, it is associated with *Amphistegina* and is assigned to the reef assemblage.

Archaias *angulatus*. This species occurs in shallow water elsewhere (Muller, 1977), and has been reported in Hawaii only at two stations of the Albatross' 1902 expedition: D.4000 in 390 m and H.4694 in 1582 m (Bagg, 1908). Upon reexamination of the Hawaiian specimen, Cushman (1910) declared them misidentified. In the Waimanalo cores, it is found in I-420 and 443A, both shallow water deposits. A possible explanation for these fossil occurrences and the subsequent disappearance of the species from Hawaiian waters is that it did not survive a sea level transition.

Cibicides lobatulus. This species lives attached to substrate or clinging to algae in shallow to moderately deep water (Murray, 1973). In the Waimanalo cores, it was usually found in association with Discorbis spp., another algal resident. This group is generally found above 82 m in DH I and III and below 125 m in DH I.

Miliolidae. Members of this family are abundant near shore and may represent 50% of the foraminifera shoreward of a reef complex (Resig, 1969). Murray (1973) reports that this family generally dominates a hypersaline environment. Most of the miliolid species are found below 128 m in DH I, suggesting a shallow water, hypersaline environment (lagoon) at this level.

Bolivina spp.. These species are often found with Trifarina sp., Glabratella patelliformis, Miliolinella spp., Hauerina spp. and Spirillina spp. in fine-grained sediments. This assemblage is associated with quiet waters and is labeled "quiet-water tropical assemblage" (Table VI).

Tretomphalus spp.. Todd (1971) considered this genus to be the reproductive float stage of the genera Rosalina and Cymbaloporetta for it reportedly survives for only 18 hours. Rosalina and Cymbaloporetta live attached to hard substrate or algae (Murray, 1973). This assemblage is labeled "shallow-water assemblage" (Table VI).

Five studies on Oahu, three of living assemblages and two of a fossil assemblage, defined facies based on diagnostic species (Table VI). The species diagnostic of the Waimanalo biofacies are included in Table VI.

Murray (1973) compiled generalized ecological data for 83 genera of foraminifera. The data consists of salinity, substrates, temperature of bottom water and depth. The four or five most common genera of each sample have been listed with the pertinent genera data (Table VII).

Other Fossils

Ostracoda. A few studies mostly taxonomic in nature have been undertaken on Hawaiian ostracodes (Izuka, 1981). Little is known about their ecology. Resig (1969) reported the presence of shallow- and brackish-water species in the Ewa cores. Coulbourn (1971) found the distribution of

Table VII

A Comparison of Environmental Factors of Common Foraminiferal Genera and Gastropods Found in DH I.

Sample (DH I)	FORAMINIFERAL GENERA / FACTOR	Depth Range (m)	Temperature (c°)	Salinity (0/00)	Substrate: Algae	Substrate: Reef	Substrate: Sediment
43	Amphistegina	5-20	25	>34	*	*	*
	Bolivina	all	1-30	32/36			m/s
	Cibicides +	0 - 2000	1-30	N	*	*	
	Cymbaloporetta	3-70			*		*
55	Amphistegina +	5-20	25	>34	*	*	*
	Cibicides	0 - 2000	1-30	N	*	*	
	Cymbaloporetta	3-70			*		*
	Fijiella	0-200					
	Hauerina						
70	Amphistegina +	5-20	25	>34	*	*	*
	Cibicides	0 - 2000	1-30	N	*	*	
	Cymbaloporetta	3-70			*		*
	Siphogenerina						
220	Amphistegina +	5-20	25	>34	*	*	*
	Cibicides	0 - 2000	1-30	N	*	*	
	Heterostegina	0-100	Tp	>32		*	*
	Quinqueloculina	0-40	Tp	>32			m/s
	Trifarina	0-400	Tm	N			

GASTROPODS / FACTOR	Depth Range (m)	Biota Association	Substrate: Beach Drift	Substrate: Lagoon/Bay	Substrate: Rubble	Substrate: Sediment	Substrate: Reef	Substrate: Solution Bench	Substrate: Tide Pool
Cautor similis	0-15			*			*		*
Gibbula marmorea	2-100	al s/c			*	*			*
Metaxia brunnicephala	0-30		*			*			
Omalogyra japonica	0-100	al						*	*
Tricolia variabilis	0-100	al							
Trochidae Fm.	0-3		*				*		*
Triphoridae Fm.	10-30	s/c							
Bittium zebrum					*		*		*
Omalogyra japonica	0-100	al						*	*
Vitricithna marmorata	3-40				*				
Cerithiidae Fm.	0-60	al				*	*		*
Hipponicidae Fm.		al		*			*		*
Lophocochilas minutissimus	0-30	al				*		*	*
Rissoina miltozona					*		*		*
Omalogyra japonica	0-100	al						*	*
Orbitestella regina	0-50	al							*
Rissoina miltozona					*		*		*
Cerithidium perparvulum	13-50			*					
Cerithiidae Fm.	0-60	al				*	*		*
Omalogyra japonica	0-100	al						*	*

\+ most common genus s-sand N-normal m-mud c-coral sp-sponges al-algae s/c-sponges and coral
p-parasitic on sponges and wormes Tp-tropical Tm-temporate (Foram genera and factors after Murray, 1973)

Table VII cont.

A Comparison of Environmental Factors of Common Foraminiferal Genera and Gastropods Found in DH I.

Sample (DH I)	FACTOR / FORAMINIFERAL GENERA	Depth Range (m)	Temperature (c^{o})	Salinity (0/00)	Substrate			FACTOR / GASTROPODS	Depth Range (m)	Biota Association	Substrate						
					Algae	Reef	Sediment				Beach Drift	Lagoon/Bay	Rubble	Sediment	Reef	Solution Bench	Tide Pool
225	*Amphistegina* +	5-20	25	>34	*	*	*										
	Cibicides	0 - 2000	1-30	N	*	*											
	Discorbis	0-50	>12	N	*												
	Quinqueloculina	0-40	>32				m/s										
270 -12	*Amphistegina* +	5-20	25	>34	*	*	*	*Acteocina* *hawaiensis*	>25					*			
	Heterostegina	0-100	Tp	>32		*	*										
	Operculina																
	Quinqueloculina	0-40	Tp	>32			m/s										
270 -52	*Bolivina* +	all	1-30	32-36			m										
	Glabratella	0-50		>35	*		*										
	Spirillina	0-100	Tp	N		*											
	Tretomphalus																
280	*Ammonia* +	0-50	15 - 30	<30>			*	*Nesiodostomia* sp.		p				*			*
	Bolivina	all	1-30	32-36			m										
	Quinqueloculina	0-40	Tp	>32			m/s										
	Spirillina	0-100	Tp	N		*											
288	*Bolivina* +	all	1-30	32-36			m										
	Ammonia	0-50	15 - 30	<N>			*										

+ most common genus s-sand N-normal m-mud c-coral sp-sponges al-algae s/c-sponges and coral
p-parasitic on sponges and wormes Tp-tropical Tm-temporate (Foram genera and factors after Murray, 1973)

Table VII cont.

A Comparison of Environmental Factors of Common Foraminiferal Genera and Gastropods Found in DH I.

Sample (DH I)	FACTOR / FORAMINIFERAL GENERA	Depth Range (m)	Temperature (c^{o})	Salinity (0/00)	Substrate			FACTOR / GASTROPODS	Depth Range (m)	Biota Association	Substrate						
					Algae	Reef	Sediment				Beach Drift	Lagoon/Bay	Rubble	Sediment	Reef	Solution Bench	Tide Pool
300	Bolivina +	all	1-30	32-36			m										
	Cibicides	0-2000	1-30	N	*	*											
	Nonion	0-180	all	<N		*											
310	Bolivina	all	1-30	32-36			m										
	Cassidella	all	1-30	32-36			m										
	Cymbaloporetta +	3-70			*		*										
	Fissurina	0-150	all	N		*	m										
	Nonionella	10 - 1000	all	N		*	m										
	Rosalina	0-100	all	N	*												
340	Bolivina	all	1-30	32-36			m										
	Cassidella																
	Cymbaloporetta	3-70			*		*										
	Rosalina	0-100	Tp	N	*												
	Tretomphalus +																
340-39	Bolivina +	all	1-30	32-36			m										
	Fijiella	0-200															
	Florilus																
	Tretomphalus																
380-39	Amphistegina +	5-20	25	>34	*	*	*										

+ most common genus   s-sand   N-normal   m-mud   c-coral   sp-sponges   al-algae   s/c-sponges and coral
p-parasitic on sponges and wormes   Tp-tropical   Tm-temporate   (Foram genera and factors after Murray, 1973)

Table VII cont.

A Comparison of Environmental Factors of Common Foraminiferal Genera and Gastropods Found in DH I.

Sample (DH I)	FACTOR / FORAMINIFERAL GENERA	Depth Range (m)	Temperature (c°)	Salinity (0/00)	Substrate: Algae	Substrate: Reef	Substrate: Sediment	FACTOR / GASTROPODS	Depth Range (m)	Biota Association	Substrate: Beach Drift	Substrate: Lagoon/Bay	Substrate: Rubble	Substrate: Sediment	Substrate: Reef	Substrate: Solution Bench	Substrate: Tide Pool
380-101	*Amphistegina*	5-20	25	>34	*	*	*										
	Cymbaloporetta +	3-70			*		*										
	Tretomphalus																
390	*Bolivina* +	all	1-30	32-36			m										
	Cassidella																
	Cibicides	0-2000	1-30	N	*	*											
	Cymbaloporetta	3-70			*		*										
	Fissurina +	0-150	all	N		*	m										
400-81	*Cymbaloporetta*	3-70	6		*		*										
	Quinqueloculina	0-40	Tp	>32			m/s										
	Rosalina	0-100	Tp	N	*												
	Spirillina	0-100	Tp	N		*											
	Tretomphalus +																
420	*Bolivina* +	all	1-30	32-36			m	*Hipponix* sp.		al		*			*		*
	Elphidium			30-50				*Vitricithna marmorata*	3-40				*				
	Massilina	0-40		N	*		s										
	Miliolinella	0-100	10-	32-50			*	Cerithium Fm.		al							*
			30					*Bittium zebrum*					*				
	Quinqueloculina	0-40	Tp	>32			m/s	Pyramidellidae Fm.		p					*		*
430-16	*Ammonia*	0-50	15-30	<N>			*										

+ most common genus   s-sand   N-normal   m-mud   c-coral   sp-sponges   al-algae   s/c-sponges and coral

p-parasitic on sponges and wormes   Tp-tropical   Tm-temporate   (Foram genera and factors after Murray, 1973)

Table VII cont.

A Comparison of Environmental Factors of Common Foraminiferal Genera and Gastropods Found in DH I.

Sample (DH I)	FACTOR FORAMINIFERAL GENERA	Depth Range (m)	Temperature (c°)	Salinity (0/00)	Substrate			FACTOR GASTROPODS	Depth Range (m)	Biota Association	Substrate						
					Algae	Reef	Sediment				Beach Drift	Lagoon/Bay	Rubble	Sediment	Reef	Solution Bench	Tide Pool
	Amphistegina +	5-20	25	>34	*	*	*										
	Bolivina	all	1-30	32-36			m										
	Siphogenerina																
	Triloculina	0-40		>32	*		s										
440-39A	*Bolivina* +	all	1-30	32-36			m	Cerithiidae Fm.	0-60	al				*	*		*
	Cibicides	0-2000	1-30	N	*	*											
	Epistomaroides																
	Quinqueloculina	0-40	Tp	>32			m/s										
	Trifarina	0-400	Tm	N			m										
440-39B	*Bolivina* +	all	1-30	32-36			m	*Omalogyra japonica*	0-100							*	*
	Cibicides	0-2000	1-30	N	*	*											
	Elphidium			30-50													
	Trifarina	0-400	Tm	N			m										
450	*Cibicides*	0-2000	1-30	N	*	*		*Finella pupoides*	3-40					*	*		
	Hauerina							*Omalogyra japonica*	0-100	al						*	*
	Miliolinella	0-100	10-30	32-50			*	*Orbitestella regina*	0-50	al							*
	Quinqueloculina +	0-40	Tp	>32			m/s										
	Triloculina	0-40		>32	*		s										

+ most common genus s-sand N-normal m-mud c-coral sp-sponges al-algae s/c-sponges and coral
p-parasitic on sponges and wormes Tp-tropical Tm-temporate (Foram genera and factors after Murray, 1973)

several species of Loxoconcha to be a function of sediment grain size. The species were more abundant in the coarser, more calcareous sediments.

