SUBSURFACE GEOLOGY OF WAIKIKI, MOILIILI AND KAKAAKO WITH ENGINEERING APPLICATION

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TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

TABLE OF CONTENTS (continued)

LIST OF TABLES

LIST OF ILLUSTRATIONS

CHAPTER I

INTRODUCTION

Since the end of World War II, and particularly in the last 15 years or so, the City of Honolulu has undergone a rapid and extensive transformation. It has evolved from an agriculture and military-oriented city into the commercial center of the Pacific and a major world tourist attraction. This transformation has been accompanied by intense building activity which has produced a large number of medium- and high-rise structures. This building boom has been particularly significant in the Waikiki area where the one- and two-story wood frame structures which once characterized this section of the city have given way to the numerous 20-plus-story hotels and apartment buildings, which now dominate the Honolulu skyline.

The construction of these buildings and other structures throughout the city has given rise to a large number of investigations of the subsurface conditions underlying the structures. Such investigations provide the subsurface information necessary for the development of design criteria for structure foundations. These foundation studies include the drilling and logging of a number of subsurface borings at each site. Thus, there exists a large amount of subsurface data for the developed areas of the city which represents a potential means of achieving a more complete understanding of the geology of Honolulu than was available previously.

It is the purpose of this thesis to synthesize the extensive subsurface information now available in the areas of Honolulu shown on the project area map (Plate I). This includes Waikiki, Moiliili and Kakaako and some adjacent areas, encompassing a total of 4.2 square miles. The data from approximately 800 borings and some related sources (such as excavation profiles and pile driving records) have been utilized to produce a detailed description of the subsurface in this area.

This description is presented in three sections. In the section on Subsurface Conditions, Chapter III, the materials present and their lateral and vertical distributions are discussed and shown on cross sections within the accuracy of the available control. The geologic implications of these data and the geologic history of the project area, as reflected in this information, is described in Chapter IV. An Engineering Geology section, Chapter V, presents the engineering properties of the subsurface materials and discusses them with regard to the suitability of the various geologic units for the purposes of foundation bearing layers.

The sources from which boring data have been obtained for this project include the Engineering Division, the Traffic Division and Sewers Division of the Department of Public Works of the City and County of Honolulu, and the Board of Water Supply and the Building Department of the City and County. Information was also provided by the Department of Accounting and General Services, the Department of Land and Natural Resources, and the Department of Transportation of the State of Hawaii. Well logs were utilized from Stearns & Vaksvik (1938). The bulk of the information used was obtained from the files of Dames & Moore, consultants in the environmental and applied earth sciences, which has maintained an office in Honolulu since 1960. In addition, a significant amount of information was provided by the consulting engineering firm of Walter Lum & Associates. Another source was Continental Drilling Company of Hawaii, a drilling contractor.

Obviously, this wide range of sources presents certain problems due to the variations in quality and presentation of boring logs. The authors of the logs range from engineering geologists and foundation engineers to soils technicians and drillers. Furthermore, the purposes for which the borings were performed range from well logging or defining high capacity pile bearing layers to determining soil bearing capacities for the cages at the Honolulu Zoo.

This wide range of sources was converted to a common terminology for correlation purposes by classifying each material description according to a single set of geologic units. Units are assigned on the basis of the probable geologic origin represented by each type of material described on the source logs. In many cases, it is necessary to interpret the source logs with a degree of flexibility and to base interpretations on correlation with other nearby borings in order to clarify otherwise obscure or misleading logs which may have been done by non-technical personnel.

To illustrate the conditions encountered in the project area, three cross sections are presented which are generally developed either parallel or perpendicular to the present coastline. These orientations permit a view of the alluvial and volcanic units (generally oriented perpendicular to the coast) and views of the marine units (generally oriented parallel to the coast).

The borings utilized in this project range in depth to over 200 feet. Well logs extend to over 1000 feet in some cases. However, the general control available limits the effective depth of study to approximately elevation -100 feet with shallower limits in many areas.

The method of presentation of the cross sections indicates the degree of control.

The use of most of the boring data for this project is predicated on the agreement that particular borings or their exact locations not be specifically identified. The private firms whose files were used require that permission of their clients be obtained in writing before the borings can be referred to specifically or shown on maps. Since the number of clients involved make this procedure prohibitive, the materials are shown and discussed with a generalized, rather than specific, indication of control. In particular cases, where specific reference is permitted, sample boring logs are presented to provide an indication of the nature of the interpretation which was applied in classifying the conditions in different locations and in different subsurface materials.

In addition to boring logs, pile driving records have been used in the engineering geology portion of this study and pile driving performance for a few representative areas is discussed briefly in the final section of this paper to illustrate the general characteristics of pile placement in the various materials encountered.

In summary, it is the aim of this thesis to produce a description of the subsurface conditions in the project area, and from this description, to develop a better understanding of the geologic history and engineering geology of the area. This paper presents the results of the most detailed geologic study (in terms of a number of control points) of any project completed to date on a section of a Hawaiian coastal plain.

CHAPTER II

METHODS OF INVESTIGATION

DATA SOURCES

The first step in developing this project involved the identification of the sources and the collection of the boring logs. In general, City and State sources include borings taken from the building plans for highways, municipal and state buildings, parking structures, sewer profiles and well logs. Many of these sources are of older vintage, when engineering practice did not place as much emphasis on the precise nature of foundation materials as is common in modern practice. Consequently, borings from these sources have a wide range of quality with the older information being generally of a cursory nature. (An example of such a log might be: 0-5 sand; 5-8 grit; 8-15 rock.)

In cases where sources are driller's logs, unique problems of interpretation arise. On these logs, the subsurface materials are referred to in local terminology which is often unrelated to conventional engineering or geologic usage.

To take advantage of these logs, the writer has correlated local drillers' terms with probable geologic equivalents as follows:

Driller's Term	Geologic Equivalent
mudrock	tuff
puka puka rock	vesicular basalt
blue rock	basalt (usually massive)
grit	sandy silt

An additional difficulty is that in many cases, drillers descriptions do not adequately reflect what is actually in the ground. For example, cemented dune or beach sand may be logged as coral. These data sources, therefore, must be used with caution, but can be useful in providing supplementary information, particulary where other more reliable data can be correlated with it.

The most extensive source of information for this study includes the borings taken from foundation investigations conducted by the consulting engineering firms. The majority of these investigations were completed since 1960. The purpose of these borings is for the preparation of foundation recommendations for various types of structures, usually in situations where large loads and therefore, high bearing strengths, are required. These projects require detailed information of the subsurface conditions. Logs from such projects are usually developed by engineers or geologists and provide thorough and relatively reliable interpretation of the subsurface data. The logs from such sources include not only detailed qualitative descriptions generally based on established geological and engineering practice, but also include quantitative information such as blow counts per foot (for sampling attempts), percent core recovery (for rock core runs), and in many cases, laboratory test results.

GEOLOGIC UNITS

In order to convert the material descriptions from the source logs into geologic units, a classification system was developed which relates to the parameters that are presented on most logs, i.e. color, hardness, and grain size. Fortunately, Hawaiian geology is such that two of the most obvious characteristics, i.e. color and hardness (consistency), are frequently sufficient to indicate the general geologic classification of a given unit. Since these parameters were the ones most consistently presented in boring logs, their relationship to the geologic units is important. A description of the charateristics of the geologic units used in this study is presented below (additional discussion of the physical properties of these units is presented in Chapter V):

Lagoonal (Low-Energy) Deposits - Characterized by gray to white color and very soft to soft consistency. Generally, the lagoonal deposits are clay and silt with low permeability. These deposits frequently include loose coralline debris and lenses of soft and loose silty sand. The environment of deposition includes low-energy zones in lagoonal areas, tidal flats, and drowned stream channels. The latter two environments are not strictly lagoonal, however, the deposits of these environments in the project area are quite similar. In areas where peat deposits are encountered within the gray clay, swamp conditions are clearly indicated. Lagoonal deposits found in Honolulu are frequently on the order of tens of feet thick.

Diagnostic features of the lagoonal deposits include the gray color, soft consistency, and low blow counts (10 blows per foot or less during drive sampling), and predominance of silt and clay size particles.

Coralline Debris - This unit includes the heterogeneous material related to the reef environment including isolated coral heads and coral fragments, shells, sand and calcareous silt. These materials are generally permeable with occasional (sometimes large), cavities. The color of coralline debris is less diagnostic than for other units. Usually white, its color may range from tan or brown to pink. In addition, hardness is extremely variable. Its classification is based principally on the nature of the material, i.e., the presence of reef detritus which is not hard enough to indicate a coral ledge. There is no doubt that in some cases competent coral and coralline debris are misidentified for one another. This is due in part to problems in sampling and generally identifying coralline materials during drilling and in part to the heterogeneous nature of coral reef deposits. In general, where there was doubt, materials were classified as coralline debris rather than ledge coral.

Coral Ledge - For the purposes of this paper, coral ledges refer to hard zones of coral which are of significant thickness and sufficient lateral extent to indicate a continuous coral deposit. The largest, strongest, and most consistent coral ledge occurrence is generally along the algal ridge of the reef mass, which is at the outer edge of the reef a few feet below sea level in the breaker zone. Its strength is derived from the binding effect of the coral organisms and their symbiotic calcareous algae known generally as *Lithothamnia*. Weaker, less consistent coral ledges may also occur in the back reef and fore reef areas although such ledges are generally thin and do not occur over large areas. (Further discussion of the coral ledges found during this study is presented in Chapters 4 and 5).

It is significant to note that coral cannot withstand such environmental influences as fresh water and siltation (Edmonson, 1928). Therefore, where streams pass over the reef, the coral is killed and eroded away. The result is that the ledges cannot be expected to be absolutely continuous; however, they tend to occur consistently at particular levels relative to previous or present stands of the sea. Therefore, for a particular site, coral presence at a given elevation might be anticipated, based on nearby information, but its occurrence must definitely not be assumed.

Diagnostic properties of coral ledges include unbroken skeletal structure in growth position, extreme hardness and high blow counts on the order of 100 blows per foot. In cases where cemented beach sand (beach-rock) is encountered, its similar strength properties cause it to be misidentified in the source borings, in some cases, as coral ledge. Wherever possible, distinctions are made between coral ledges and beachrock.

<u>Alluvial Deposits</u> - This unit includes stream deposits which are generally composed of stiff silt with varying amounts of sand, gravel and boulders. Compressibility and permeability are variable; however, a brown color is generally characteristic. Alluvial deposits are, of course, the result of stream erosion

and deposition. Although the alluvium is generally characterized by a substantial fraction of detritus of terrestrial origin, the alluvium found in Honolulu frequently contains a considerable amount of coral gravel and/or coral sand. This coralline material may be eroded from some point upstream or may have been mixed with the alluvium during its deposition in a reef zone. Localized alluvial lenses frequently occur within coralline deposits.

Within some of the deeper alluvial channels, low-energy alluvium with peat layers is found. This material is similar in properties to the lagoonal deposits discussed above; however, its location in an alluvial channel suggests that it probably is a product of a drowned channel, or estuarine, environment. In order to emphasize the alluvial origin of the channels, the term low-energy alluvium is used for such deposits.

Cinders and Uncemented Ash - Poorly graded fine to coarse black sand characterizes this unit. It is a volcanic/aeolian deposit occurring within and in the lee of ash and cinder cones. Frequently, however, cinders are reworked and redeposited by stream action and found interbedded with alluvial materials. This unit is highly permeable with firm to dense compactness, and it is sometimes cemented.