In most of the Waimanalo samples, the carapaces were recrystallized. Generally, only a single valve of the carapace was preserved and that was often broken, however the complete carapace was present in a few samples. The intact carapaces suggest deposition in a low-energy environment, with little or no postmortem transport.

Gastropoda. Gastropods were useful for detailing specific environments of the reef and shallow-water facies (Table VII). For example, the foraminiferal assemblage of I-70 indicates a back-reef area; the gastropod assemblage points to a tide pool containing the algae Padina (Kay, 1979). All three of the species found in this sample live in tide pools and Omalogyra japonica (Habe) is common on algae such as Padina (Kay, 1979). Padina is found in Kaneohe Bay on the barrier reef growing both in sandy and on hard substrate (Smith, 1973).

Magnetostratigraphy and Geochronology

Validity of the Data

The validity of paleomagnetic data is determined by assessing sample stability and degree of magnetic cleaning. A Lambert equal-area plot (App. C) is used to display the NRM directions of the sample through the various levels of demagnetization. If the NRM directions plot within a fairly compact region, the sample is considered to be stable (Collinson, 1983).

A Zjiederveld plot, which records intensity and directional change through progressive demagnetization, is the key to sufficient magnetic cleaning. Treatment between 25 and 100 Oe removes a small viscous secondary magnetization from the samples (App. C). This removal isolates the primary stable remnance direction as evidenced by linear decay to the origin, with further A.F. treatment up to 600 Oe. Such behavior of samples demonstrates that the observed directions of magnetization are not the result of complex multicomponent magnetization or magnetic overprinting due to secondary high temperature oxidation, i.e. multidomain titanomaghemite grains. Instead, the univectorial magnetization component isolated after 125 Oe is likely to represent a record of the magnitude of inclination directions of the geomagnetic field acquired during deposition.

Many of the samples appear to be unstable, i.e., Wai 104.0 (App. C). Most often, these samples are located in a zone of transition from one polarity to the other (Fig. 8). The plug is 2.5 cm. high and may represent up to 500 years of time depending on the sedimentation rate. Several thousand years are required for the earth's field to reverse itself and the transition, which itself is poorly constrained, is somewhat erratic (Fuller et al., 1979). Unstable samples are also found in weakly magnetized and altered sediments. Each polarity has at least one stable sample indicating that the reversals registered are valid.

Geomagnetic Polarity Time Scale

In order to place the sequence of reversals in the absolute age framework of the Geomagnetic Polarity Time Scale (Fig. 7), the age of Koolau basalts, the weathering and erosion rates of Hawaiian volcanoes, the rate of sediment deposition, and the fossil assemblage must be evaluated. McDougall (1964), using K-Ar dating methods, reported that the subaerial part of the Koolau Volcano was built in 0.5 my between 2.56 and 2.15 Ma. Doell and Dalrymple (1973), using similar methods, found that the Koolau Volcano erupted subaerially between 2.6 and 1.8 Ma. Consequently, the oldest sediments from Waimanalo can be no older than 2.60 my.

Moberly (1963), using the amount of calcium in solution in stream waters draining Koolau rocks above Kaneohe Bay, Oahu, estimated the rate of erosion to be one meter in 7700 year. At this rate, it would take 5 million years to attain the present state of dissection. Reevaluating with elevated rates of erosion, he concluded that the beginning of the present cycle of erosion began at least 1.3 Ma.

Stearns (1970), after studying the well preserved Bellow Field Dunes of Waimanalo which he labeled Illinoian, stated that erosion and weathering on Oahu in the past 325,000 years have been slight.

The entire windward flank of Koolau Volcano has been dissected and carried away within the past 1.8 million years. Obviously, the weathering and erosion rates have been variable. Volcanic degassing, which leached the rocks of the windward flank, sea-level fluctuations, and increased precipitation when the volcano was younger and much higher account for the elevated rates. The entire process slowed when the total height was lowered below the zone of higher rainfall (up to 1000 cm per year) and unaltered basalts of the leeward flank were encountered (Macdonald et al., 1983).

Four interpretations of the Late Cenozoic Polarity Time Scale (Mankinen and Dalrymple,1979; Fig. 7) are possible for the four transitions from normal to reversed and reversed to normal (Fig. 13) if 2.60 Ma is the basement age of the deposits. All interpretations end with soil formation in the present. The first one proposes that deposition begins about 1.67 Ma at the Olduvai termination and the second at the Upper Reunion termination (2.04 Ma), the third at the Lower Reunion termination (2.12 Ma), and the fourth at the Gauss/Matuyama boundry (2.48 Ma). If 1.8 Ma is the basement age of the deposits, only one

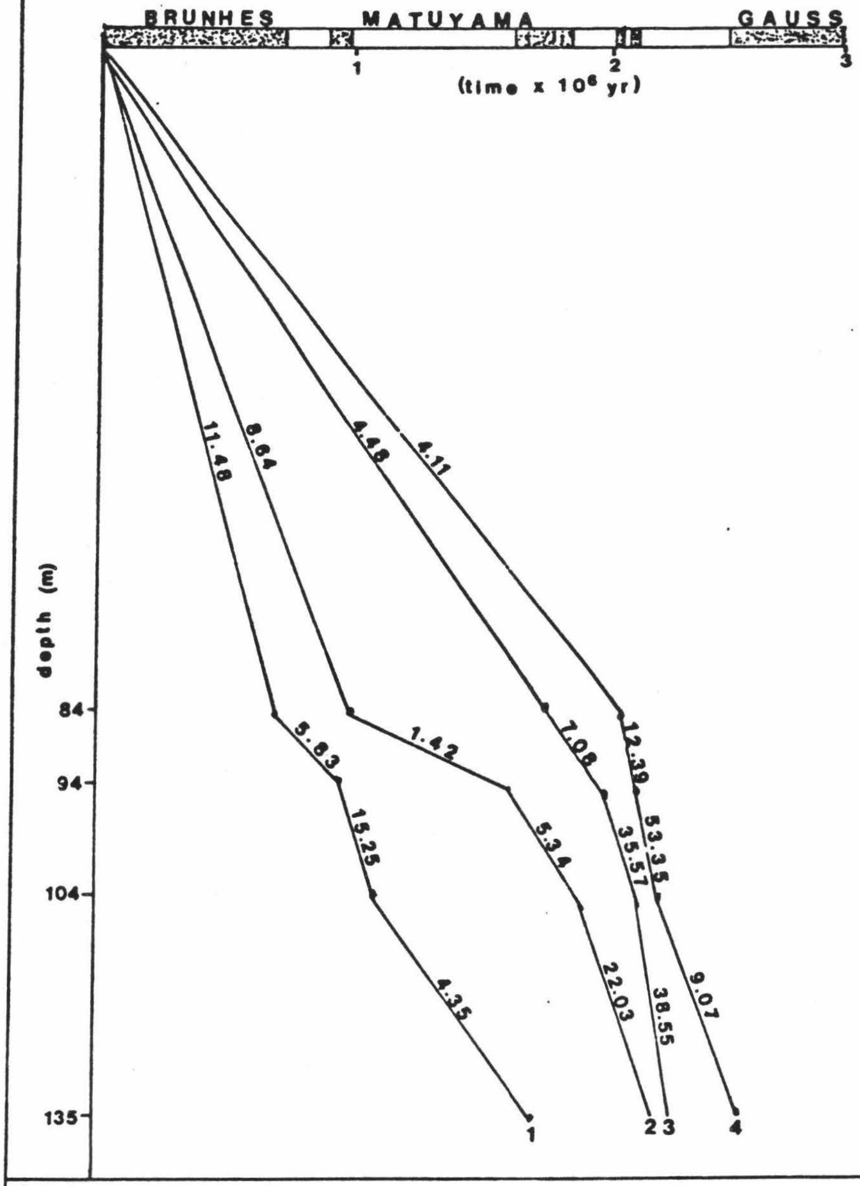


Figure 13. Four interpretations of the four paleomagnetic reversals recorded in Drill Hole I. Deposition rate is given in cm/1000 yr. on appropriate line segments.

interpretation is possible--the first solution. These interpretations will be examined in light of the evidence to follow.

Deep sea sediments accumulate at the very slow rate of 1 mm/ 1000 year while maximum deposition rates are found on continental margins which accumulate sediments at rates of 4 to 30 cm/ 1000 year. (Press and Siever, 1978; Kennett, 1983; Seibold and Berger, 1983). A deposition rate >30 cm per 1000 year is very unlikely in the Waimanalo section due to the presence of unconformities. The sedimentation rates for the four scenarios are given in Fig. 13. A generalized sedimentation rate for any section is most reliable when taken from an area free of unconformities. A sedimentation rate of 15.25 cm per 1000 year is determined from Section C which satifies this condition.

Solutions 3 (Lower Reunion) and 4 (Gauss) are not tenable. They assume rates of sediment deposition greater than 30 cm per 1000 year.

If present-day weathering and erosion rates are lower than those of earlier times, than a scenario with elevated rates for the more recent part of the section with respect to the earlier part would be unacceptable. Interpretation 2 (Upper Reunion) is invalid for this reason.

The fossil record is the final factor to be considered. In other areas, the Plio/Pleistocene boundary is marked by the first appearance of cold water species, a change in coiling direction of some planktonic foraminifera, the disappearance of discoasters, and the first appearance of *Globorotalia truncatulinoides* (1.85 Ma). Drastic climatic changes did not occur in the tropical Pacific (CLIMAP, 1976). Consequently, planktonic foraminifera do not show any change in coiling direction and no northern species appeared. This is a moot point for there are very few planktonic foraminifera present, nor were discoasters found in these sediments.

The Plio/Pleistocene boundary is presently the subject of controversy. Depending on which interpretation of "first evidence of arrival of northern guest" one holds, the boundary is placed at 1.6 or 1.8 or 2.8 Ma (Haq et al., 1977). If the boundary is taken to be between 1.6 and 1.8 Ma, then Solution 2, 3, and 4 are Pliocene in age. If, however, 2.8 Ma is taken as the boundary, all deposition occurred within the Pleistocene.

Solutions 2, 3, and 4 have been eliminated previously based on sedimentation and erosion rate considerations. The microfossils are not indicative of age. Solution 1 is valid whether the Plio/Pleistocene boundry is placed at 1.6 or at 2.8 Ma. Therefore, the paleomagnetic transitions are correlated as follows: (1) normal to reversed at 135 m as the Olduvai termination (1.67 Ma); (2) reversed to normal at 104 m as the Jaramillo onset (0.97 Ma); (3) normal to reversed at 94 m as the Jaramillo termination (0.90); (4)

reversed to normal at 84 m as the Brunhes/ Matsuyama boundry (0.73 Ma).

Comparison of Ice Volume Curves with Sea Level Changes Recorded in DH I

Lum and Stearns (1970) reported the presence of four major regressions and four major transgressions of the sea. These major events were thought to correlate with the four major continental glacial epochs. This study reported the presence of nine regressions and eight transgressions, of which six regressions and five transgressions are found above the Brunhes/Matuyama boundary (84 m). The polar ice volume changes recorded as oxygen isotope cycles in deep sea cores indicate a minimum of 22 world-wide sea level changes (ths Stages of Shackleton and Opdyke, 1973) in the past 900,000 years of which 19 occur at or above the Brunhes/Matuyama boundary.

One approach to the study of sea-level history is to consider the oceanic islands as "Pleistocene dip-sticks" (Bloom, 1967). Then polar ice volume changes recorded as oxygen isotope cycles in deep sea cores (Shackleton and Opdyke, 1973) should correspond with sea level changes recorded in DH I (Fig. 14) and the transgressive-regressive cycles would appear to correlate more closely with deep sea records than with continental glacial records.