Tuff - Tuff is a volcanic/aeolian deposit generally composed of cemented ash with some cinders. It occurs within and in the lee of tuff cones. Tuff is usually dark brown in color with low permeability and compactness ranging from firm to very hard depending on the degree of weathering. It also may be reworked by stream action.

Residual Soil - Residual soil includes in-situ, completely decomposed basalt or tuff with a variable red-brown or dark brown color, respectively. It is composed principally of silt sized particles with stiff to hard consistency and low compressibility if undisturbed. This unit usually occurs overlying unweathered rock and often includes less weathered boulders of the parent material.

Basalt - Partially weathered to unweathered basalt is included within this unit. Color ranges from gray-black to red with high permeability due to vesicularity, jointing, clinker layers, and lava tubes. It is usually very hard, and where it occurs in substantial thicknesses, it has the highest strength of any material available in the Hawaiian Islands. Basalt flows in the subject area are generally found within sedimentary sequences where their lateral and vertical distributions can be highly variable.

Fill - Material placed by man is classified as fill. This material is heterogeneous and highly variable in composition and strength. Thickness of fill is inconsistent, but fill deposits generally become more extensive near the existing shoreline where land areas have been reclaimed from previously low lying wetlands. In many cases, the identification of fill is difficult and its classification is generally more tenuous than that of the other units.

Sand and Gravel Layers - Subunits of sand and gravel are found within many of the various units mentioned above, including lagoonal deposits, coralline debris, alluvial deposits, cinder, and fill. The characteristics of these layers of granular material generally depend on the unit within which they occur.

In converting boring log descriptions to this geologic unit system, examples of distinctions which were made between materials of similar grain size--on the basis of color, include: alluvium (brown) versus lagoonal deposits (gray), cinder sand (black) versus coral sand (white or tan); and on the basis of degree of compactness, include: coral ledge (very hard, high blow counts), lagoonal deposits (very soft, very low blow counts).

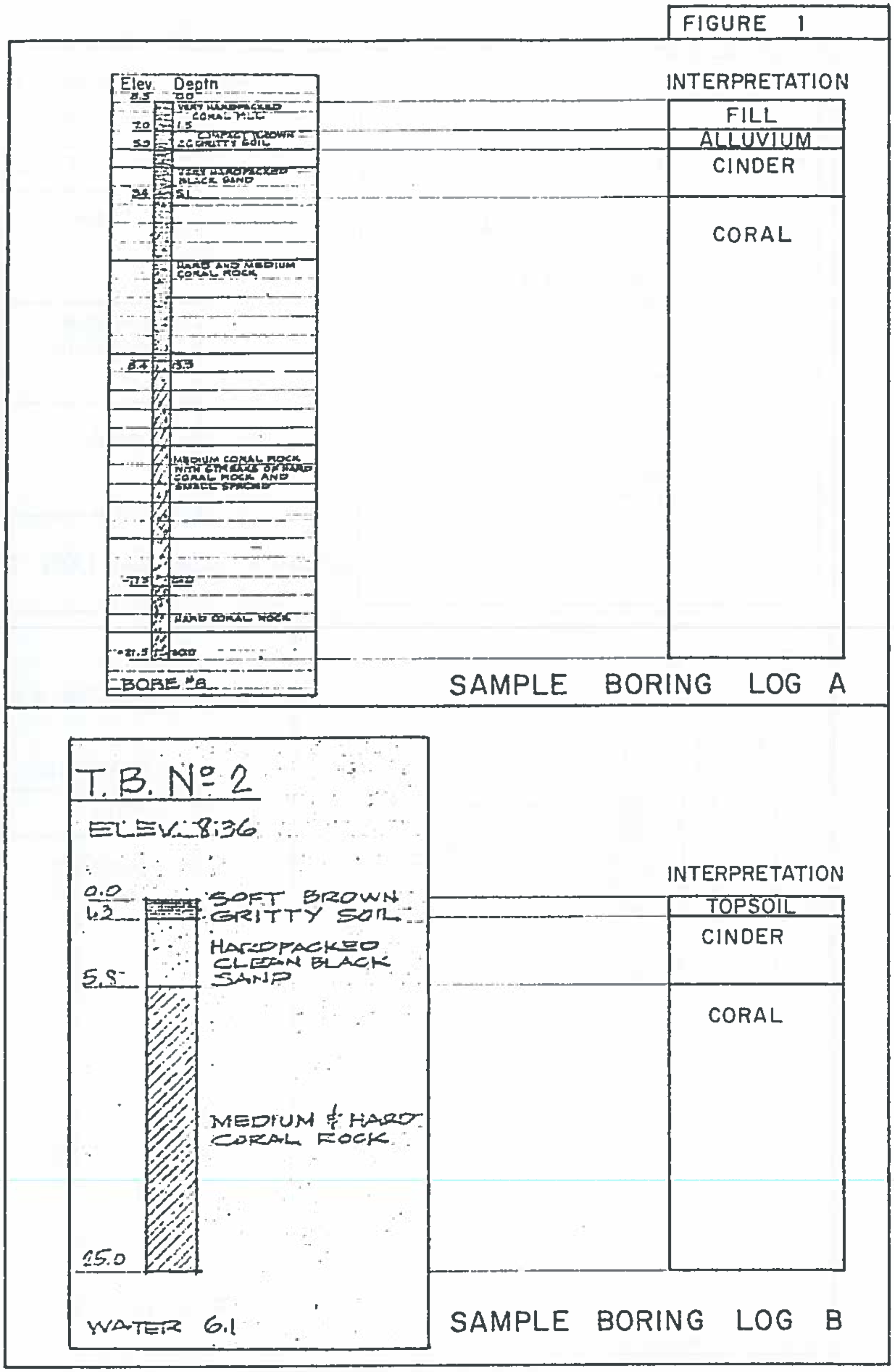
Due to the frequent interbedding of facies in the subject area, many of the subsurface materials encountered in the boring logs do not satisfactorily fall within one particular geologic unit. For this reason, a method of combining units was utilized in order to indicate zones of transition and to facilitate correlation. Combination classifications were developed by assigning to a given material as many units as appear to be significantly represented, with the most dominant unit providing the major classification for that material. Therefore, a stiff brown silt with coral gravel is represented as alluvium with coralline debris. Such a deposit might be interbedded with reef detritus.

This procedure allows for more realistic correlation of materials. The inevitable inconsistencies and inaccuracies in the source logs tend to become less significant with this method of combining units; and general trends may be more readily followed where they might otherwise be masked by very local changes.

SAMPLE BORING LOGS

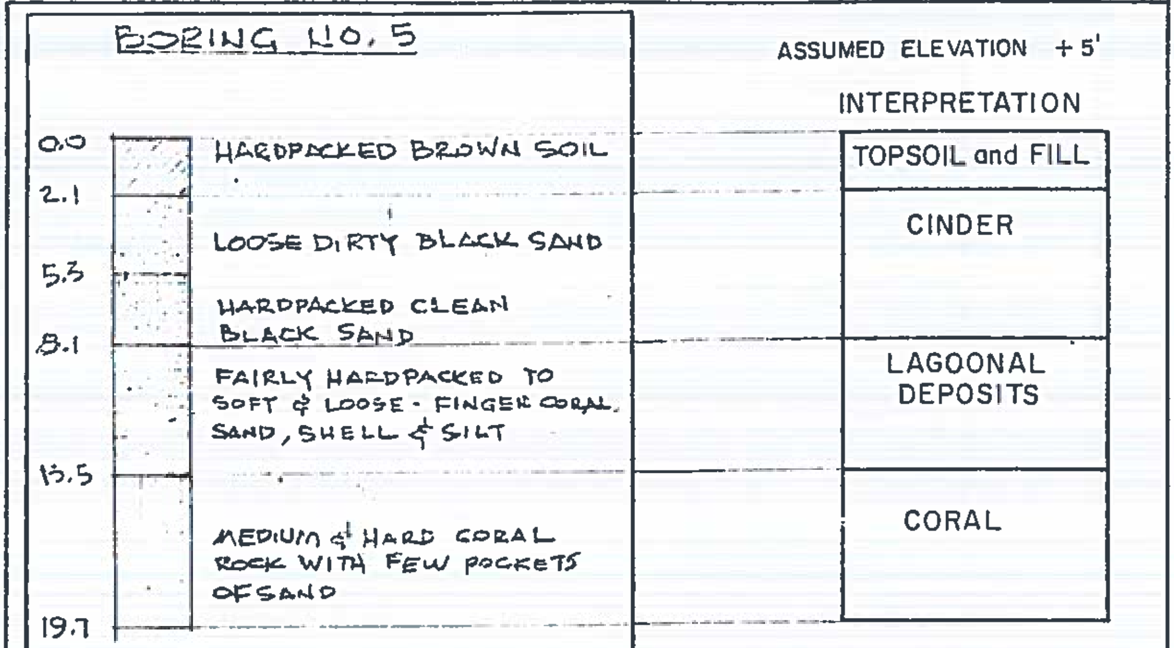
In order to specifically illustrate the method of interpretation which was used in relating boring log descriptions to the geologic units described above, Sample Boring Logs are presented on Figures 1 through 6. The location of these borings are shown on the project area map (Plate 1). In these figures, actual logs are reproduced on the left side of the page and the interpretation of the different units is indicated on the right side.

Figure 1, Sample Boring Logs A and B, shows the occurrence of a coral ledge at +3.4 feet, and +3.5 feet, respectively. This is a coral ledge which is consistently found along the landward side of the project area and is referred to as the +5 Coral Ledge on the geologic map (Plate II). This coral is typically described as "medium and hard coral rock" on source logs and has been observed in cores to be skeletal coral and/or calcareous algae. Empty spaces occur in some areas in this coral--the larger spaces presumably due to solution activity and the smaller ones attributable to either solution or to the growth forms of the coral. Immediately above the coral is a cinder layer, called "black sand", which consistently overlies the +5 coral. The surface unit, described as "brown gritty soil" is interpreted to be fill and/or alluvium. Sample Boring Log C (Figure 2) describes a lower occurrence of the coral (-8 feet) at the seaward edge of the +5 coral ledge. (Boring surface elevation is assumed to be +5 to +6 feet based on U.S.G.S. Honolulu Quadrangle contours and the ground water depth). The "fairly hardpacked to soft and loose finger coral, sand, shell, and silt" described on this log is somewhat confusing terminology which is frequently used in source logs to describe the soft lagoonal deposits. The layer of "loose dirty black sand" is interpreted to be an interval where the cinder is intermixed with some alluvial silt, hence the "dirty" description. This material is

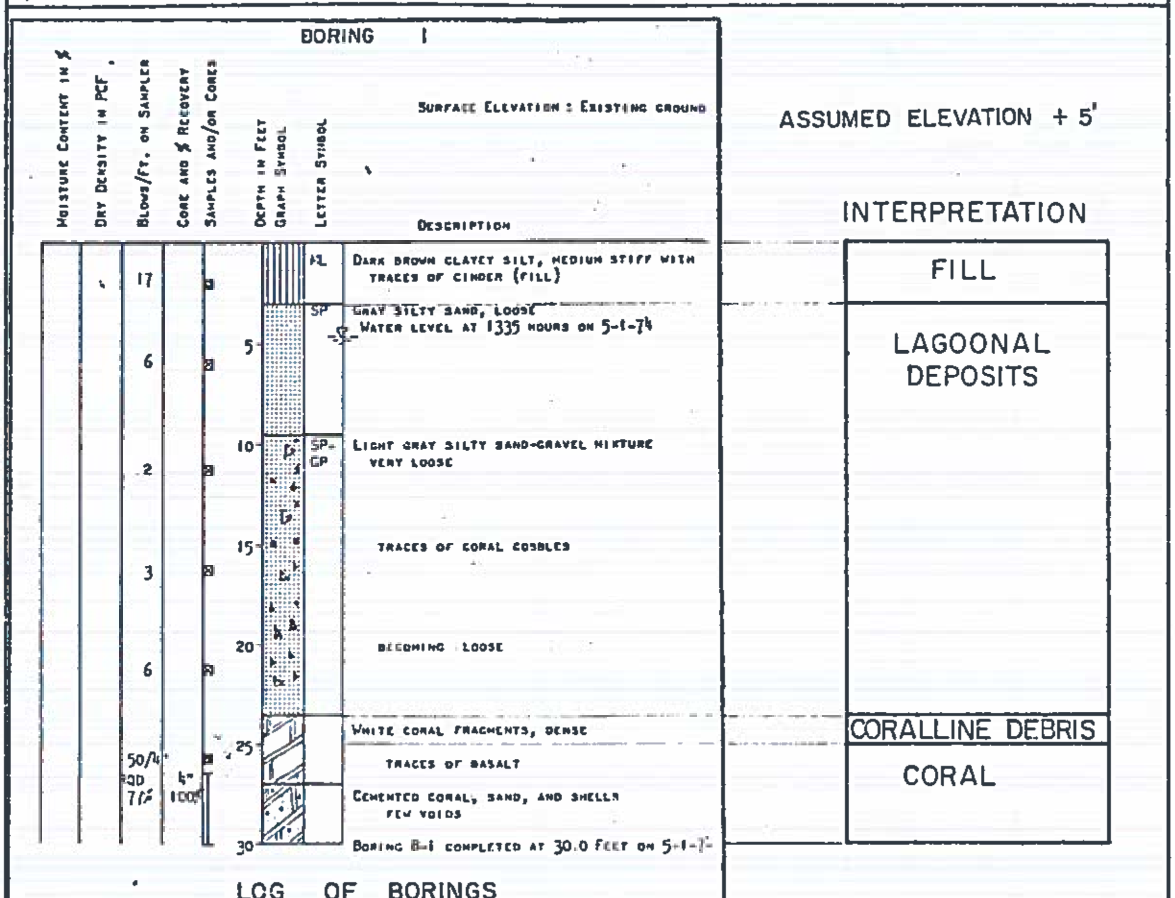


REFERENCE: LOG A, STATE HIGHWAY BUILDING
LOG B, MCKINLEY HIGH SCHOOL

FIGURE 2



SAMPLE BORING LOG C



SAMPLE BORING LOG D

REFERENCE: LOG C, KAPIOLANI COMMUNITY COLLEGE
LOG D, DAMES & MOORE, ALA WAI PARK

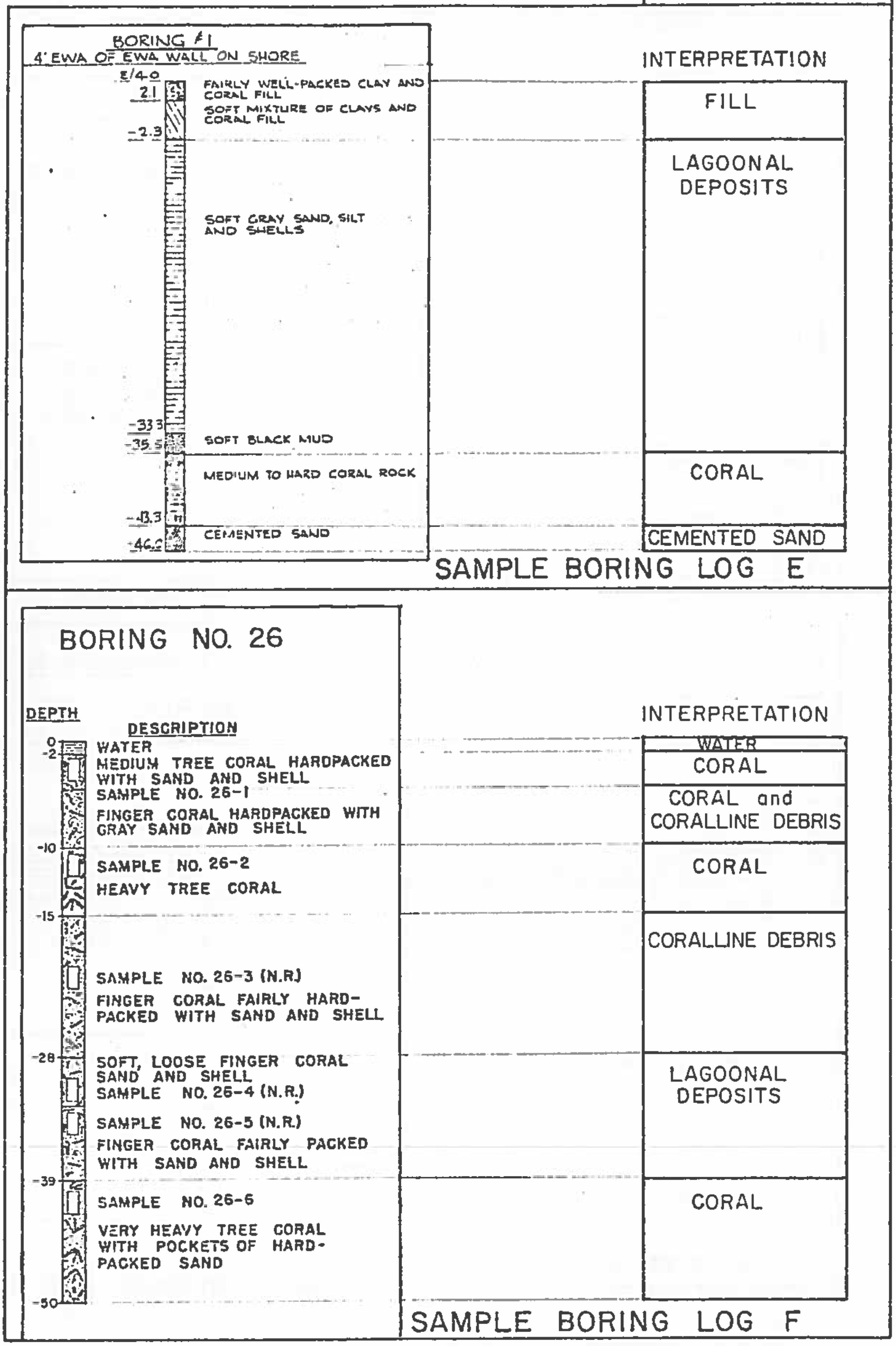
included within the "cinder" interpretation. It is likely that in many cases the cinder in the study area is reworked to greater or lesser degrees and therefore can be assumed to have at least a minor alluvial history.

Sample Boring Log D (Figure 2) describes coral at -20 feet (assumed surface elevation is +5 feet). This is part of the -15 coral ledge shown on the geologic map. The interpretation of the source log in this case varies somewhat from the original log description. The top of the coral, based on the high blow counts, is interpreted to be about two feet higher than that shown on the original log. However, it is possible that the entire "coral" unit here is a cemented coralline debris. This is one of the difficulties of interpreting logs without seeing the actual cores. In lieu of actually looking at the core, it has been necessary to rely on the availability of a large number of boring descriptions of a given unit and to characterize the unit by the description which occurs most frequently. Also, descriptions have been double-checked where cores are available. In the case of the -15 ledge, although it may be characterized as either coral or coralline debris on the basis of Sample Log D, consideration of nearby borings and a review of nearby cores of this interval indicates that the interpretation of this unit as being coral ledge appears to be more realistic. The description of "traces of basalt" within the coral in this log is baffling. It may be that these "traces" are actually cinders which fell from the fill unit during drilling and were then brought up during sampling. No "traces of basalt" have been found elsewhere in this stratigraphic location.

Sample Boring Log E (Figure 3) describes coral at -35.5 feet which reflects the -30 coral ledge shown on the geologic map (Plate II). Sample Boring Log F (Figure 3) also shows the -30 ledge--at -39 feet. However, in this boring, which is offshore of the existing shoreline, the modern reef is found at -2 feet over the -30-foot ledge with the two coral ledges being separated by a layer of coralline debris over a layer of lagoonal deposits.

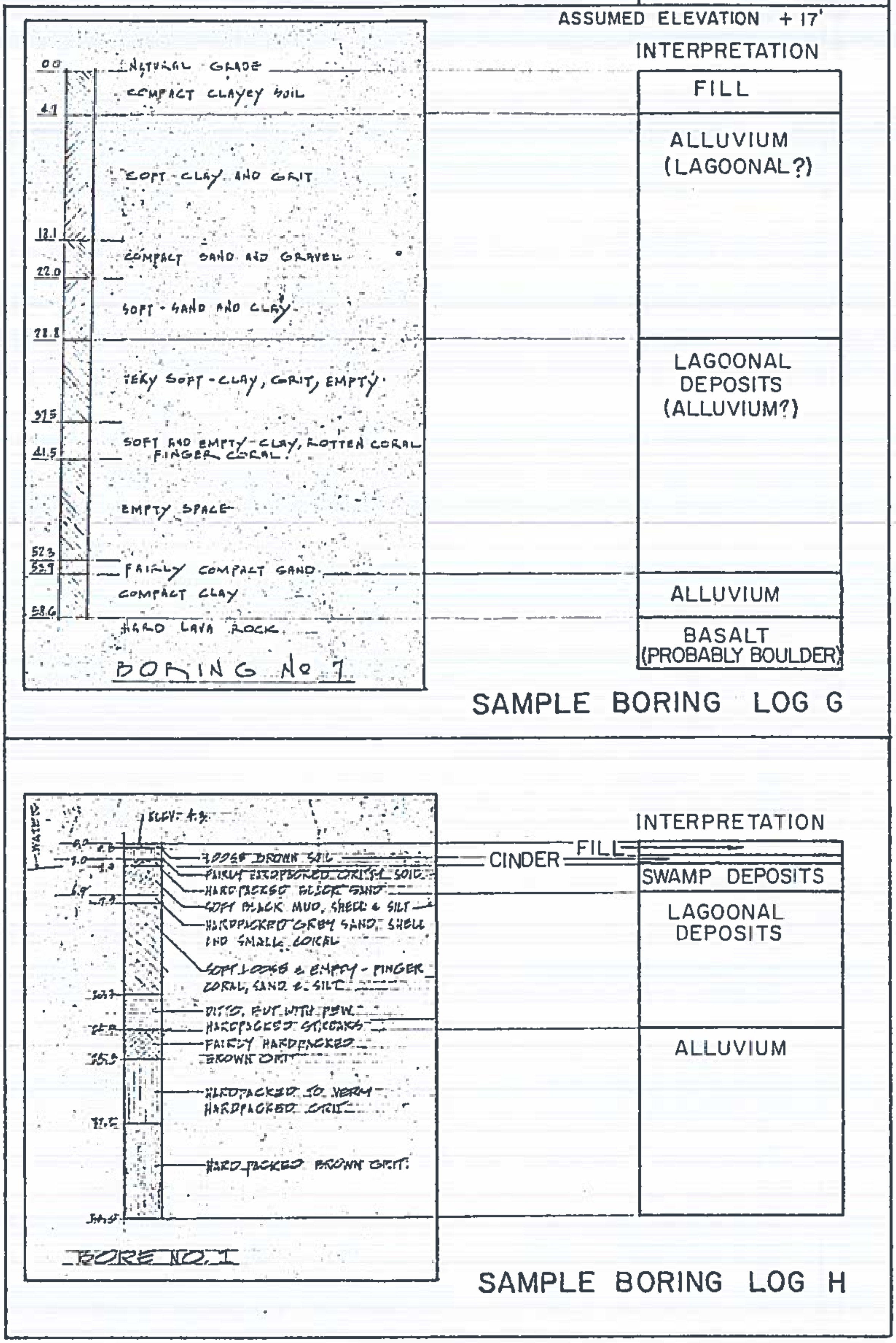
Sample Boring Logs G, H, and I (Figures 4 and 5) describe the conditions in alluvial channels which cut the various coral ledges. Log G presents a log which is difficult to interpret because of the lack of color descriptions. The lower unit is assumed to be lagoonal based on the "soft" description and the occurrence of coralline material. Due to the lack of coralline material which might be subject to solution, the "empty space" described in the source log is interpreted to be a layer of very soft clay through which drill rods fell under their own weight with very little resistance, thus giving the appearance of an "empty space". In Log H, the "soft black mud, shell, and silt" is interpreted to be a swamp deposit grading to lagoonal with depth. Log I interprets considerable "low-energy alluvial deposits".