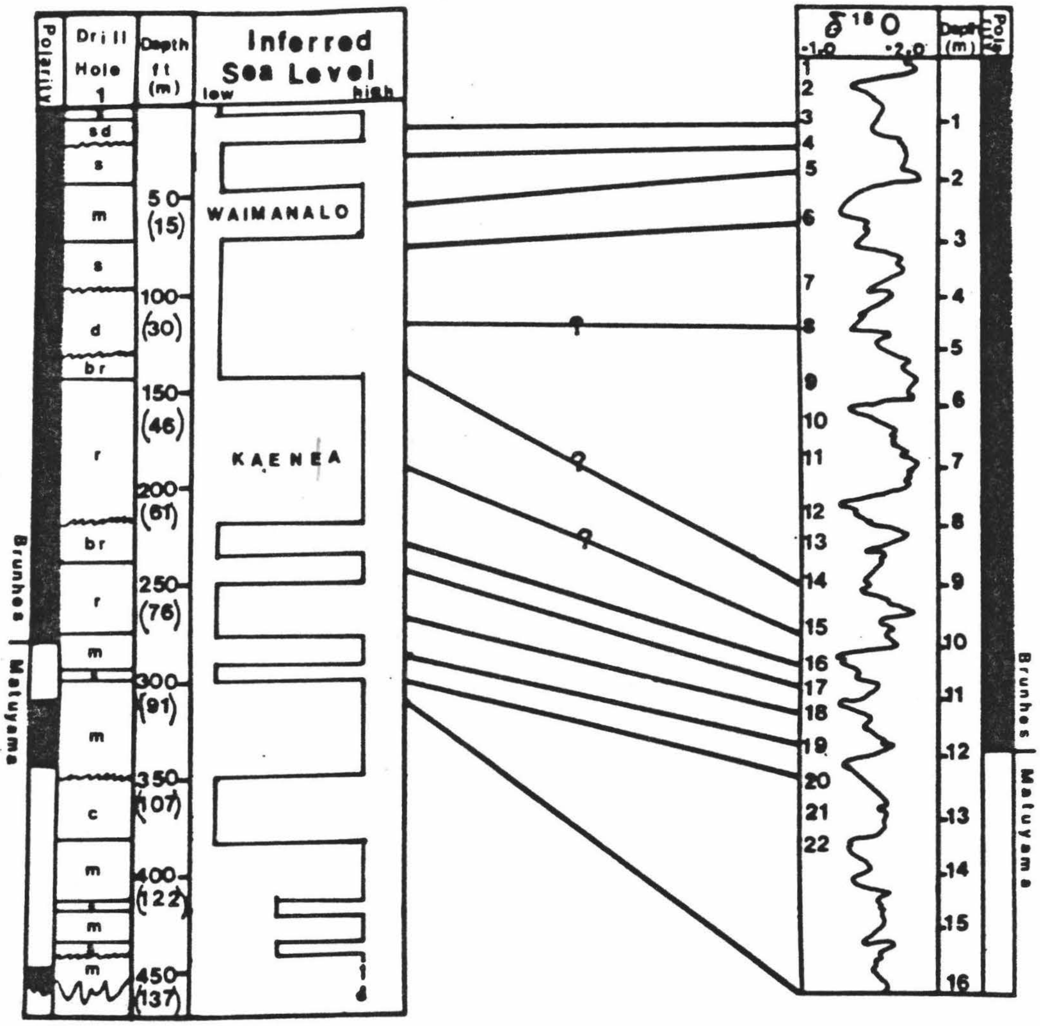


Figure 14. Correlation of the sea level curve inferred from the litho- and biofacies in DH I with the ice volume curve of Shackleton and Opdyke (1973). Questionable correlation is appropriately noted.

<u>Lithology</u> c-conglomerate m-marl r-reef limestone
br-beachrock s-soil d-dune sandstone
sd-sand
unconformity

The Waimanalo shoreline (120,000 B.P.) and the Brunhes/Matuyama boundary (730,000 B.P.) can serve as planes of reference in comparing the two data sets. High ice volume is indicated by high $\delta^{18}O$ values (even number stages), by brackish-water faunal associations and by terrigenous deposits and unconformities in the stratigraphic section. Low ice volume is indicated by low $\delta^{18}O$ values (odd number stages) and by the presence of marine sediments in the stratigraphic section. Thus, Stage 5, which is 120,000 years old, corresponds with deposits of the Waimanalo stand of the sea from 11 to 20 m in DH I. Stages 3, 4 and 6 of the deep sea cores correspond to the section between 3 to 11 and 20 to 23 m in DH I (Fig. 14) and Stages 14 to 19 are represented in DH I by the sequence between 62 and 84 m.

Correlation between unconformities is based on origin, thickness and location of deposits in the stratigraphic section and on similar characteristics of the various stages with which correlation is feasible. Stage 8 was deposited in approximantly 46,000 years beginning 251,000 B.P. (Shackleton and Opdyke, 1973). This compares favorably with the Illinoian age assigned to the dune deposits between 23 and 39 m in DH I (Lum and Stearns, 1970), estimated to begin about 300,000 years ago (Stearns, 1978). Deposition of the thick reef (Kaena ?) sequence (39 to 62 m) implies an extended period of marine transgression more than 500,000 years ago. Stage 15 lasted more than 50,000 years between 542,000 and 592,000 B.P. which corresponds well in age and duration with this sequence.

According to this interpretation, Stages 1, 2, 7 and 9 to 13, covering more than 300,000 years, are not represented. The sediments of Stages 1 and 2 were lost in the drilling process and an unconformity exists where Stage 7 sediments should be found at 30 m in DH I. The great dune deposits were constructed during Stage 8, a regressive sea stand. The materials from which they were constructed most likely represent a good portion of Stages 9 to 13 sediments.

Below the Brunhes/Matuyama boundary, only Stage 20 can be labeled with any certainty in DH I. The absence of much of the section between the Brunhes/Matuyama boundary and the Jaramillo termination (about 900,000 years at 94 m) as evidenced by an unconformity at 91 m, precludes further correlation.

V. HISTORICAL SUMMARY

Shallow Lagoon. Between 137 and 126 m, a lagoon shallower than 15 m existed behind a barrier reef. For about 15,000 years, it was very rich in fauna and of normal marine salinity. Then, at 1.67 Ma, the extremely abundant foraminiferal population was terminated as evidenced by a faunal and lithologic unconformity at 135 m. The lagoon environment was interrupted twice by retreat of the sea, causing the lagoon to become salinity stressed. The first subaerial exposure is found between 134 and 132 m, and the second is between 127 and 125 m., possibly representing fluctuations within the same regression. Both of these exposures were accompanied by swampy conditions.

Deep Lagoon. From 125 m the lagoon began to deepen, eventually reaching depths greater than 15 m at 120 m. At this time, the sea began another retreat creating a swamp at 114 m. This was followed very quickly by subaerial exposure. Four meters of cobble conglomerate were deposited before the sea began another transgression with a return once again to swampy conditions. Lagoonal sediments below 117 m were altered during this regression.

A lithologic unconformity is found at 106 m suggesting a rapid return to deep lagoon conditions. Subsidence may have been very active at this point. These lagoonal conditions continued, for 3 more meters for similar material was deposited. The earth's magnetic field reversed itself at 104 m (0.97 Ma). About the same time, the sea began another retreat. This regression lasted for more than 70,000 years for the magnetic field was reversed once again at 94 m (0.90 Ma). Beginning at 89 m, terrigenous sediments were deposited for 2 m. A transgressing sea renewed the lagoon but a reef was slowly advancing. The magnetic field of the earth reversed itself one last time, at 84 m (0.73 Ma), before the lagoon was superseded by the reef at 82 m.

Reef. A nobby algal reef containing few corals was built for the next 30 m. This reef section was interrupted by a regression of the sea seen at 69 m. Sediments preceding this were altered once again by meteoric waters. Seven meters of beach sediments were deposited containing a midsection of basaltic beach sand. An extended period of arid weather conditions or a regressive fluctuation are suggested by these conditions.

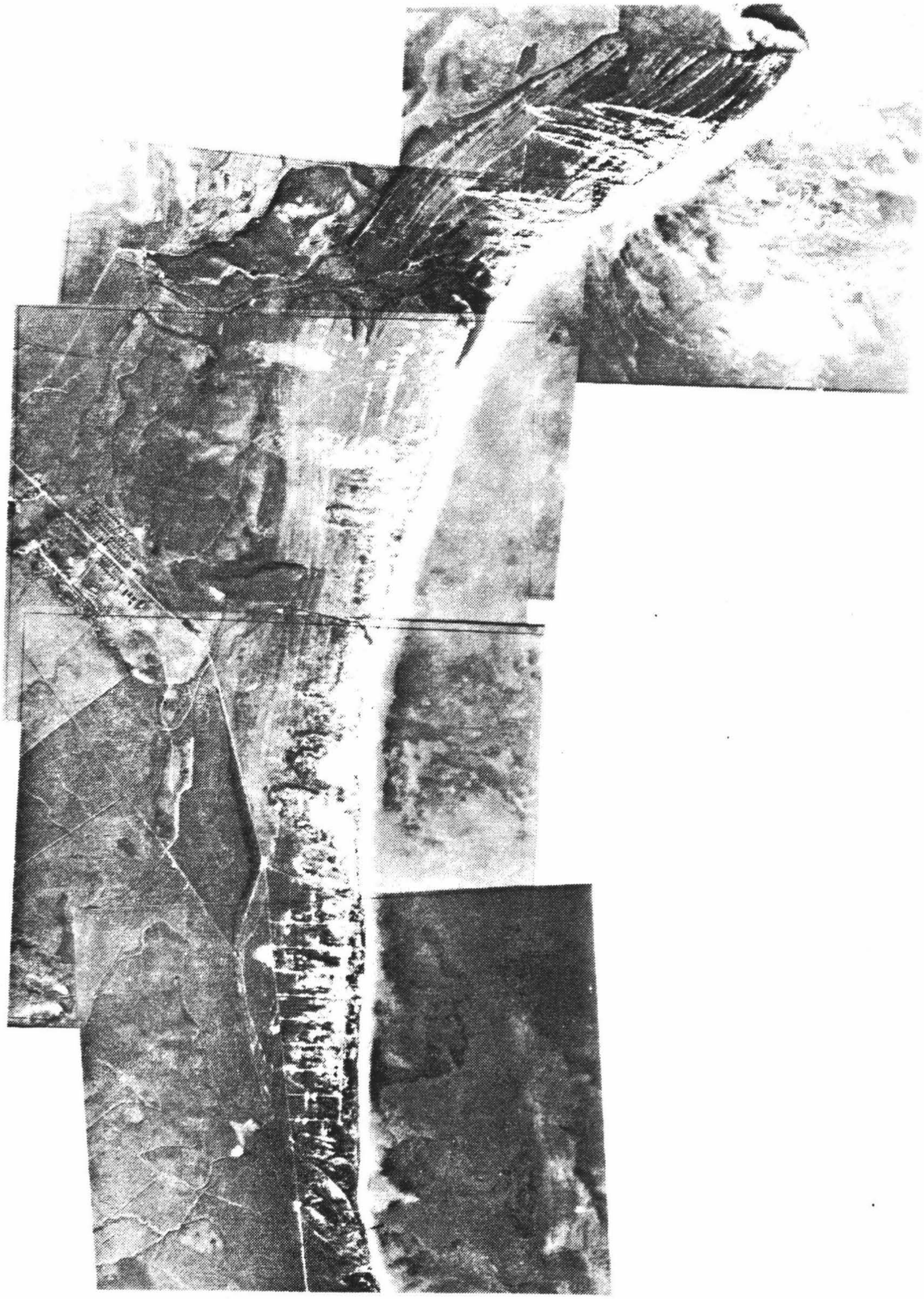
Algal-reef growth returned as the sea deepened slightly, creating a low energy back-reef environment. At least 23 m of reef material was constructed before the sea slowly retreated once again, for more beach sand is seen at 32 m. This beach deposit is considered by Stearns to be the beginning of the Illinoian glacial period (320,000 years ago). This time, however, a stream cut a channel through the beach and into the surface of the older reef. An extended emergent period ensued during which the exposed reef flat was weathered providing material for the large dunes which were built at this time. The stream channel was filled with dune material and a large barrier dune (18 m) was constructed seaward of this core behind which a swamp or marsh formed. The sea made one last great advance about 120,000 years ago, building a reef to the crest of the large barrier dune and cutting nips into dunes that existed further inland. A small lagoon with restricted circulation replaced the swamp. The environment slowly became normal marine as circulation within the lagoon increased.