FIGURE 3



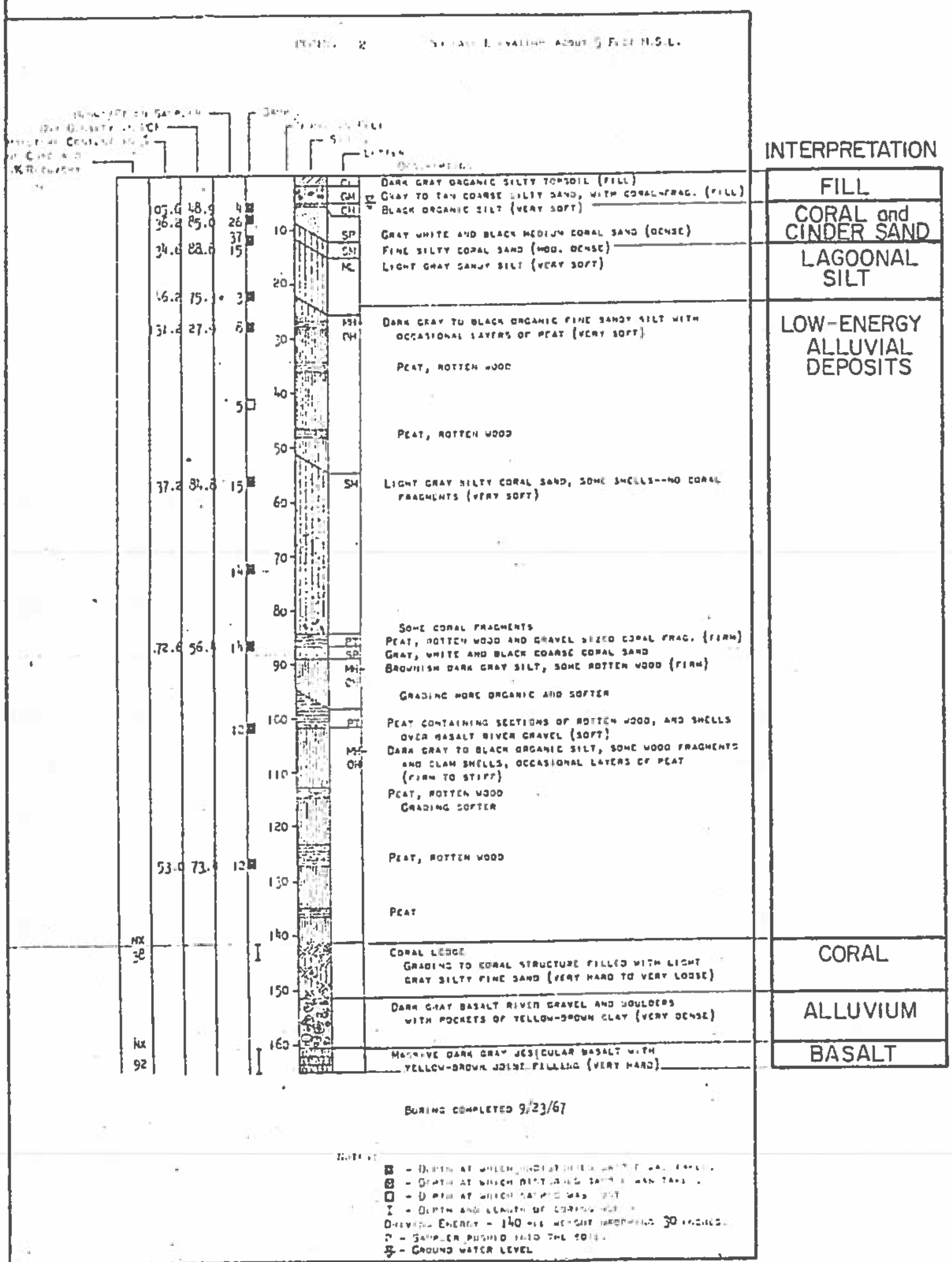
REFERENCE: Log E, Ala Moana Bridge over Ala Wai Canal
Log F, H.A.R. Austin/Law & Wilson, Ala Moana Reef

FIGURE 4



REFERENCE: Log G, Kaimuki High School
Log H, Ala Wai Elementary School

FIGURE 5



SAMPLE BORING LOG I

REFERENCE: LOG I, DAMES & MOORE, ALA WAI BOULEVARD

This interpretation is based on the fact that the deposits appear to be low-energy swamp-type deposits, with some alluvium, and were deposited in an alluvial channel. These deposits probably characterize a drowned stream channel.

GRAPHIC PRESENTATION

Visual presentation of the results of this study is presented on the project area map, a modified geologic map, and three subsurface sections. These items are described as follows:

Project Area Map (Plate I) - This map is a reproduction of part of the U.S.G.S. Honolulu Quadrangle Map at a scale of one inch equals 2000 feet. It shows the boundaries of the project area, its relation to the surrounding area, and the section lines along which the subsurface sections are prepared. Also, Sample Boring Locations are shown.

Geologic Map (Plate II) - This map presents a generalized view of the geologic units which dominate the near-surface strata in the project area. It was originally prepared at a scale of one inch equals 400 feet and is presented herein at a scale of one inch equals 800 feet. This is a modified geologic map in the sense that, in areas overlain by the very soft lagoonal/low energy deposits, it indicates the first competent geologic unit rather than simply showing the surface units. Furthermore, the modern coral reef is not shown so that the underlying ledges may be more clearly defined. In this manner of presentation, this map could be characterized as a paleogeologic map, presenting the conditions which existed immediately prior to the advance to the present sea level during which the formation of the modern reef and deposition of the lagoonal material took place. An additional diversion from the typical geologic map is the indication of areas in the eastern part of the study area where basalt occurs immediately below competent surface units. The purpose of this type of presentation is to provide a map which is useful to both geological and engineering geological purposes.

Subsurface Sections - Three subsurface sections (Plates III, IV, and V) are presented. The sections were originally prepared at a horizontal scale of one inch equals 200 feet and a vertical scale of one inch equals 20 feet, producing a 10:1 vertical exaggeration of the features shown. This vertical exaggeration was found necessary in order to provide appropriate detail in the subsurface conditions on a section with a reasonable horizontal dimension. The sections are presented here at a horizontal scale of one inch equals 400 feet and vertical scale of one inch equals 40 feet. Section lines are shown on the project area map (Plate I). These locations were chosen to take maximum advantage of the available subsurface control and to illustrate particular subsurface conditions (as discussed in later chapters). A plan view of the area traversed by the section is also shown on the section page--corresponding to the section line in the manner of a plan and profile. Each section actually represents the conditions found in borings within a 400-foot wide corridor (200 feet to either side of the section line). In some cases, control on more than one geologic unit exists within the corridor. For example, an alluvial channel may occur on one side of the corridor and a coral ledge may occur on the other side. In these cases, the units which appear to best represent the conditions along the actual section line are shown on the section.

The degree of control is shown on the sections by intervals classified according to the frequency of borings which occur within the section corridor. The descriptions of control presented are based on the following criteria:

Excellent - 3 or more borings per 100 feet
Good - 2 borings per 100 feet
Fair - 1 boring per 100 feet
No control- No boring within 100 feet.

Therefore, an interval indicated to have "good" control would, at any point within that interval, have two borings within the section corridor within 100 feet or less (measured parallel to the section). The degree of control is indicated on the sections by graphical symbols. In addition, the depth of control is shown by utilizing thick solid lines for contacts where information is available and thinner, broken lines where conditions are interpolated or extrapolated. The upper coral ledges, which are discussed in considerable detail in this thesis, are shaded on the section for easy reference.

CHAPTER III

SUBSURFACE CONDITIONS

Within this chapter, the subsurface conditions encountered in the project area are described. The intent in this section is to present an objective indication of what is found at each site. Chapters IV and V deal with interpretations of these conditions.

The format of the subsurface conditions descriptions is keyed to a grid system which is shown on the geologic map (Plate II). Each quad within the grid is a square 2000 feet on a side. To facilitate access to specific area descriptions, the chapter is divided into subsections with headings which indicate the quad(s) which are covered in the section. These headings are given in the Table of Contents.

The subsurface conditions discussed in detail below, yield a reasonably complete picture of the subsurface of this area of Honolulu (see Plate II). In general, the area is dominated by three coral ledges, all of which occur as bands more or less parallel to the existing shoreline. The +5 coral ledge is found from the landward boundary of the project area (King Street) to about 2000 feet seaward of King Street. The top of this ledge generally occurs between +5 feet and -5 feet. Seaward of this ledge, the -15 coral ledge occurs, at elevations ranging from -15 feet to -29 feet. This ledge is on the order of 1600 feet wide and its seaward boundary roughly coincides with the Ala Wai Canal, and west of the canal, with Ala Moana Boulevard. From this ledge to beyond the existing shoreline, the -30 coral ledge is encountered at elevations ranging from -30 to -48 feet. The modern reef overlies the -30 ledge seaward of the existing shoreline. Elsewhere, above the -15 and -30 ledges, lagoonal deposits are found grading to swamp deposits near the existing sea level. All of the coral ledges are dissected by various alluvial channels, some of which extend to elevation -180 feet and deeper. In addition, various basalt flows are found, both above and below the coral ledges, and in some cases within the alluvial channels. In the northeast corner of the project area, basalt occurs at the surface in two, apparently unrelated, locations.

The remainder of this chapter is addressed to the detailed description of the subsurface conditions in the project area.

QUAD A-1/B-1

At the east end of the project area, at the intersection of Harding and Kapahulu Streets, the subsurface is characterized by near-surface basalt, possibly the product of flows from the Kaimuki shield volcano and the Mauumae and Kaau volcanics. Basalt layers occur in one boring well above sea level and in all the borings at slightly above sea level. A maximum of three basalt layers, roughly 15 feet, 17 feet, and up to 14 feet thick are found here, occurring at elevations of about +25 feet, +5 feet, and -17 feet, respectively. Koolau basalt is apparently encountered at about -75 feet in this area with intervals of alluvium overlying each basalt flow.