The sea retreated one last time, until 17,000 B.P., to 100 m below its present level. The lagoon became a swamp and was finally in-filled with detritus. A thin layer of soil covered the barrier dune and the seaward reef.

The sea returned rapidly to its present level. Beach sands cover the soil. The occurrence of multiple beach ridges are evidence of a general prograding seaward of the coastal plain during the recent past (Plate V). Sand dunes formed once again and began to cover the beach ridges.

Plate V

1927 air photo of multiple accretionary beach ridges along Waimanalo Bay. Photo courtesy of U.S. Geological Survey.



VI. CONCLUSIONS

The principal objectives of this study were to determine the environments that existed at the time of deposition on the Waimanalo coastal plain, to use paleomagnetic techniques to gather evidence of the age of the sedimentary sequence, and to reconstruct a geologic history of the area.

1. Three primary environments are represented in the Waimanalo cores: shallow lagoon, deep lagoon, and reef. Seven facies were identified: dune, beach, tidal flat, back reef, reef flat, reef edge, and lagoon.
2. Eighteen genera of ostracodes, 155 species of foraminifera, and 20 kinds of gastropods were identified. Foraminifera were very useful diagnostic tools in determining the primary characteristic of the major environments. Gastropods, however, were equally useful tools in detailing specific regions of some of those environments. Ostracodes proved to be of little value as diagnostic tools.
3. Each of the primary environments was interrupted by a minimum of two regressions of the sea. A total of nine regressions are represented, of which eight are

most likely major regressions. These were probably the result of glacio-eustatic changes of sea level.

4. With each transition of the sea, faunal abundances were altered. Evidence exists that certain species did not survive sea level transitions. *Archaias angulatus* was only found below 128 m. It has not been reported in modern Hawaiian sediments. Possibly the lagoon deepened too quickly, or it was forced out of its niche by competing species.

5. Sediments below regressive, terrigenous deposits were greatly altered by meteoric phreatic diagenesis due to the release of water from the basal lens as the sea retreated. Foraminiferal abundances typical of the various environments were greatly modified by these events.

6. Of the possible solutions of the magnetostratigraphic polarity sequences presented, only Solution 1 (Olduvai) satisfies all conditions presented: thus the transition at 135 m is the Olduvai termination, at 104 m is the Jaramillo onset, at 94 m is the Jaramillo termination, and at 84 m is the Brunhes/Matuyama boundry.

7. The transgressive-regressive cycles recorded in DH I correlate more closely with deep sea records than with continental glacial records.

Further study of DH II and III should be conducted to reconfirm the polarity reversals reported in DH I. A study of the oxygen isotope characteristic of the cements found throughout the reef environment should be considered to establish the origin of waters within the diagenetic environments.

Appendix A

DEFINITIONS OF LITHOLOGIC TERMS

Definitions of the lithologic terms used in this paper are presented below. They have been taken from papers by Stearns and Chamberlain (1967), Lum and Stearns (1970), and from the Glossary of Geology (1980).

Reef limestone. A sedimentary rock consisting of the remains of calcareous algae, various corals, mollusks, etc., essentially in growth position. Much of the original skeletal material has been replaced by secondary calcite.

Beach rock. A sedimentary rock consisting of calcareous beach sand cemented by calcium carbonate. Beach rock is commonly found forming within the beaches of tropical islands and owes its origin to the seepage of carbonate-rich ground waters through a beach composed of calcium carbonate particles. Beach rock is formed only at or within the tidal range and positively indicates a former shore line.

Marl. Calcareous silt and/or clay.

Dune rock. An eolianite consisting of blown sand piled by the wind into sand dunes. It is distinguished from beach rock by having a higher bedding plain ($>20^{\circ}$) and is better sorted with no inclusions larger than 2 mm in diameter (Pottratz, 1968). A wind velocity exceeding 13 knots is necessary to develop dunes in Hawaii.

Conglomerate. A sedimentary rock composed of rounded cobbles and pebbles intermixed with finer material.

Mud. A marine or fresh water sediment consisting of particle diameters mainly in the silt and clay size range, i.e. 1/16 mm to about 1/1000 mm, and composed of various detrital minerals resulting from terrestrial weathering. Marine shells may be present. The various types of muds are described in terms of their colors which are the result of the listed constituents: a) brown, oxides of iron and aluminum; b) black, iron sulfides and organic detritus; c) gray, calcium carbonate and brown or black mud; d) white, clay sized calcium carbonate; e) green, clay minerals, and ferrous iron.

Soil. The term is used in a general way to mean regolith and any sediment altered by weathering.

Cobbles, pebbles, gravel, sand, silt, clay. The usage herein follows the usual geological definitions.

Appendix B

DRILL HOLE LABELING AND CORE RECOVERY

Drilling Data.

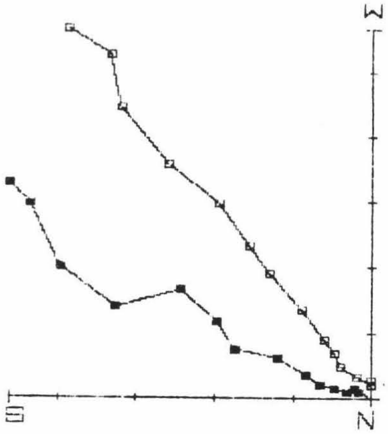
Drill Hole Number	USGS Number St Dept LNR Number.	Length of Recovered Core ft.(m)	Elevation ft.(m)	Total Depth Down Hole ft.(m)	% Core Recovery
I	T-136 3-2042-05	270 (83)	7 (2)	450 (137)	60
II	T-137 3-2042-06	156 (48)	12 (4)	340 (104)	46
III	T-138 3-2042-07	129 (39)	10 (3)	330 (101)	39
IV	T-139 3-2042-08	120 (37)	8 (2)	300 (91)	40
V	T-140 3-2042-09	129 (39)	10 (3)	340 (104)	38
VI	T-141 3-2042-10	20 (6)	14 (4)	50 (15)	40
VII	T-142 3-2042-11	78 (24)	10 (3)	190 (60)	41
VIII	T-142-1 3-2042-12	?	10 (3)	285 (88)	mis-placed

Appendix C

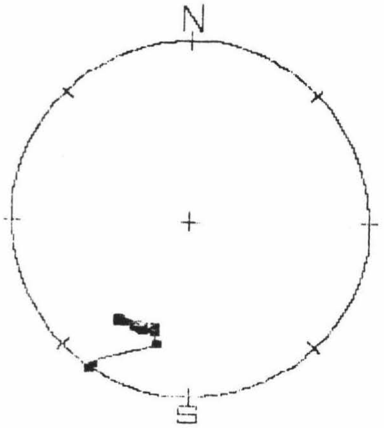
PALEOMAGNETIC DATA

PROGRESSIVE DEMAG OF WAI 071.0

DEMAG	GDEC	GINC	INT.
NRM	215.5	34.4	6.85E-5
AF 25	214.2	32.2	6.23E-5
AF 50	206.9	35.6	5.48E-5
AF 75	203.6	36.1	4.41E-5
AF 100	214.6	33.3	3.54E-5
AF 125	210.7	34.1	2.79E-5
AF 150	203.5	34.7	2.31E-5
AF 200	206.4	33.7	1.63E-5
AF 250	202.5	33.9	1.09E-5
AF 300	197.0	35.2	8.39E-6
AF 350	197.5	38.6	6.32E-6
AF 400	194.6	29.5	3.92E-6
AF 500	213.3	4.3	1.90E-6
AF 600	213.3	.2	2.76E-6

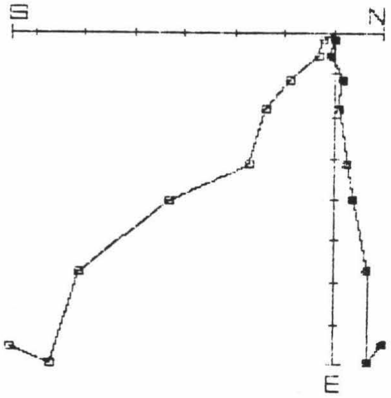


ONE DIVISION IS E-5 EMU



PROGRESSIVE DEMAG OF WAI 091.0

DEMAG	GDEC	GINC	INT.
NRM	82.7	40.6	9.93E-5
AF 25	84.9	35.5	9.78E-5
AF 50	83.6	41.6	7.69E-5
AF 75	84.5	39.4	5.22E-5
AF 100	85.6	28.9	3.55E-5
AF 125	86.9	37.4	2.25E-5
AF 150	82.4	38.8	1.46E-5
AF 200	98.1	28.3	6.48E-6
AF 250	93.7	53.6	3.06E-6



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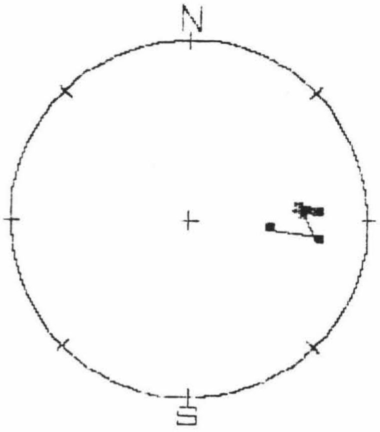
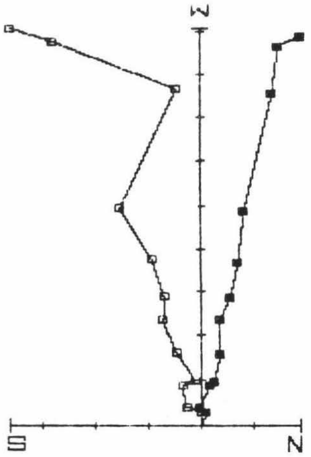
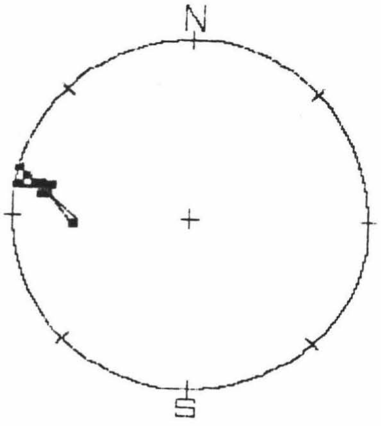


PROGRESSIVE DEMAG OF WAI 091.1

DEMAG	GDEC	GINC	INT.
NRM	281.9	21.6	9.78E-5
AF 25	279.6	17.6	9.20E-5
AF 50	280.1	3.5	7.66E-5
AF 75	279.4	17.3	5.17E-5
AF 100	280.7	13.6	3.86E-5
AF 125	280.8	13.3	2.98E-5
AF 150	278.3	17.3	2.47E-5
AF 200	281.9	16.1	1.68E-5
AF 250	282.9	6.8	1.01E-5
AF 300	278.6	20.9	9.70E-6
AF 350	266.5	35.7	4.72E-6
AF 400	285.2	.3	2.88E-6

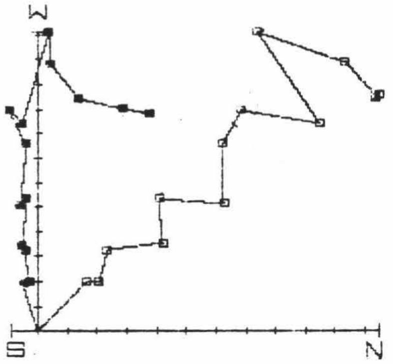


ONE DIVISION IS E-5 EMU

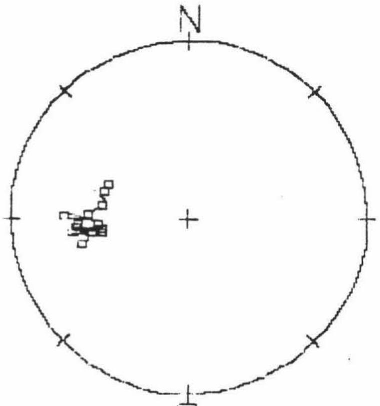


PROGRESSIVE DEMAG OF WAI 092.2

DEMAG	GDEC	GINC	INT.
NRM	292.7	-50.1	1.50E-4
AF 25	287.4	-50.2	1.48E-4
AF 50	278.0	-49.9	1.48E-4
AF 75	272.0	-43.6	1.50E-4
AF 100	271.5	-31.2	1.42E-4
AF 125	266.0	-48.2	1.27E-4
AF 150	264.0	-37.2	1.13E-4
AF 200	266.6	-39.0	9.83E-5
AF 250	262.9	-50.7	8.08E-5
AF 300	265.7	-37.2	6.75E-5
AF 350	260.2	-50.1	5.48E-5
AF 400	262.8	-35.5	4.00E-5
AF 500	261.4	-45.4	2.87E-5
AF 600	256.1	-39.1	2.58E-5