Further to the south, at Leialoha Avenue about 200 feet west of Kapahulu (Well No. 9, Stearns & Vaksvik, 1938), a 70-foot basalt layer is found at +6 feet overlain by coral at +13 feet. At this location, Koolau(?) basalt is at about -240 feet. Seaward of this point, at the intersection of Makaleka and Kapahulu Streets (northeast corner of Quad B-1) the log of Well No. 11 (Stearns & Vaksvik, 1938) indicates basalt occurring at about -2 feet overlain by soil. This basalt is 75 feet thick and overlies coral and clay which extends to the Koolau(?) basalt at -337 feet.

At the east boundary of Kaimuki High School, (about 400 feet north of the south side of A-1), basalt (possibly a boulder) is encountered at an elevation of -17 feet to at least -19 feet, overlain by alluvium. Basalt is found at roughly the same level (about -15 feet) in Quad B-1 on Makaleka Street, about 300 feet from Date Street. At this location, the basalt is at least 9 feet thick. A 10-foot thick coral layer (the +5 coral) overlies the basalt here with its upper surface at about +3 feet. Further seaward, at the intersection of Palani and Date Streets, the basalt is found at -5 feet (at least 13 feet thick) overlain by coral up to +5 feet. South of Date Street, no further control is available on this near-surface basalt, however, it probably continues for some distance beneath the Ala Wai Golf Course.

Two other borings are available along Date Street which provide control on the near-surface coral layer. Near the intersection of Date Street and Kapahulu Avenue, coral is found at -3 feet and further west, at the intersection of Date Street and Lukepane Avenue, coral occurs at sea level. In both of these borings, the coral layer is at least 10 to 15 feet thick. (The near-surface basalt layer may underlie the coral at these locations, but the basalt is not found within the depths explored, i.e. to -20 feet and -12 feet, respectively).

At the northwest corner of Quad A-1, underlying the channel of Manoa-Palolo Stream, basalt occurs at roughly -40 feet at King Street, and roughly -60 feet at Kapiolani Boulevard. Beneath Kaimuki High School, at about the center of A-1, basalt is apparently found at -48 feet. However, in these cases the basalt was not penetrated and these occurrences may be only boulders.

The soft sediments of Manoa-Palolo Stream overlie the basalt (boulders?) in this area in a wide band extending from the existing west bank of the Stream to about the east boundary of Kaimuki High School. The channel maintains roughly this width from the H-1 Freeway to just south of Date Street at which point the old Manoa-Palolo Stream Channel diverts to the east across the Ala Wai Golf Course and the existing stream veers to the west (see Plate II). Previously, the area between the existing Manoa-Palolo Stream channel and the eastern boundary of Kaimuki High School was occupied by two separate stream channels--Manoa Stream (on the west) and Palolo Stream (on the east) (Stearns & Vaksvik, 1938, Plate I). These two channels joined at about Date Street.

The subsurface conditions encountered in the stream channel north of Date Street include alluvium extending to basalt (boulders?) at a depth rising from greater than -86 feet near Date Street to the -40 foot basalt level (mentioned in the preceding paragraph) at King Street. In general, the Manoa Stream sediments include alluvial silt with sand and gravel lenses. Immediately overlying the basalt (boulders?) deposits of black sand are found.

In the neighborhood of Kaimuki High School, in the old Manoa-Palolo Stream Channel (outside of the existing channel), the surface deposits include about five feet of fill over a layer of lagoonal/swamp deposits extending from sea level to about -16 feet. These lagoonal deposits are similar in characteristics and elevation to the lagoonal material found further seaward over the -15 and -30 coral ledges. In the central area of the high school, a small coral layer occurs at a depth of about -20 feet. This ledge is not well defined, however, and may represent a portion of the +5 ledge (which occurs in the adjacent areas) which was eroded to -20 feet by Manoa-Palolo Stream. This ledge may account for a source of the coralline gravel in the Manoa-Palolo Stream deposits.

In the southern half of Quad B-1 alluvial channels, interpreted to be the old Manoa-Palolo drainage, are found as shown on the geologic map (Plate II) based on old maps (circa 1887). The presence of these channels is supported by aerial photographs taken before the completion of Ala Wai Golf Course which show a definite color change in the soil corresponding to these channel locations. However, no subsurface information is available within these channels.

QUAD A-2/B-2

Between King Street and Kapiolani Boulevard, west of the present Manoa Stream Channel, basalt occurs at the surface, forming a topographic high with maximum elevation of about +30 feet. The surface occurrence of this basalt extends just west of Kuhio School and about two blocks seaward of King Street. It apparently represents the seaward extension of the Sugarloaf lava flow(s) which crops out further north in the old Moilili Quarry. The Sugarloaf lava has been interpreted to have pushed the lower portion of Manoa Stream from the center of Manoa Valley to its present course on the east side of the valley (Stearns & Vaksvik, 1938). This basalt overlies coral and beach sand (apparently similar in age to the +5 ledge) at about +20 feet in the Moiliili Quarry (Stearns & Vaksvik, 1938). Immediately southwest of Kuhio School, however, the basalt occurs within three feet of the surface and is at least 27 feet thick--i.e. extending to at least -10 feet. The fact that the basalt does not overlie the +5-foot coral (found further west) at this location suggests that this area is within the original channel of Manoa Stream and that the coral has been eroded out by the stream. The Sugarloaf lavas apparently flowed down this channel and filled it with a considerable thickness of basalt--displacing the stream to more or less its present course further east.

Seaward of Kapiolani Boulevard, in the area subtended by Kapiolani Boulevard, Date Street, and Manoa-Palolo Stream, the Sugarloaf basalt occurs at lower elevations, about -5 feet, overlain by alluvium. Between Date Street and the northeastern boundary of Iolani School, the basalt is found at depths ranging from -10 feet to -20 feet. Boring control on this flow is not available seaward of this area. The terminus of the Sugarloaf flow probably occurs within about 1000 feet southwest of Date Street.

West of the Sugarloaf lavas, from the northwest corner of A-2, an extensive coral ledge occurs at an elevation of about +5 feet--i.e. the +5 ledge. This coral has been affected by solution and is particularly cavernous in the vicinity of the intersection of King Street and University Avenue. On the northwest corner of this intersection, cavities up to 10 feet in height have been encountered. It is understood that a building which previously occupied the southeast corner of this intersection was severly damaged by the undermining of its foundation by dissolution of the coral. Similarly, 5-foot high cavities were found about 300 feet southwest of the intersection of Kullei Lane and University Avenue. The coral in these areas is generally about 10 to 15 feet thick and underlain by alluvium. The cavities appear to occur at the bottom of the coral layer immediately over the alluvium. Presumably this is the result of acidic rainwater flowing on top of the relatively impermeable alluvium. Cores of the coral ledge from this area were examined by the writer. The coral is generally characterized by well developed algal coral (coralline algae) with small voids along the contacts between beds. These voids may be related to solution.

To the east of this area, on King Street between Kahoaloha Lane and Kahuna Lane, a cemented beachrock is found with a surface elevation of about +2 feet. This beachrock is about 20 feet thick and overlies alluvium. It takes the place of the coral found further seaward and may represent a shoreline of the sea which formed (or planed off) the +5 coral. (This unit and the subsurface between this point and the existing shoreline are presented on Plate III, subsurface section A-A'.)

Roughly 400 feet southeast of University Avenue, at the end of Kuilei Lane, control is available to about -84 feet. In the borings here, coral (and/or cemented sand) is underlain by alluvium at about -13 feet. The alluvium generally extends to the maximum depths explored and is reported to include some tuff within the alluvium from about -28 to -36 feet. Also, some coralline debris is found within the alluvium from about -50 to -60 feet. In one boring, coralline debris is found beneath the alluvium at about -70 feet.

QUAD A-3

As shown on the subsurface section A-A' (Plate III), conditions similar to those described in the last paragraph, i.e. characterized by the +5 coral ledge, dominate this area to south of Date Street. On Hausten Street, opposite the end of Kapaakea Lane, the coral surface elevation ranges from -1 to +1 foot and is overlain by about 2 feet of alluvium with some organic debris and cinders under about 3 feet of fill. The coral is about 7 feet thick and underlain by coralline debris to about -35 feet where alluvium is encountered. Between this location and Date Street, good control indicates that similar conditions characterize this area.

Just south of Date Street, on University Avenue, control is available at McCully Fire Station. The borings here identify the seaward limit of the +5 coral ledge and the inland boundary of the -15 coral ledge. Specifically, at this location the +5 coral is found at about -5 feet within 100 feet seaward of Date Street. This coral is only about 6 feet thick here and is underlain by coralline gravel to -27 feet over alluvium from -27 feet to -36 feet followed by coralline debris with some coral to the maximum depth explored of -56 feet. Further seaward, lagoonal deposits (with coralline gravel) occur at +3 feet (under about 2 feet of fill) and extend to about -15 feet where coral is found. This coral is about 8 feet thick and underlain by sand and coralline debris to at least -25 feet. It should be noted that the upper (+5) coral in this area is not nearly as well developed as it is 300 feet to the northwest (which is the nearest control point).

From this point, the seaward boundary of the +5 ledge appears to run more or less along Lime Street, however, control is poor. Further inland, control is available on the upper coral at the intersection of Date and Paani Streets and at King and Makahiki Streets. At the latter location, the coral occurs at the highest elevation of any occurrence within the project area. In two borings, coral is found at +10 feet, extending to about -21 feet where it overlies sand to at least -23 feet. In the third boring in this vicinity, coral is encountered at +2 feet, overlain by alluvium with coralline debris. Just across Makahiki Street, opposite the intersection with Algaroba Street, one boring indicates the coral ledge at about sea level. At the Date and Paani location, the coral occurs at -8 feet in two borings. This coral is about 20 feet thick and underlain by sand and coralline debris to at least -75 feet. In one boring here, coralline debris dominates the entire section and no real ledge is found. In all three borings at this location, the upper units are characterized by a thin layer of topsoil over a one foot cinder layer. Between the cinder and the coral, a fine gray sand (probably lagoonal or swamp deposit) occurs.

QUAD A-4

One block further west, at the corner of Date and Wiliwili Streets, conditions are very similar to those described in the preceding paragraph. Two borings here indicate the +5 coral at -5 feet and -7 feet extending to at least -43 feet. Lagoonal deposits, about 11 feet thick, overlie the coral; and the surface unit is about three feet of fill. No cinder was reported here.

On the block bounded by Waiola, McCully, Citron, and Pumehana Streets, six borings are available. The +5 coral was encountered in four of the six borings at elevations ranging from sea level to -4 feet. The ledge here is characterized by coral layers interlayered with sand and this ledge extends to at least -15 feet. Above the coral is a surface unit of about two to three feet of fill with lagoonal deposits and a trace of cinder occurring between the fill and the coral. In two borings on the east side of this location, the coral is poorly cemented and occurs only as coralline debris. In one of these latter borings, cemented sand is found from -12 to -15 feet.

Further toward King Street, two borings are available on Algaroba Street, one at the intersection with McCully Street and one at the intersection with Wiliwili Street. Coral is encountered at both of these locations, at sea level and +5 feet, respectively, overlain by alluvium and fill. Control at these locations extends to about -6 feet.

At King Street and Hauoli Street, two borings indicate that no coral ledge occurs here to a depth of at least -31 feet. Alluvium with some lenses of cinder occurs at this location to the depths explored. This alluvium is probably related to the Kaheka Channel found further west.

The seaward boundary of the +5 coral ledge appears to extend more or less along Lime Street in Quad A-4, however, the only control for this assumption is at the southwest corner of the quad. In the area just west of the intersection of the existing channel of Makiki Stream and Kapiolani Boulevard, three borings are available. In these borings, a thin coral ledge is described at about -28 feet which is on the order of three to five feet thick and underlain by coralline debris, coral and sand to at least -57 feet. At this location, fill occurs from the surface to about sea level (in one boring, a layer of cinder occurs from sea level to -2 feet) followed by soft lagoonal deposits and coralline gravel extending to about -23 feet. A 4-foot layer of alluvium immediately overlies the coral. It appears that the coral here is an eroded surface of the -15 ledge and, where eroded, has been partially replaced by alluvium.