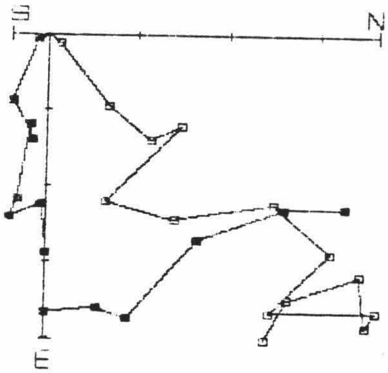


ONE DIVISION IS E-5 EMU

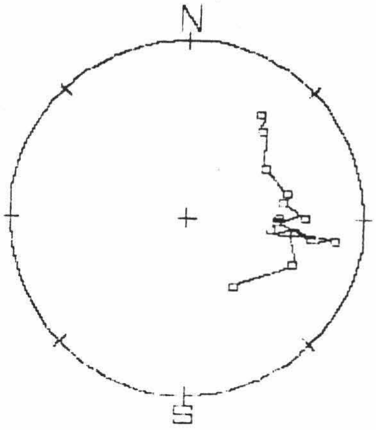


PROGRESSIVE DEMAG OF WAI 093.2

DEMAG	GDEC	GINC	INT.
NRM	34.8	-31.2	4.70E-5
AF 25	41.3	-37.5	4.40E-5
AF 50	58.2	-47.6	4.71E-5
AF 75	76.0	-42.7	5.22E-5
AF 100	80.9	-45.2	5.16E-5
AF 125	90.0	-34.0	4.42E-5
AF 150	89.8	-47.4	4.27E-5
AF 200	91.6	-48.4	3.37E-5
AF 250	99.0	-30.3	2.83E-5
AF 300	97.8	-17.1	2.29E-5
AF 350	97.7	-50.9	1.92E-5
AF 400	96.5	-39.3	1.82E-5
AF 500	113.1	-35.8	1.18E-5
AF 600	144.7	-51.8	1.92E-6

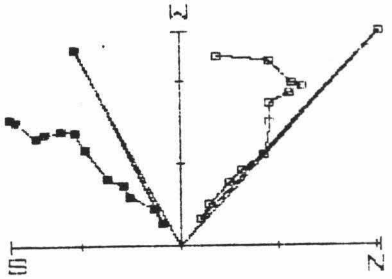


ONE DIVISION IS E-5 EMU

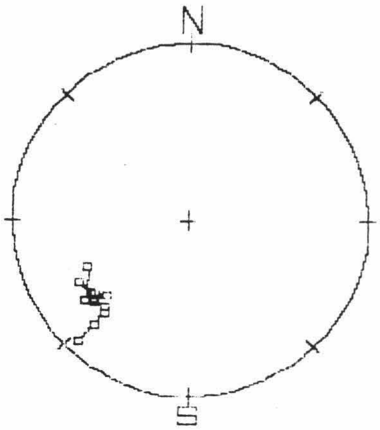


PROGRESSIVE DEMAG OF WAI 094.0

DEMAG	GDEC	GINC	INT.
NRM	221.8	- 9.1	2.34E-5
AF 25	221.9	-21.9	2.43E-5
AF 50	221.9	-30.2	2.28E-5
AF 75	224.3	-32.8	2.31E-5
AF 100	228.9	-31.2	2.16E-5
AF 125	232.3	-27.6	1.96E-5
AF 150	230.6	-31.0	1.76E-5
AF 200	227.5	-37.8	1.40E-5
AF 250	232.4	-33.7	1.12E-5
AF 300	230.2	-32.6	9.32E-6
AF 400	240.6	-30.4	5.98E-6
AF 500	233.4	-32.9	3.77E-6
AF 600	245.7	-38.0	3.32E-5

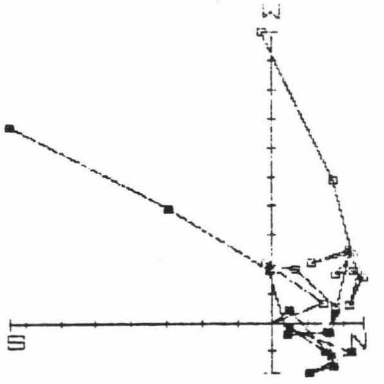


ONE DIVISION IS E-5 EMU

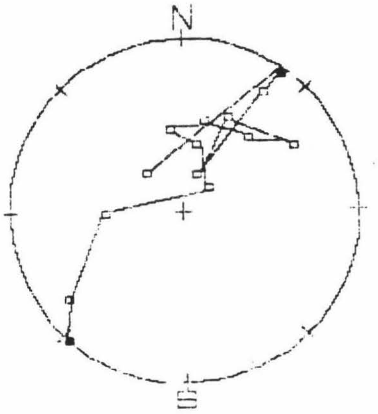


PROGRESSIVE DEMAG OF WAI 104.0

DEMAG	GDEC	GINC	INT.
NRM	222.2	1.8	1.00E-6
AF 25	233.3	-19.1	5.17E-7
AF 50	268.0	-53.5	2.95E-7
AF 75	45.5	-74.6	2.27E-7
AF 100	11.4	-58.7	3.03E-7
AF 125	350.4	-51.7	2.87E-7
AF 150	13.2	-46.9	2.40E-7
AF 200	41.9	-44.0	3.25E-7
AF 250	59.1	-27.8	2.35E-7
AF 300	25.2	-41.0	3.29E-7
AF 350	18.7	-72.9	1.83E-7
AF 400	34.4	-19.5	1.92E-7
AF 500	35.5	4.5	2.08E-7
AF 600	317.3	-66.1	1.56E-7

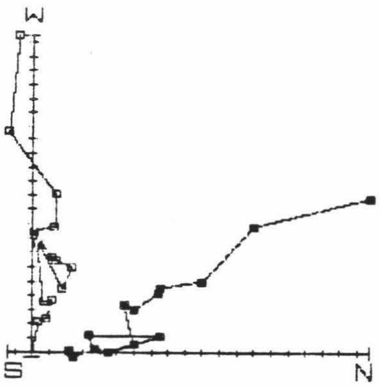


ONE DIVISION IS E-7 EMU

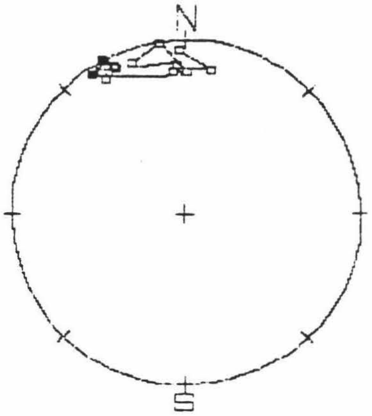


PROGRESSIVE DEMAG OF WAI 111.1

DEMAG	GDEC	GINC	INT.
NRM	331.5	2.2	2.25E-6
AF 25	325.8	5.0	1.57E-6
AF 50	333.6	- 7.1	1.12E-6
AF 75	329.0	- 8.0	8.83E-7
AF 100	331.0	- .3	8.47E-7
AF 125	334.0	- 9.2	6.79E-7
AF 150	328.6	-12.4	6.56E-7
AF 200	354.7	-20.7	6.45E-7
AF 250	.8	-20.5	4.80E-7
AF 300	351.2	- 2.4	7.61E-7
AF 350	339.9	- 9.8	3.66E-7
AF 400	356.5	-16.2	3.84E-7
AF 500	9.6	-18.4	2.56E-7
AF 600	357.9	- 8.1	2.15E-7



ONE DIVISION IS E-7 EMU

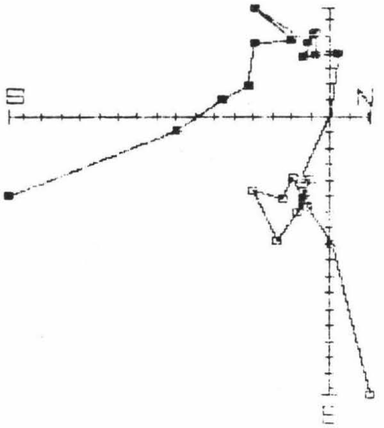


PROGRESSIVE DEMAG OF WAI 111.2

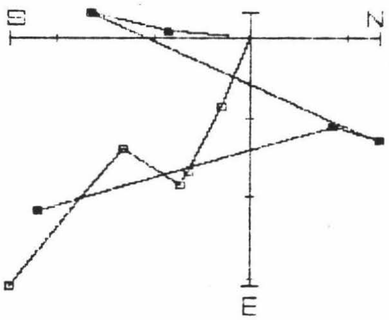
DEMAG	GDEC	GINC	INT.
NRM	163.4	- 7.0	1.75E-6
AF 25	173.7	- .2	8.00E-7
AF 50	190.7	11.7	5.80E-7
AF 75	204.0	16.7	4.89E-7
AF 100	229.0	16.4	6.27E-7
AF 125	246.8	12.6	5.33E-7
AF 200	239.7	19.8	8.25E-7
AF 250	255.3	40.8	6.12E-7
AF 300	261.6	25.5	5.73E-7
AF 350	258.6	26.9	4.32E-7
AF 400	260.0	15.0	5.33E-7
AF 500	249.1	14.1	4.08E-7
AF 600	276.4	21.4	4.25E-7

PROGRESSIVE DEMAG OF WAI 113.1

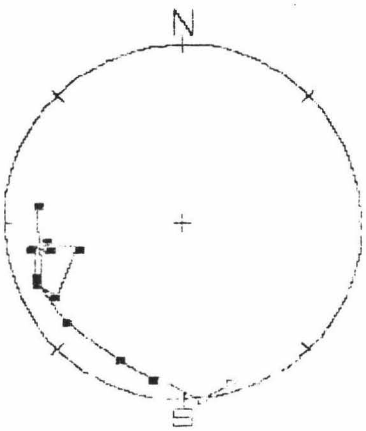
DEMAG	GDEC	GINC	INT.
NRM	135.4	38.8	3.96E-7
AF 25	52.0	43.3	1.91E-7
AF 50	43.6	21.3	2.00E-7
AF 75	190.9	20.5	1.80E-7
AF 100	184.7	19.2	9.04E-8

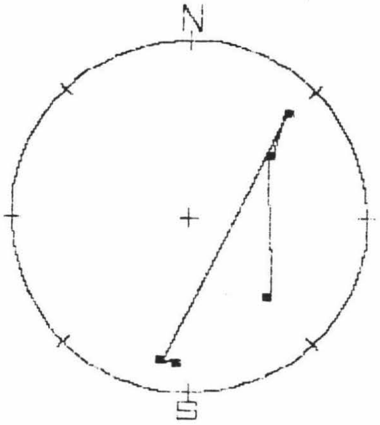


ONE DIVISION IS E-7 EMU



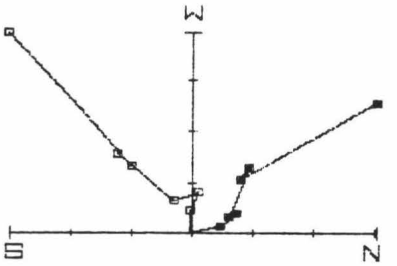
ONE DIVISION IS E-7 EMU



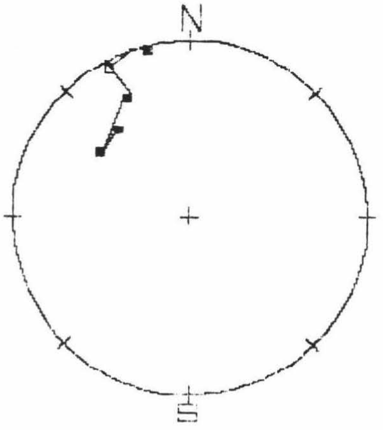


PROGRESSIVE DEMAG OF WAI 113.2

DEMAG	GDEC	GINC	INT.
NRM	320.2	37.5	4.98E-7
AF 25	306.0	37.9	1.67E-7
AF 50	305.1	38.4	2.01E-7
AF 75	331.8	26.2	7.38E-8
AF 100	331.1	- 5.8	8.34E-8
AF 150	345.6	4.5	4.75E-8

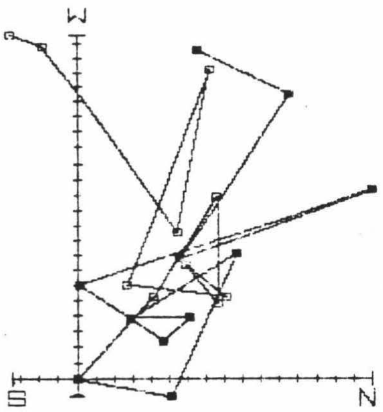


ONE DIVISION IS E-7 EMU

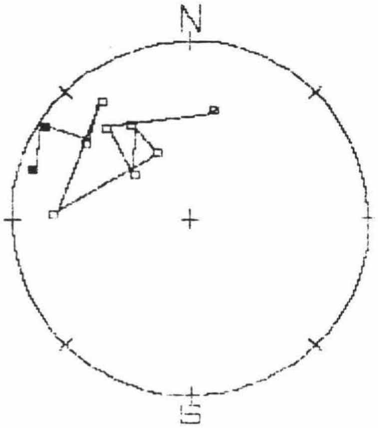


PROGRESSIVE DEMAG OF WAI 113.3

DEMAG	GDEC	DINC	INT.
NRM	287.0	8.9	2.28E-7
AF 25	301.9	4.9	2.18E-7
AF 50	305.2	-29.5	1.10E-7
AF 75	322.5	-19.5	2.15E-7
AF 100	272.0	-24.4	6.60E-8
AF 125	332.7	-57.1	9.66E-8
AF 150	327.2	-39.0	9.41E-8
AF 200	307.2	-58.2	9.03E-8
AF 250	316.9	-32.5	1.40E-7
AF 300	12.5	38.6	6.65E-8

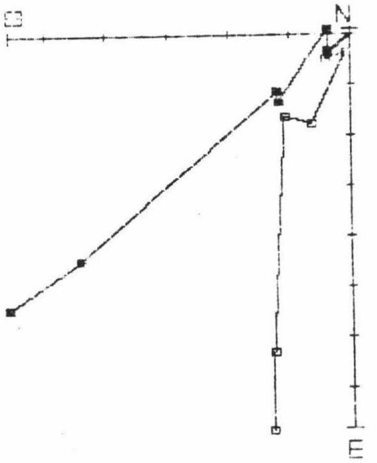


ONE DIVISION IS E-8 EM

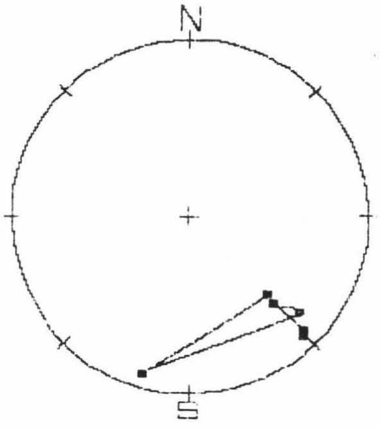


PROGRESSIVE DEMAG OF WAI 114.0

DEMAG	GDEC	GINC	INT.
NRM	135.9	9.5	7.91E-7
AF 25	134.7	11.2	6.40E-7
AF 75	135.9	33.0	1.97E-7
AF 100	130.8	19.2	1.89E-7
AF 125	196.2	10.3	3.71E-8
AF 150	134.8	38.2	6.32E-8

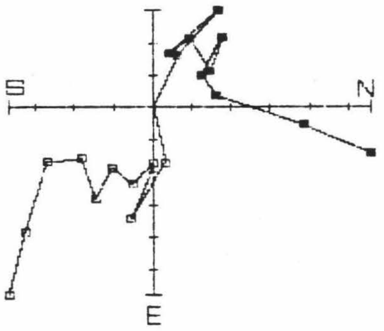


ONE DIVISION IS E-7 EMU

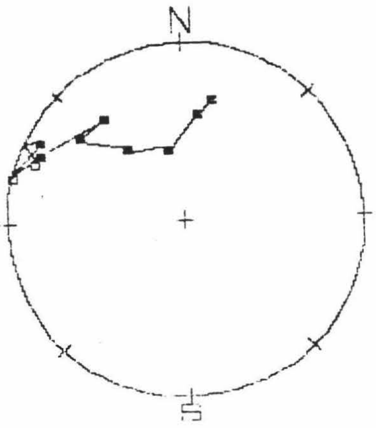


PROGRESSIVE DEMAG OF WAI 114.1

DEMAG	GDEC	GINC	INT.
NRM	14.2	32.3	6.84E-7
AF 25	7.9	40.3	5.08E-7
AF 50	347.6	58.0	3.18E-7
AF 75	321.5	48.8	2.39E-7
AF 100	309.6	27.4	3.17E-7
AF 125	322.6	29.6	2.13E-7
AF 150	294.7	12.8	2.38E-7
AF 200	284.8	- .6	1.70E-7
AF 250	299.2	8.8	3.50E-7
AF 300	291.0	-11.5	1.75E-7

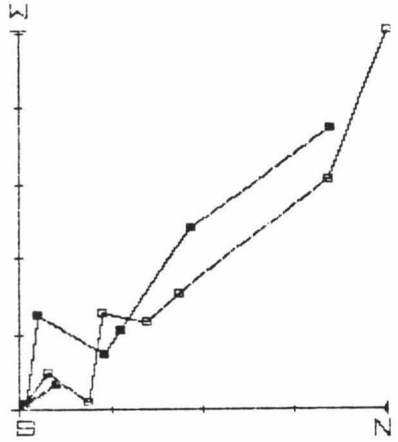


ONE DIVISION IS E-7 EMU

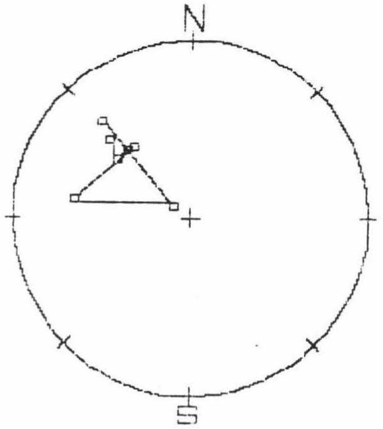


PROGRESSIVE DEMAG OF WAI 121.0

DEMAG	GDEC	GINC	INT.
NRM	312.4	-38.6	6.48E-7
AF 25	307.7	-47.7	4.57E-7
AF 50	315.6	-48.5	2.32E-7
AF 75	320.0	-49.3	1.83E-7
AF 100	278.9	-34.7	1.57E-7
AF 125	301.1	-81.2	7.60E-8
AF 150	316.4	-28.6	6.05E-8

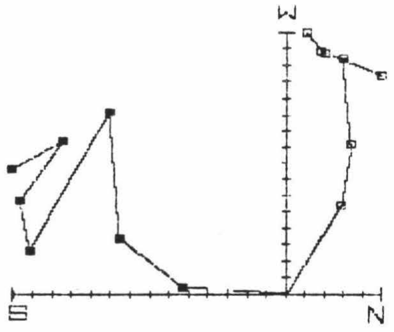


ONE DIVISION IS E-7 EMU

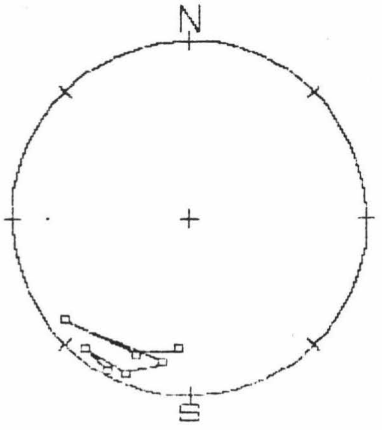


PROGRESSIVE DEMAG OF WAI 143.0

DEMAG	GDEC	GINC	INT.
NRM	208.7	- 3.8	1.60E-7
AF 25	219.3	- 7.9	1.49E-7
AF 50	202.5	- 6.9	1.49E-7
AF 75	191.2	-20.4	1.43E-7
AF 100	231.0	-11.7	1.47E-7
AF 125	201.6	-19.8	9.79E-8
AF 150	184.8	-28.5	6.05E-8

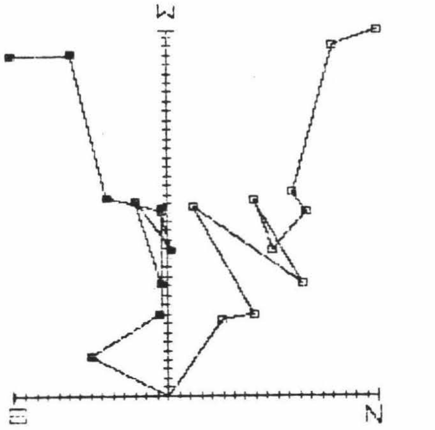


ONE DIVISION IS E-8 EMU

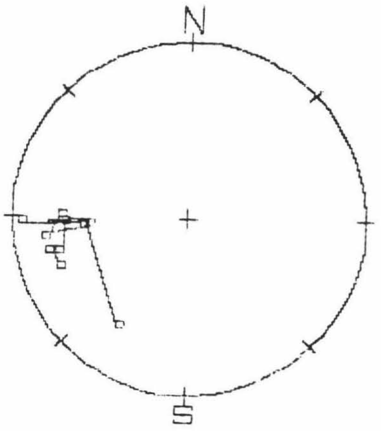


PROGRESSIVE DEMAG OF WAI 144.0

DEMAG	GDEC	GINC	INT.
NRM	249.0	-25.7	4.40E-7
AF 25	256.6	-21.4	4.09E-7
AF 50	255.7	-26.9	2.49E-7
AF 75	268.2	-32.3	2.37E-7
AF 100	271.2	-30.7	1.84E-7
AF 125	262.1	-20.3	2.28E-7
AF 150	267.0	-44.9	1.72E-7
AF 200	268.5	- 6.7	2.07E-7
AF 250	265.5	-41.1	1.19E-7
AF 300	211.9	-30.6	9.68E-8

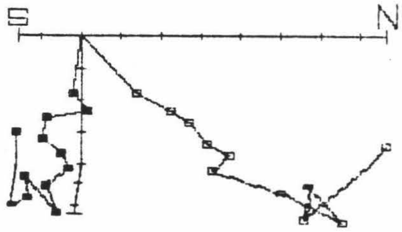


ONE DIVISION IS E-8 EMU

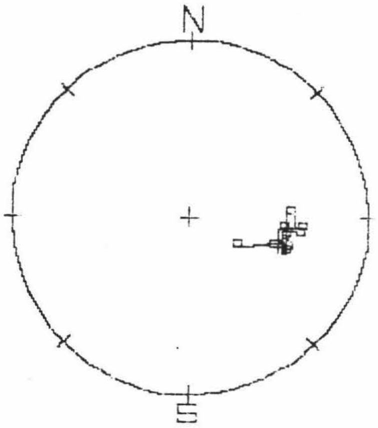


PROGRESSIVE DEMAG OF WAI 152.0

DEMAG	GDEC	GINC	INT.
NRM	117.8	-66.1	8.39E-7
AF 25	104.6	-42.9	8.47E-7
AF 50	101.8	-45.2	8.27E-7
AF 75	106.0	-49.8	7.56E-7
AF 100	94.2	-47.0	9.17E-7
AF 150	99.1	-44.7	7.28E-7
AF 200	94.1	-37.8	5.44E-7
AF 250	97.3	-45.4	5.27E-7
AF 300	106.7	-43.6	4.62E-7
AF 400	109.0	-45.4	3.81E-7
AF 500	85.9	-43.8	3.23E-7
AF 600	96.8	-37.9	2.24E-7