The existing Makiki Stream crosses the southwest corner of Quad A-4 in a lined channel. However, based on old maps of Honolulu (circa 1887) the natural channel of this stream appears to be further east. Therefore, in the absence of information to the contrary, alluvium, possibly a channel cutting through the coral layers, can be expected in this area.

QUAD A-5

In the southeast corner of Quad A-5, between the existing channel of Makiki Stream and Kalakaua Avenue (northwest of the location discussed in the preceding paragraph) four borings are available. The conditions disclosed are consistent from boring to boring but inconsistent with the surrounding area in that no coral ledge is found in the upper 165 feet. The deposits encountered include fill from +6 feet to about +2 feet over lagoonal deposits to -24 feet followed by a layer of alluvium (with occasional cinders) which overlies sand and coralline debris at about -30 feet. The sand unit extends to alluvium at -48 feet. Coralline debris with occasional alluvial lenses is found below the alluvium from about -70 to the top of a coral ledge at -165 feet. The coral ledge is about 8 feet thick and underlain by alluvium and coralline debris to the maximum depth explored of -194 feet. The fact that there is no +5 coral ledge here suggests that this location is seaward of the margin of the +5 ledge. In addition, coralline related deposits (namely the sand and coralline debris) occur at roughly the same elevation as the -28 foot occurrence of the eroded -15 ledge in the southwest corner of Quad A-4, discussed above. It is possible that the entire coral unit has been removed by erosion and only the sand and coralline debris remain with the alluvium deposited in place of the ledge coral.

The existing channel of Makiki Stream and the channel shown on older maps extends from the southeast corner of Quad A-5 toward Punahou Street. This stream may have been the agent of erosion which caused the conditions described in the preceding paragraph. In addition, thicker intervals of alluvium may occur east of the existing stream.

Between the channel of Makiki Stream and Kalakaua Avenue, opposite the intersection with Makaloa Street, three borings are present. Two borings indicate the +5 coral ledge at about -8 feet which extends to about -46 feet and is underlain by alluvium to at least -53 feet. Above the coral, fill and lagoonal deposits occur. In the third boring (adjacent to the stream), conditions are essentially the same, with the exception that sand and coralline debris occurs from -8 feet to -48 feet (where there is coral in the other two borings).

Adjacent to Washington School, along Philip Street and along Punahou Street, a total of nine relatively shallow borings are available. These indicate alluvium with some cinders extending to at least -17 feet. It appears that the +5 coral has been eroded out in this area by an alluvial channel--the Kaheka Channel, which is discussed below.

In the block between Punahou Street and Kalakaua Avenue, about 200 feet south of King Street, two borings are available which extend to about -153 feet. These borings also indicate an alluvial channel which extends to at least the depths explored. The alluvium is brown silt with occasional layers of cinder and peat. The cinder occurs in thin layers at elevations ranging from -29 feet to -99 feet. Essentially no coralline sand or gravel is present above elevation -53 feet. Below -122 feet, coralline materials dominate the alluvium. (Note: No lagoonal material was encountered above the alluvium in these borings). This alluvial channel is named herein the Kaheka Channel, due to its course which more or less parallels Kaheka Street.

Well No. 59 (Stearns & Vaksvik, 1938) is located across Kalakaua Avenue from the location discussed in the last paragraph. The log of this well indicates coral at elevation -45 feet. This location is apparently near the edge of the alluvial channel such that the coral has not been completely removed. A post-erosional basalt flow reported here at -81 feet, is tentatively interpreted by Stearns to be Rocky Hill basalt. This basalt is about 10 feet thick and underlain by coralline deposits and alluvium down to basalt at -305 feet. The latter basalt was penetrated for 130 feet and is interpreted to represent Koolau bedrock.

Five borings are available in the area between Kalakaua Circle and Kaheka Street, and opposite the intersection of Kaheka and Rycroft Streets. These borings indicate that this area also overlies a former deep alluvial channel. Alluvium and fill extends from the surface to a layer of lagoonal (swamp) deposits which occurs from about +3 feet to about -13 feet. Beneath this layer, alluvium extends to at least -89 feet (the maximum depth explored). Some coralline material occurs within the alluvium below -56 feet.

Within 300 feet of Kaheka Street, at the east end of the block bounded by Rycroft, Kanunu, and Kaheka Streets, four borings indicate alluvial deposits to about -123 feet. At this site, fill extends from the surface to about sea level, underlain by lagoonal deposits with coralline debris to about -20 feet. Below this level, in three of the borings alluvium and cinders extend to at least -97 feet, with coralline material occurring in the alluvium below -67 feet. Basalt boulders were reported in the alluvium from -85 to -97 feet. The fourth boring in this group encountered sand and coralline debris from -29 feet to -39 feet, underlain by alluvium to -123 feet, where coralline debris is found extending to at least -143 feet.

On the north end of the block bounded by Amana, Kanunu, and Kaheka Streets, three borings continue to define the Kaheka Channel. Here, fill occurs at the surface (+8 feet) over lagoonal deposits at sea level. Cinders occur within these deposits from -18 feet to -20 feet. Alluvium underlies the lagoonal deposits from -20 feet to -128 feet. The alluvium contains occasional cinder layers and, below about -72 feet, coralline materials occur within the alluvium. Below -128 feet coralline debris and sand is found to about -154 feet.

Just below the previous site, about 200 feet south of Kanunu Street on the east side of Amana Street, two borings are available. In these borings fill is described from +7 feet to +1 feet followed by lagoonal deposits extending to -14 feet and alluvium from -14 to at least -45 feet. Cinders were found in the upper seven feet of the alluvium.

Adjacent to and just south of the preceding site, four borings define similar conditions. Alluvium with cinders is described (below lagoonal deposits) from -18 feet down to coralline debris which is found at elevations ranging from as high as -70 feet to -136 feet. Partially cemented beach(?) sand 5 feet thick is found in two borings at -105 feet. The coralline debris (below the alluvium) extends to at least -210 feet and includes sand and some layers of alluvium.

At the intersection of Kaheka and Makaloa Streets (northwest corner), three borings indicate fill from +6 feet to -2 feet over lagoonal deposits. At about -17 feet, a weak coral ledge is encountered which, in one boring, occurs as coralline debris. This site is apparently just outside the Kaheka Channel. In the other two borings, this ledge is 6 to 9 feet thick but not very well cemented. This coral appears to be part of the -15 ledge. Below the ledge, coralline debris and sand are described to about -80 feet. From this point to the maximum depth explored of -195 feet, alternate layers of alluvium, sand and coralline debris are indicated. These units are not correlatable from boring to boring. Cemented sand is encountered in one boring from -182 feet to at least -195 feet.

Across Kaheka Street from the previous site, on the northeast corner of the intersection with Makaloa Street, four shallow borings are available. These describe fill from +7 to +3 over lagoonal deposits which extend to a coral ledge occurring at -19 feet in two of the borings and at -25 feet and -30 feet, respectively, in the other two.

On the southwest corner of this intersection, two additional borings are available within Quad A-5; however, the majority of this site occurs within Quad B-5 and therefore the entire site is described in the Quad B-5 section.

On Makaloa Street, opposite the intersection with Poni Street, two borings indicate fill from +5 feet to -3 feet over lagoonal deposits. The -15 coral ledge is found at -17 and -22 feet with thicknesses of 4 and 10 feet, respectively. Below the ledge, coralline debris and sand is found to -75 feet, overlying alluvium. Sand and coralline debris occur from about -85 feet to -107 feet with alluvium extending from -107 to at least -145 feet.

QUAD A-6

Although no subsurface control is available on the east side of Quad A-6, based on the information from Quad A-5 it appears that alluvium probably dominates the subsurface within about 200 feet of the east boundary of A-5 from Rycroft Street to Quad B-6. West of this channel, the +5 coral ledge occurs with its seaward boundary apparently extending roughly parallel to, and 100 to 200 feet north of, the south boundary of A-6.

One boring is available at the corner of Sheridan and Makaloa Streets which describes fill from about +5 feet to +3 feet underlain by coral sand to sea level and lagoonal deposits from sea level to -9 feet. A coral ledge occurs from -9 feet to -25 feet, followed by coralline debris and alluvium to -32 feet and coral from -32 feet to at least -43 feet.

On the block subtended by Elm, Sheridan, Rycroft, and Cedar Streets, three borings describe fill over cinders at +1 foot over a coral ledge at -3 feet. This coral extends to at least -10 feet.

At the south end of the block bounded by Kamaile, Piikoi, and Alder Streets, three borings indicate the +5 coral ledge at about -2 feet overlain by 5 feet of fill/alluvium and 2 feet of swamp deposits. The coral ledge is 24 to 28 feet thick and contains a four-foot layer of coralline debris at about -5 feet. Below the ledge, coralline debris and alluvium (with some cemented sand) occurs to at least -37 feet.

Near the intersection of King Street and Birch Street, the log of Well No. 76 (Stearns & Vaksvik, 1938) describes fill(?) from +17 feet to +13 feet over a cinder layer to +7 feet where coral is encountered. The coral extends to -43 feet where a 40-foot thick post-erosional lava flow is found. This basalt is interpreted by Stearns to be from Rocky Hill. Below the basalt, alluvium and coral layers extend to Koolau(?) basalt at -518 feet.

QUAD A-7

In the block bounded by Pensacola, Rycroft, Piikoi, and Hoolai Streets, four borings encounter the coral ledge at -4 feet, overlain by about five feet of lagoonal (swamp) deposits and five feet of fill/alluvium. The actual ledge thickness varies from 7 to 30 feet and is underlain by partially cemented coralline deposits to at least -35 feet.

At the northeast corner of McKinley High School, five borings encounter the coral ledge at about +2 feet (in one case characterized by coralline debris over coral at -9 feet). The coral here extends to at least -22 feet. It is overlain by fill/alluvium and sand from +8 to the coral surface.

On this same block, at the northwest corner of the intersection of Kapiolani Boulevard and Pensacola Street, the coral occurs, in various stages of cementation, at elevations ranging from -5 feet to -12 feet, extending to at least -15 feet (11 borings are available here). This coral is interpreted to be the eroded surface of the +5 coral occurring at the seaward boundary of the +5 reef. Overlying the coral, fill/alluvium occurs from the surface to +3 feet followed by cinder sand to -3 feet over lagoonal deposits which extend to the surface of the coral.

Well No. 82 (Stearns & Vaksvik, 1938) is located at the northwest corner of Quad A-7, on the south side of King Street about 100 feet west of the intersection with Victoria Street. The log for this well indicates fill/alluvium from +16 to +11 feet where black sand (cinder) occurs. From +5 feet, coral sand is found over coral at +1 foot. The coral is indicated to be 180 feet thick followed by intervals of coralline deposits, including yellow or white clays, down to Koolau(?) basalt at -488 feet (drilled to -523). Coral ledges are described at -113 feet (9 feet thick) and -354 (3 feet thick).