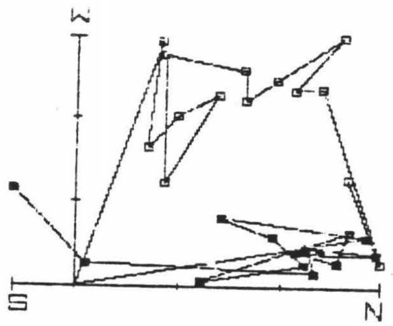


ONE DIVISION IS E-7 EMU

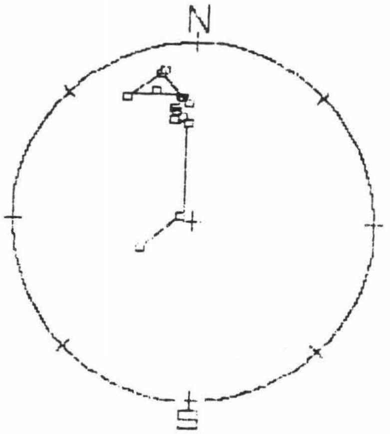


PROGRESSIVE DEMAG OF WAI 153.0

DEMAG	GDEC	GINC	INT.
NRM	242.5	-64.0	2.95E-7
AF 25	290.9	-84.5	3.00E-7
AF 50	356.0	-45.6	3.35E-7
AF 75	348.3	-42.7	3.14E-7
AF 100	352.7	-41.2	3.94E-7
AF 125	350.3	-38.8	3.12E-7
AF 150	349.4	-36.7	2.74E-7
AF 200	353.5	-32.3	3.03E-7
AF 250	346.3	-17.4	2.88E-7
AF 300	356.8	-35.1	1.51E-7
AF 350	353.3	-31.7	2.65E-7
AF 400	343.0	-26.0	2.25E-7
AF 500	330.8	-23.3	1.79E-7
AF 600	348.5	-16.0	3.01E-7

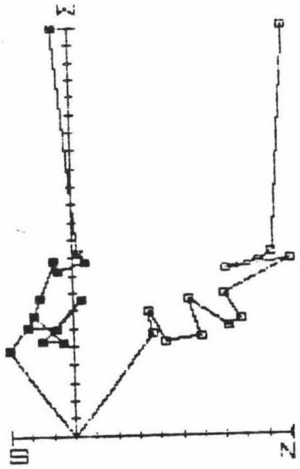


ONE DIVISION IS E-7 EMU

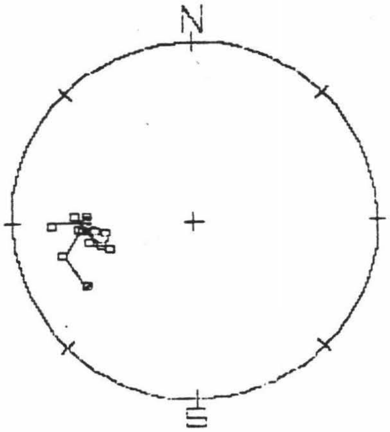


PROGRESSIVE DEMAG OF WAI 154.0

DEMAG	GDEC	DINC	INT.
NRM	268.1	-23.3	2.51E-6
AF 50	271.6	-42.0	1.37E-6
AF 75	273.4	-41.7	1.30E-6
AF 100	265.8	-37.3	1.17E-6
AF 125	264.8	-45.6	1.41E-6
AF 150	258.7	-41.5	1.05E-6
AF 200	251.1	-50.5	1.01E-6
AF 250	262.8	-50.1	9.42E-7
AF 300	272.9	-35.2	9.34E-7
AF 350	255.0	-47.4	8.05E-7
AF 400	264.7	-39.6	6.70E-7
AF 500	255.0	-26.5	7.76E-7
AF 600	238.2	-32.8	6.73E-7

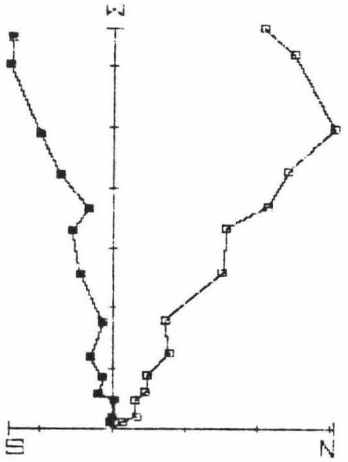


ONE DIVISION IS E-7 EMU

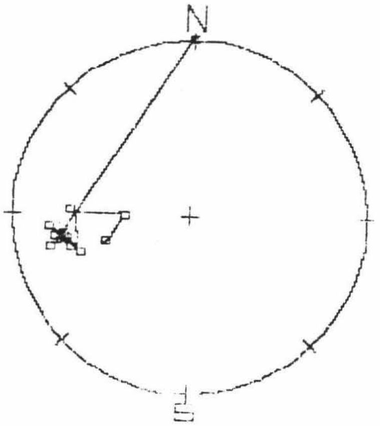


PROGRESSIVE DEMAG OF WAI 163.0

DEMAG	GDEC	GINC	INT.
NRM	257.7	-17.4	6.95E-5
AF 25	256.7	-21.9	6.69E-5
AF 50	258.4	-31.5	5.84E-5
AF 75	260.0	-29.5	4.93E-5
AF 100	264.6	-30.1	4.26E-5
AF 125	260.1	-24.8	3.68E-5
AF 150	260.0	-30.2	2.98E-5
AF 200	265.0	-22.0	1.90E-5
AF 250	254.7	-32.0	1.45E-5
AF 300	260.8	-27.8	9.89E-6
AF 350	250.4	-36.4	7.45E-6
AF 400	271.7	-33.4	5.36E-6
AF 500	269.7	-60.8	3.58E-6
AF 600	253.1	-49.8	1.54E-6

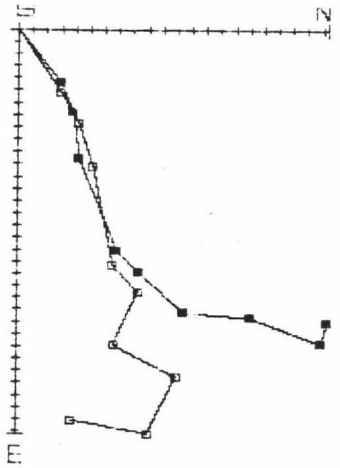


ONE DIVISION IS E-5 EMU

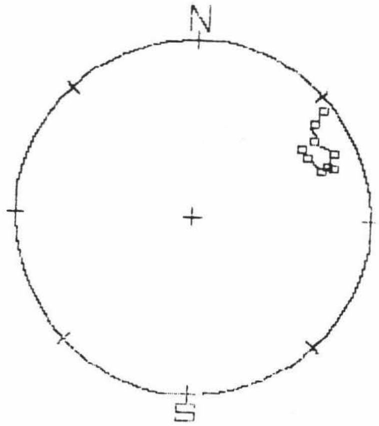


PROGRESSIVE DEMAG OF WAI 164.0

DEMAG	GDEC	GINC	INT.
NRM	48.5	- 6.7	3.24E-5
AF 25	50.8	-15.2	3.44E-5
AF 50	56.0	-21.1	3.06E-5
AF 75	63.8	-14.5	2.67E-5
AF 100	67.1	-21.3	2.31E-5
AF 125	69.1	-18.7	2.04E-5
AF 200	68.4	-24.8	1.24E-5
AF 250	60.7	-28.6	8.79E-6
AF 300	56.5	-29.2	6.02E-6

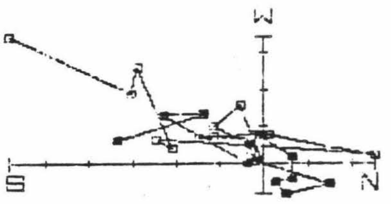


ONE DIVISION IS E-6 EMU

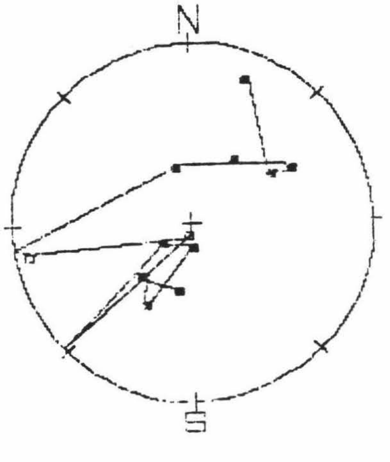


PROGRESSIVE DEMAG OF WAI 173.0

DEMAG	GDEC	GINC	INT.
NRM	190.4	59.5	6.76E-7
AF 25	224.1	57.7	3.57E-7
AF 50	209.4	47.7	3.87E-7
AF 75	179.9	79.5	2.12E-7
AF 100	237.4	75.0	2.53E-7
AF 125	192.3	-85.4	2.56E-7
AF 150	258.8	- 9.4	8.07E-8
AF 200	343.9	65.2	1.61E-7
AF 250	34.5	57.0	1.39E-7
AF 300	62.0	38.3	7.73E-8
AF 350	58.9	48.4	1.54E-7
AF 400	21.4	17.9	1.68E-7

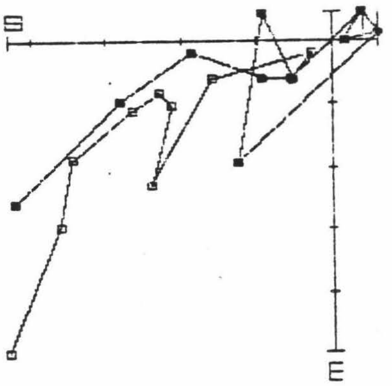


ONE DIVISION IS E-7 EMU

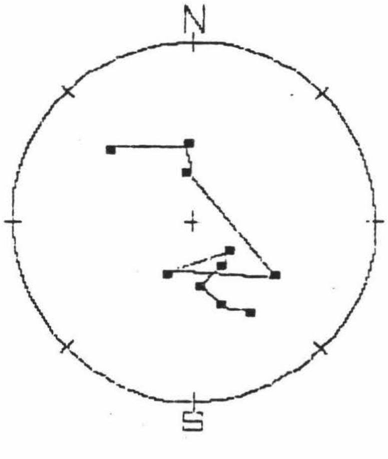


PROGRESSIVE DEMAG OF WAI 173.1

DEMAG	GDEC	GINC	INT.
NRM	148.7	40.9	6.54E-7
AF 25	161.0	50.5	4.67E-7
AF 50	173.8	61.4	3.92E-7
AF 75	147.5	67.5	2.88E-7
AF 100	127.8	70.4	2.42E-7
AF 125	205.7	64.3	2.35E-7
AF 150	123.0	46.6	3.32E-7
AF 200	350.5	69.0	1.70E-7
AF 250	356.8	55.7	3.33E-8
AF 300	309.8	40.8	8.08E-8

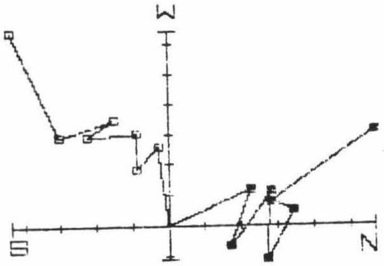


ONE DIVISION IS E-7 EMU

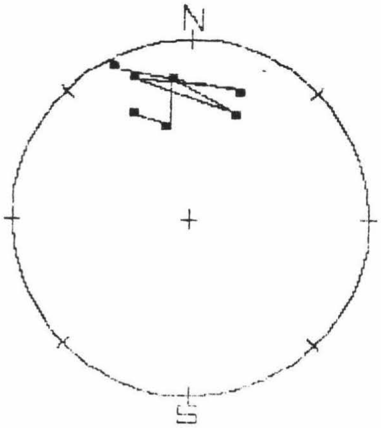


PROGRESSIVE DEMAG OF WAI 174.0

DEMAG	GDEC	GINC	INT.
NRM	331.5	33.9	7.78E-7
AF 25	344.7	46.1	4.21E-7
AF 50	351.9	23.1	3.80E-7
AF 75	22.4	37.3	3.68E-7
AF 100	338.1	15.8	3.18E-7
AF 125	21.1	26.1	2.04E-7
AF 150	332.5	5.5	2.59E-7