Along the west side of Quad A-7, starting about 900 feet south of King Street, are the borings which were drilled for the HIC Arena (now Neal Blaisdell Center). Nineteen of the borings for this structure are located within Quad A-7, with the remaining 75 borings in Quad A-8. The borings within Quad A-7 all indicate the +5 coral ledge (of varing hardness) at elevations ranging from -4 feet (at the north end) to -8 feet (at the seaward end). These conditions are fairly consistent and the coral extends to at least -25 feet. Over the coral, lagoonal deposits (swampy near the top) occur from about +3 feet to the coral surface. Alluvium occurs from about +5 to +3 feet.

QUAD A-8

The HIC Arena borings within this quad provide detailed control on variable conditions which characterize this site. At the southwest corner of the arena and at the northeast corner (see also Quad A-7), the coral (+5 ledge) occurs consistently at elevations ranging from about -4 feet to -11 feet. Units overlying the coral include fill from the surface (+5 feet) to +2 feet followed by swamp deposits which extend to -2 feet over cemented cinder sand which overlies the coral surface. In some areas, the coral ledge is overlain by four or five feet of partly cemented coralline debris. The coral generally extends beyond the depths explored--roughly -25 feet. In one deeper boring, a 7-foot cavity is reported in the coral from -36 feet to -43 feet.

However, in the central area of the arena, this coral is not present. It has apparently been removed by a former alluvial channel, herein named the HIC Channel, which passes across the site from the northwest to the southeast. It ranges from 100 feet to 300 feet wide as shown on the geologic map (Plate II). Within this channel, the coral has apparently been eroded out and alluvium with cinder sand has been deposited. Over this alluvium, swamp deposits occur up to about -10 feet--roughly co-elevational with the top of the coral. Above this level, the deposits are equivalent to those found over the coral outside of the channel. In the deepest boring, channel deposits were described down to -82 feet where coral was encountered.

Across Kapiolani Boulevard from the HIC, on the corner of Ward and Kapiolani, control on the HIC channel is available. Six borings indicate about four feet of fill over lagoonal deposits which extend from about +1 foot to about -10 feet. From -10 to about -40 feet, alluvium with some cinders and coralline gravel is found. This alluvium appears to correlate with the channel found beneath the HIC. Below -40 feet, to the maximum depth of -197 feet, coralline debris and alluvium are interlayered. These coralline deposits probably mark the bottom of the channel here. At about -60 feet, a 10-foot layer of beach deposits is described.

To the southeast of this site, about 300 feet from Ward Avenue, on the south side of Kapiolani Boulevard, two borings are available which are outside the alluvial channel and therefore delimit the east side of the HIC Channel. Here, the coral ledge occurs at about -8 feet, overlain by 4 feet of fill and about 10 feet of lagoonal deposits. The coral extends to at least -25 feet.

Further down Kapiolani, about 700 feet southeast of Ward Avenue, one boring indicates coral at -9 feet overlain by 4 feet of fill and 10 feet of lagoonal deposits with coralline debris.

On the west side of Ward Avenue, at Waimanu Street, the log of one boring describes coral at -7 feet beneath 6 feet of fill and 5 feet of lagoonal deposits. This location therefore brackets the HIC Channel on the west side.

Seaward of these areas, in the direction in which the HIC Channel appears to continue, no control is available. However, there is little doubt that the channel does extend across this area. An estimate of its path is shown on Plate II, however, given the sinuous course of this channel in the area where control is available, it could be expected to meander considerably from the direct route to the sea which is shown.

Further west, in the area bounded by Waimanu, Kamani, and Kawaiahao Streets, four borings are available. At this location, the +5 coral ledge occurs at roughly -6 feet overlain by lagoonal deposits with lenses of cinder sand (mainly occurring immediately over the coral) and up to four feet of fill. The coral extends to at least -54 feet, grading less cemented below -20 feet.

Ten borings are located on the west side of Ward Avenue, across from the HIC, which further define the HIC Channel (discussed above). This channel extends from the HIC in a northwesterly direction across Ward Avenue, extending toward the intersection of Cooke and King Streets. The area for which control exists extends about 600 feet west from Ward Avenue. Within the channel, the deposits are characterized by alluvium with extensive cinder layers overlying poorly cemented coralline debris at roughly -34 feet. The occurrence of various lenses of cinder sand within the alluvium is extremely variable and not correlatable from boring to boring. In a number of borings, alluvium is found beneath the coralline gravel to at least -77 feet. In one boring, relatively well defined coral is found at -78 feet extending to at least -113 feet. It appears that the depth of this channel is similar to that under the HIC, i.e., to about -80 feet. Lagoonal/swamp deposits occur over the alluvium above elevation -8 feet. Fill occurs from the surface to about +3 feet over a cinder layer which overlies the swamp deposits. Boring data available north of King Street (outside the project area) indicate that the HIC alluvial channel continues toward the northwest as shown on Plate II.

Northeast of this area, at the intersection of King Street and Ward Avenue, one boring encounters the +5 coral at +2 feet overlain by cinder and alluvium and possibly some fill.

QUAD A-9

Within the block bounded by South, Kawaiahao, Emily and Marmion Streets, four borings have been drilled. Fill extends from +6 to a cinder layer at about +3 feet. The cinder includes lenses of swamp mud. Coral underlies the cinder at about -2 feet extending to at least -44 feet. A cemented sand layer is described in one boring from -10 feet to -16 feet. The cores of the coral from these borings were examined by the writer and algal coral (coralline algae) was found at the top of the ledge with *Porites lobata* characterizing the coral found below about -8 feet.

Further west, on the southeast corner of the intersection of Punchbowl and Queen Streets, ten borings are found which disclose consistent conditions with coral occurring at +2 feet overlain by a 2-foot layer of cinder and 2 feet of fill and alluvium. The coral extends to at least -23 feet.

Further west across Punchbowl Street, two borings occur at the west boundary of Quad A-9. These borings indicate coral at -4 feet overlain by about 2 feet of cinder sand and 7 feet of fill and alluvium. The coral extends to at least -26 feet.

There is no control in the southern half of this Quad. The seaward margin of the +5 coral ledge probably extends across this area in the vicinity of the southern boundary of the quad.

QUAD A-10

Within Quad A-10, an additional 13 borings are available for the last site described in the preceding section. Conditions are essentially consistent with those described above. The elevation of the top of the +5 coral ledge ranges from -5 to -8 feet and it is overlain in some borings by a variable 3- to 5-foot layer of cinder and 8 to 10 feet of fill and alluvium.

In the block bounded by Mililani, Richard, Queen and Halekauwila Streets, a total of 12 borings are available for subsurface control. These borings are located on the south and east side of the block. Conditions disclosed are relatively consistent. Fill from about +6 feet to +3 feet overlies interlayered cinder and swamp deposits to the top of the coral ledge which occurs at elevations ranging from sea level to -9 feet. The coral grades to coralline debris at about -24 feet. Sand with coralline debris extends from -69 feet to -77 feet over alluvium which is encountered to at least -86 feet.

Further west, the block bounded by Queen, Richards, Alakea, and Halekauwila Streets contains nine borings of which six are within Quad A-10 (the remaining three are beyond the project area). The conditions disclosed at this location include five to ten feet of fill over cinder at about sea level (with occasional lenses of alluvium/swamp deposits) overlying coral at elevations ranging from -3 feet to -14 feet. The lower occurrences of coral generally occur on the seaward side of the site. The coral ranges from 8 to more than 40 feet in thickness. In four of the six borings, the coral grades to coralline debris and sand at roughly -25 feet. In all the borings, the coral contains less cemented layers up to ten feet in thickness, however, most of these weaker zones are not correlatable from boring to boring. This coral is interpreted to represent the eroded surface of the +5 coral. Its proximity to the existing shoreline suggests that it may have been planed to its present level by wave action during a high sea stand subsequent to the formation of the +5 ledge. Alluvium is encountered below the coral, at about -78 feet and extends to basalt at -81 feet. This basalt is assumed to be related to one of the post-erosional Nuuanu flows (Luakaha or Makuku). Drilling was extended 24 feet into this basalt.

Well No. 103 is also located on this block. The log of this well (Stearns & Vaksvik, 1938) indicates: alluvium from +2 to -3 feet over coral to -108 feet; alluvium from -108 to -143 feet; and Nuuanu(?) basalt boulders from -143 to -188 feet. Below the boulder layer, interlayered coral and alluvium occur down to the surface of the Koolau(?) basalt at -808 feet. This basalt was drilled to -1148 feet. It is unclear why the basalt found at -81 feet (described in the previous paragraph) was not encountered in this well drilling.

In the block bounded by Ala Moana Boulevard, Bishop, Richards, and Halekauwila Streets, the log of Well No. 101 (Stearns & Vaksvik, 1938) indicates fill from +4 feet to -2 feet over coral which extends to -114 feet. Nuuanu(?) basalt boulders are found from -114 feet to -149 feet. Below this layer, coral and alluvium are interlayered down to the Koolau(?) basalt at -982 feet. This basalt was drilled to -1147 feet.

At the east end of this same block, four shallow borings are also available. These indicate fill from +5 feet to -5 feet overlying cinder which, in turn, overlies the coral. The elevation of the coral surface ranges from -9 to -12 feet and it is at least 2 feet thick. This coral is interpreted to be the planed off +5 coral ledge.

On the block within Ala Moana Boulevard, Kakaako, Halekauwila, and Richards Streets, 13 borings describe the conditions. Fill from about +6 feet to -4 feet overlies cinder which extends to the coral surface. This cinder deposit contains occasional pockets of alluvium on the order of three feet thick. Coral occurs at elevations ranging from -6 to -14 feet, with the lower (planed off) occurrences generally closer to the existing shoreline. The coral grades less cemented with depth and contains some lenses of coralline debris at various elevations. At roughly -34 feet, a layer of coral sand with coralline debris occurs which is of variable thickness, on the order of 10 to 20 feet. In one boring, a three-foot cavity was found in this layer. Below this sand, the coral is variously cemented and correlation of the hardness of the coral cannot be readily made from boring to boring. In one deep boring, a coral ledge is encountered from -95 feet to -102 feet overlain by about three feet of alluvium. At -102 feet, a 2-foot layer of basalt (boulder?) was encountered, followed by alluvium and, at -108 feet, another coral layer. This coral layer extends to at least -125 feet. In another deep boring, basalt (Nuuanu?), 11 feet thick, was encountered at -76 feet, over alluvium which was found to at least -94 feet.

As with Quad A-9, no control exists in the southern portion of this quad. The margin of the +5 ledge probably occurs in this quad within 300 to 600 feet of its southern boundary. At the seaward margin of the +5 ledge, the coral is apparently planed off and occurs at relatively low elevations, ranging from -10 to -15 feet.

QUAD B-3

Returning to the east side of the project area, the data in Quad B-3 provide good control on both the -15 ledge and the -30 ledge (Quads B-1 and B-2 were discussed previously with Quads A-1 and A-2).

On the seaward side of Kapiolani Boulevard, opposite the intersection with Isenberg Street, two borings and a number of supplementary borings and probes are available which describe the -15 coral at about -15 feet. Overlying the coral is about 3 feet of fill and about 16 feet of lagoonal deposits. The coral ledge is on the order of 11 to 13 feet thick and underlain by sand and alluvial silt layers to at least -176 feet. The existing channel of a small stream passes across this site; however, this channel does not appear to have affected the underlying coral ledge and appears to be a relatively recent drainage feature.

To the east of this area, within 100 feet east of University Avenue between Kapiolani Boulevard and Hihiwai Street, 11 borings are available which consistently define the -15 ledge. The coral occurs here at elevations ranging from -17 feet to -25 feet and is generally 10 feet to 15 feet thick with some thicker occurrences (for conditions in this area, see subsurface section A-A' (Plate III)). The coral is overlain by a few feet of fill over lagoonal deposits which extend to the surface of the coral. Coralline debris is described beneath the coral ledge, to about -55 feet where alluvium occurs, interlayered with coralline debris, extending to at least -95 feet.