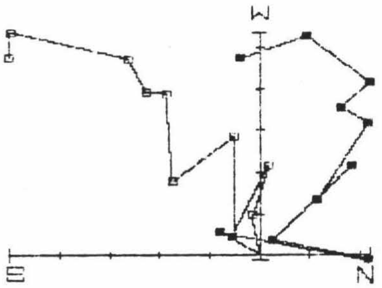


ONE DIVISION IS E-7 EMU



PROGRESSIVE DEMAG OF WAI 174.1

DEMAG	GDEC	GINC	INT.
NRM	265.1	46.4	6.90E-7
AF 25	280.2	42.7	7.32E-7
AF 50	298.2	29.1	5.40E-7
AF 75	294.0	29.9	4.52E-7
AF 100	304.3	25.7	4.29E-7
AF 125	310.4	44.2	2.49E-7
AF 150	310.3	10.0	2.88E-7
AF 200	303.8	50.6	7.24E-8
AF 250	3.2	-5.0	2.17E-7
AF 300	216.4	7.8	1.01E-7



ONE DIVISION IS E-7 EMU

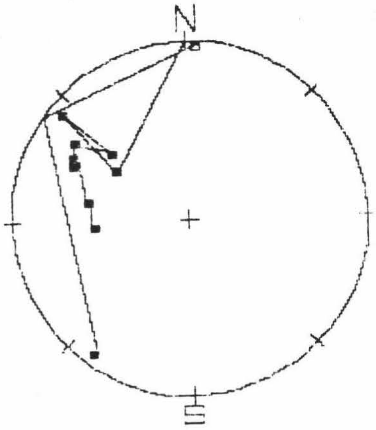


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TABLE I

(Lee, Patricia D.: Paleoenvironments at
Waimanalo, Oahu, Hawaii)

TABLE I

Distribution of Foraminifera

Waimanalo, Oahu, Hawaii
(Figure in % frequency) X < 1
Depth in core (feet - inches)

species	DRILL HOLE I																									DRILL HOLE III								
	25-4	43	55-10	70	220-41	225-48	270-12	270-52	280-35	288-67B	288-67A	300-8	310	340	340-39	380-39	380-101	390-44	400-81	420	430	430-16	440-39A	440-39B	450	255-6	260-10	270-19	299	299-57	299-92	310	320-12	330
Benthonics:																																		
Acervulina inhaerens																									×									
Alabamina tubulifera		4		×																		×										×		
Ammonia beccarii							×	×													9													
A. beccarii tepida									5	9										×		1		×	×	4	1		32	15	13	1		
Amphisorus hemprichii		×																				2	×											
A. sp																				×		×												
Amphistegina lessonii		7	23	30	33	26	25	×								82	17			×	10	10	2	×		4	7	37	48	×	21	11		
A. lobifera		1	1		4											18					56	21	6		×	2		×	5					
Anomalina glabrata		×	×	×					×															×						1				
Archaias angulatus																				×		×	1											
Articulina pacifica																				×				×	×									
Astrononion sp.								×																										
Baggina cf. B. parva																													×					
Bolivina bierigi																		×						×								7		
B. capitata													6																					
B. compacta		3							2			41	×	22	16			×	3	13	×	×								23		12		
B. glutinata									×					5			2	1				×		×	×									
B. cf. B. laevigata														2				×		×														
B. limbata			1	3	1	3	×	9	3				6		2					1	3	×	14	4	×	×	4		8	1		13		
B. mayori									×																									
B. rhomboidalis		6												×				×				×	5	×	2									
B. robusta									×																									
B. sp									×					×	3			×	1		4										8	17		
B. spinescens																				×														
B. striatula								10	1	85		36		1	×		2	×	3					×		3	6			2	54		55	36
Bolivinella elegans																								×						×				
Borelis pulchra																										×								
Buliminoides milletti																								×	×									
Cassidella pauciloculata																																		35
C. schreibersiana														4	×			×		1														
C. sp.													6																				44	14
Cassidulina sp.																																3		
cibicidids																								×	×									
Cibicides lobatulus		12	4	8	6	16	×	×	×			4						×		×		2	12	4	9	6	17	8	4	3		6		
C. pseudoungerianus																										1	2							
C. sp.				1			×																		×									
Cornuspira involvens																										×								
C. planorbis																				×				×	×	4	×							
Cymbaloporetta bradyi		6	×	6				×				1	13	3	3		19	×	17	×	×	×	2	×	×	×								
C. squammosa		8	5			×			3				6	8	4		32	×	3	1	×	×	4	×	1	×	×	3						
Discorbis fulva						×																					×							
D. mirus		×			1	4	×																	×				×	2					
D. sp.			×																						×									
Dyocibicides sp.		×		×		×	×																	×										
Elphidium advenum		×	×			×		×																	3		2	5	4					
E. oceanicum																				6			×	×						9				
E. simplex									×																									
E. sp. A			1	×	×	2																		3	2									3
E. sp. B																						1												
Epistomaroides polystomelloides						×																1	8		×									
Epistominella pulchra																																×		
Eponides repandus							×																											
E. sp.		×																																
Fijiella simplex		4	11			2		×	×					3	13			×	1	2	×		3	×	×	4	3	2				6		
Fischerinella pellucida					1				×																	×								
Fissurina circularis																								×	×									
F. lacunata																							×	×	×									
F. cf. F. lucida																																		4
F. marginata		1																1						×								3		
F. wrightiana																																		1
F. sp.													6					×																
Florilus sp. B. of Resig			×									1		2	9					×														
Gaudryina sp.																								×										
Glabratella patelliformis						2		2	×															1	2	1			×	1				
G. pulvinata																									×							×		
Guttulina regina																								×	×									
Hauerina cf. H. bradyi																										2								
H. orientalis				1																		5		×	2			×		×				
H. pacifica			4																			17		×	6	7	15	5						
Heterostegina suborbicularis			×	×	5	×	4	×	×													1				×	×	3	6					
Hopkinsina pacifica										×		1																						
Lagena hexagona																									×									
L. laevis																		×																
Lingulina sp.																		×						×								×		
Marginopora vertebralis					2																		×											
Massilina cf. M. durrandi																						1			×	×								
M. cf. M. planata																				4														
M. protea																				×														
M. pseudoclara													1							3														
M. speciosa																										×	×			×				
Other Microfossils:																																		
holothurian spicules			R					A	A						C			C		R		R		R					R	C		A		
sponge spicules		C		C	C	C	R		C												R	R		C	C		A	C		C				
echinoid spines		R	C	C	C	C	C	R	R	A		R	C	R		A	R		R	C	C	C	A	R			C	C	R	R		C		
pteropod tests									R					A	A				R	R						C								
bryozoans				R	R	R		R	R											R					R		C							
teeth (count)			1							1	1	2	2	3	6				1															
pelecypods							R			C				A	A		C		A	C	A			R		C						R		
corals		C												C		C							C											

species	DRILL HOLE I																									DRILL HOLE III								
	25-4	43	55-10	70	220-41	225-48	270-12	270-52	280-35	288-67B	288-67A	300-8	310	340	340-39	380-39	380-101	390-44	400-81	420	430	430-16	440-39A	440-39B	450	255-6	260-10	270-19	299	299-57	299-92	310	320-12	330
Massilina sp.								×		×																								
Miliolinella australis									×																									
M. circularis																						×		×	×	1								
M. labiosa		×							×											×					×									
M. oceanica var.		1																																
M. procera																				4					6									
M. sublineata																							1											
M. subrotunda			×																	1					×									
Mississippina sp.															×																			
Monalysidium politum																									×									
Murrayinella murrayi									×																									
Nonion aff. N. pacificum												9						×		×				×					2	×				
Nonionella cf. N. auris																		×																
N. sp.													6					×																3
Oolina sp.									×											×														
Operculina ammonoides							3	2																										
Pateoris sp.						×																												
Peneroplis pertusus																						2												
Planorbulina acervalis			×					×																	×		×							
Pyrgo denticulata								×																×	×	×			×					
Quinqueloculina bosciana					7			×	×	1											×		2			6	3							
Q. cf. Q. bradyana																				×	1													
Q. distorqueata																				×					×		3							
Q. laevigata																				2					1	×			3					
Q. lamarckiana		4				4			×													×			13		×			17				
Q. cf. Q. parkeri																						1			×									
Q. polygona		1		×	4		5	×	2	×									5	9			3	×	2	4				6				
Q. poeyana							×													2				×	1	×	2							
Q. seminulum								×																×	×	×		19						
Q. cf. Q. sulcata																									×									
Q. tropicalis							×															×	9	×	2									
Rectobolivina glabra									×												×		×											
Reussella sp.														×										×	×									
Robulus limbosus																						×		×	×									
Rosalina concinna																																2		
R. floridana			×	×																		×												
R. micans									×				6	8	×			×	5		×		1	×	×									
R. orientalis			×			2		×													×			×	×	1	2	9	3					
R. cf. R. vilardeboana		2																		×				×		×								
R. sp.								×	×					×							×									4		5		
Rotorbinella sp.																								×	×									
Sigmoilina sp.																													×					
Sigmovirgulina tortuosa		2	×	3		×												×					3	2	3	1								
Siphogenerina costata		×	×	5				×	×	×											4	×		×	×			1		×	4	3		
S. raphana																												×						
Siphonina philippinensis																												×						
S. tubulosa																									×									
Siphoninoides echinata																						1				×		×						
Sorites marginalis																									×	×	2							
Spirillina denticulogranulata						×																				×								
S. tuberculatolimbata																						×												
Spirillina vivipara			×					4	1									×	17	×										×				
Spiroloculina communis									×																	×								
S. corrugata							×													×		×	2	×	1	×		×		10				
S. sp.		×																																
Tretomphalus bulloides		×						2		×				2	5		4	×	30			×												
T. milletti								2						31													×							
Trifarina sp.		2	×	×	5	3		2	×					3			2	×	1	×		2	10	2	3	1	1	1		4		×		
Triloculina bikiniensis		×	×																					×	1	×								
T. cf. T. fichteliana							1																											
T. kerimbatica philippinensis								×																	×		×							
T. linneiana		×																		×		2			×	3				×				
T. oblonga							×	×	×																1	2		×		2				
T. striatotrigonula																						4		×	3									
T. tricarinata							×	×	×																	3								
T. trigonula		×				×		×															3	×	×				×	4				
T. sp.			×																					×					×					
Tubinella sp.									×																×	×	2		×	1				
Vertebralina striata		×		×																		×		×	×	1								
Wiesnerella auriculata									×																					×				
hyaline juv.		13	21	26	×	13	26	36	32	×		×	6	2	11			95		19	4	17	1	19	18	9	9	3		1		9		
mis. miliolids		5	12	16	13	18	32	23	47	3				×						24	5	4	4	64	7	12	16						1	
unidentifiable specimens, poorly preserved	100	×	×	×	19	×		4		?		6	38		×	×	21	×	12									12						
Planktonics:																																		
Globigerinoides conglobatus																										×						×		
G. ruber		2																×						×	×	×								
G. trilobus																		×		×				×	×	8	×		3					
Globigerina sp. juv.									1									×							×				×					
Globorotalia menardii																								×		×								
Foram. Number (no./gm)		38	122	60	32	306	62	154	186	37	0	8	2	32	98	4	4	[illegible]	9	969	73	41	18	[illegible]	[illegible]	191	170	97	21	63	5	65	7	15
% Hyaline		66	86	84	57	50	60	74	64	95	0	100	100	99	100	100	99	100	95	48	94	44	74	52	45	61	57	60	96	67	100	100	99	100
% Porcelaneous		34	14	16	43	50	40	26	36	5	0	0	0	1	0	0	×	0	5	52	6	56	26	48	55	39	43	40	4	33	0	0	1	0
Ostracod Number (no./gm)		2	1	6	3	3	9	29	21	6	0	1	×	8	6	×	4	3	×	20	×	5	×	4	9	12	10	×	1	5	10	49	2	3
Ratio Foram./Ostra.		21	87	10	11	95	7	5	9	7	0	6	4	4	16	38	1	580	31	76	746	211	59	[illegible]	625	17	16	480	16	12	×	1	3	5
Diversity (s) (no. species/sample)		29	26	17	12	19	17	29	34	8	0	7	8	17	12	2	7	23	11	35	16	35	23	33	63	42	25	19	18	25	5	18	2	7

R (Rare 1 - 5)
C (Common 6 - 15)
A (Abundant > 15)

* The following depths were barren of specimens: 1 - 74, 145, 350-47, 350-80, 368-27, 412-38, 430-34.