However, just east of this area, about 220 feet east of the intersection of Kapiolani Boulevard and University Avenue, one boring indicates that an alluvial channel cuts the -15 coral ledge. In this boring, the upper lagoonal deposits, which were described occurring above the coral in the preceding paragraph, immediately overlie a 9-foot alluvial layer from -22 feet to -31 feet. Coralline debris occurs from -31 feet to -53 feet followed by alluvium to at least -57 feet. An alluviual channel apparently cuts the coral ledge here and it is likely that it may represent the continuation of the alluvial channel found further inland which, near King Street, appears to have been filled by the Sugarloaf basalts. This channel is interpreted to be the ancient Manoa Stream Channel (Plate II). There is no control on the east bank of this channel.

Cores of the -15 foot coral ledge in this area have been examined by the writer. These cores are from just west of the channel and they show well developed *Porites lobata*. Immediately over the coral, a light brown silt is found which includes fragments of relatively fresh basalt. This material appears to fill depressions (solution pits) in the surface of the coral. It is likely that this material is alluvium containing fragments of the Sugarloaf basalt which terminates within 400 feet east of this location.

Further seaward, below Hihiwai Street, 15 borings are available at Ala Wai School. Over most of this site, coral is consistently encountered below lagoonal deposits at elevations ranging from -15 to -24 feet. The coral thickness is not determined. However, at the east end of this site, opposite the end of Kamoku Street, the coral is not found. In three borings, alluvium is encountered below the upper lagoonal deposits, extending from -20 feet to at least -50 feet (see Figure 4, Sample Boring Log H). This alluvial channel is presumably a continuation of the ancient Manoa Channel discussed in the preceding paragraphs. At this site, the channel is at least 350 feet wide.

It appears that this channel is also traceable on the seaward side of the Ala Wai Canal. On the two blocks between Kalaimoku and Kaiolu Streets, along the south side of Ala Wai Boulevard, three borings are available which indicate a deep alluvial channel. The upper units include about 3 feet of fill over lagoonal deposits (swampy in the upper 3 feet) which extend to about -23 feet. Below this elevation, alluvial deposits dominate. The alluvium is characterized by brown silt with varying amounts of cinders and basalt gravel extending to at least -198 feet. Layers of mixed cinder and coral sand also occur. Conditions are generally correlatable between the borings but do not correlate at all with borings outside of the channel. The logs of the borings (at the intersection of Launui Street and Ala Wai Boulevard) describe a coral gravel layer within the alluvium (beneath three feet of cinders) from about -26 feet to -63 feet with some cementation in the lower 7 feet of the unit. The complete absence of this unit in the third boring, and the good correlation of the underlying alluvial units between borings, indicates that the coralline gravel is probably a localized layer of coral eroded from the adjacent reef and deposited in the channel.

This channel is named herein the Launiu Channel. It appears to run more or less parallel to Launiu Street with the axis of the channel occurring beneath the block between Launiu and Kaiolu Streets (Plate 11). Additional control on this channel is discussed under Quad C-3. Control outside of this channel on the coral ledges is not available in the southeast corner of Quad B-3. However, the general indication is that the boundary between the -15 ledge and the -30 ledge occurs within about 400 feet north of the south boundary of Quad B-3.

Control on the -30 ledge is available on the seaward end of the block enclosed by Ala Wai Boulevard, Kalaimoku Street, Olohana Street, and Kuhio Avenue. At this location, three borings define the -30 coral, in two borings at about -35 feet and in one boring at -40 feet. The coral is overlain by about 5 feet of fill and lagoonal/swamp deposits from sea level to about -30 feet. Alluvial silt and sand occurs from about -30 to the coral surface. The coral ledge ranges from 18 to 30 feet thick and is underlain by coralline gravel to about -70 feet. Alluvium extends from -70 to -73 feet followed by cemented sand to -87 feet over another alluvial layer from -87 feet to -94 feet. Coralline debris occurs from -94 to a coral ledge which is found from -119 feet to at least -124 feet.

Further west, at the seaward end of the block bounded by Kuamoo Street, Namahana Street, and Kuhio Avenue four borings are available. On the west side of the block coral is found at about -25 feet, on the order of 15 to 23 feet thick, and on the east side at -32 and -36 feet, on the order of 6 to 8 feet thick. These ledges contain some poorly cemented zones. This site overlaps the area where transition apparently occurs from the -15 ledge and the -30 ledge (Plate V). In both areas, the upper units are characterized by about five feet of fill over lagoonal deposits which extend from about sea level to the coral surface. Below the coral ledges, coralline debris and sand dominates the section with alluvial lenses at -91 feet (five feet thick) and -130 feet (15 feet thick).

QUAD B-4

North of the preceding site, on the two blocks between Pau Street and Kuamoo Street, a total of nine borings are available. Most of these borings define consistent conditions characterized by a coral ledge at about -24 feet interpreted to be part of the -15 ledge. This ledge is 10 to 15 feet thick. It is overlain by a 5-foot fill layer over lagoonal deposits which extend from about sea level to the coral surface. In one boring, on Keoniana Street, about 250 feet north of Kuhio Avenue, cemented sand occurs at -25 feet over the coral at -30 feet. Within about 400 feet of Kuhio Avenue, the coral overlies coralline debris with one boring encountering a cemented sand layer from -130 feet to about -150 feet. Landward of this point, however, within 250 feet of the Ala Wai Canal, the coral ledge overlies alluvium to at least -55 feet. In one boring, about 200 feet from the canal between Keoniana and Pau Streets, the coral ledge occurs at -30 feet and is only about 5 feet thick, underlain by coralline debris to -48 feet, followed by alternate layers of alluvium and coralline debris (on the order of 10 to 15 feet thick) to at least -188 feet. At -115 feet, a 6-foot tuff layer is described. The coral ledge in this boring may have been eroded somewhat by the stream which previously followed, roughly, the course of the Ala Wai Canal. This stream is shown on old maps of the area (circa 1887) and is referred to herein as the old Ala Wai Drainage.

Further north across the Ala Wai from these sites, two borings are available in Ala Wai Park (Figure 2, Sample Boring Log D). These borings indicate the -15 coral ledge at -18 and -20 feet, overlain by a 5-foot fill layer and lagoonal deposits from sea level to the coral. The coral is at least 10 feet thick. No other control is available in this quad on the north side of the canal.

Seaward of the canal, in the area bounded by Ala Moana Boulevard, Kalakaua Avenue, and the Ala Wai Canal, borings are available which define variable conditions. On the southeast side of the canal, roughly 200 to 400 feet southwest of Kalakaua, seven borings are available. The logs of six of these describe the -15 coral ledge at -23 feet with a thickness of at least 20 feet. The coral is overlain by roughly eight feet of fill over lagoonal deposits which extend to the coral surface. Beneath the coral, coralline debris occurs to at least -170 feet with a few 5- to 10-foot lenses of alluvium. Coral ledges also occur at -80, -125, and -155 feet, each on the order of 5 to 10 feet thick. In one boring, the upper coral occurs as low as -35 feet, however, in this case, alluvium extends from the bottom of the lagoonal deposits at -23 feet to -28 feet over coralline debris which overlies the coral surface. Since this location is immediately adjacent to the existing canal, it is possible that the coral here was eroded by the old Ala Wai Drainage thus accounting for the alluvium over the coral.

On the block bounded by Ena Road, Ala Moana Boulevard, and Kalakaua Avenue, two borings are available, roughly 300 feet from Kalakaua, which apparently define the boundary between the -15 coral ledge and the -30 ledge. In these borings, coral is encountered at -28 feet and -37 feet, respectively (subsurface section C-C' (Plate V)). These borings indicate about 7 feet of fill over lagoonal deposits which extend to the coral surface. The coral ledges are about 25 and 12 feet thick, respectively, and overlie coralline debris to at least -66 feet.

On the west corner of the intersection of Ala Moana Boulevard and Ena Road, eight borings (four within Quad B-4) indicate similar, variable conditions. The coral ledge here occurs at elevations ranging from -26 feet to -34 feet and the coral is relatively thin--on the order of

5 to 10 feet thick--and not well developed. In some of the borings, an uncemented layer of silty sand occurs within the coral from -35 to -40 feet with roughly 5 feet of coral both above and below this layer. The ledge is overlain by about eight feet of fill over lagoonal deposits down to the coral. In one boring, no actual ledge is found, with only coralline debris occurring at -30 feet beneath the lagoonal deposits. Below the coral, coralline debris extends to about -70 feet where an alluvial layer occurs, ranging from 8 to 20 feet in thickness. This is followed by coralline debris extending to a partially cemented sand layer which is found from -115 to -125 feet. Another coral layer occurs from about -125 to at least -140 feet.

Just north of the preceding location, in the area enclosed by Lipeepee Street, Hobron Lane, and Kaioo Drive, three borings are available which define more consistent conditions. The coral ledge is described at -25 feet beneath a five-foot fill layer and lagoonal deposits from the bottom of the fill to the coral surface. This coral appears to represent the -15 ledge. The ledge is on the order of 40 feet thick and underlain by coralline debris and sand. A layer of cemented sand and cemented coralline debris is found from about -105 feet to at least -135 feet.

Only 200 feet north of this site, however, conditions are again quite variable. On the landward side of the intersection of Lipeepee Street and Hobron Lane, four borings reveal coral ledges at -42, -23, -35, and -30 feet with thicknesses of 5, 4, 30 and 10 feet, respectively. These ledges are overlain by about five feet of fill over lagoonal deposits. A 10-foot layer of alluvium with basalt gravel overlies the coral found at -35 feet and coralline debris and sand, 10 to 17 feet thick, overlies the coral at -30 and -42 feet, respectively. Conditions are so variable that correlation from boring to boring is quite difficult. The ledges are generally underlain by coralline debris with occasional cemented zones. At -102 feet in one boring, a 10-foot coral ledge is found overlying cemented sand which extends to at least -116 feet. In the other deep boring on the site, weathered basalt boulders are encountered from -112 to -116 feet over alluvial sand with coral gravel to at least -119 feet.

The apparent boundary between the -15 ledge and the -30 ledge in this quad is shown on the geologic map (Plate II), however, the highly variable conditions found here make the position of the boundary uncertain.

QUAD B-5

On the northwest side of the Ala Wai Canal, in the vicinity of Kahakai Drive, six borings are available within 250 feet of the Canal. One boring, within 100 feet of the canal, does not encounter any coral ledge within the depth explored to -170 feet. Below the usual surface units (five feet of fill over lagoonal deposits from about sea level) a sand layer is described from -28 to -35 feet. This is followed by cinder sand from -35 to -44 feet and alluvium from -44 to -49 feet. From -49 feet, coralline debris occurs to -85 feet over alluvium extending to -110 feet. A 5-foot layer of cemented sand occurs within the alluvium at -93 feet. Coralline debris is described from -110 to -128 feet and alluvium occurs from -128 to at least -170 including basalt gravel below -160 feet. The absence of the coral ledge here is interpreted to be the result of erosion of the coral by the old Ala Wai Drainage. The occurrence of the cinder interval is particularly indicative of an alluvial channel here. The deposits within this boring do not correlate with the other borings in this area above an elevation of about -98 feet. In these other borings, the -30 coral ledge is defined at elevations ranging from -30 feet to -34 feet. In one case, cemented beach sand is found at --25 feet over coral ledge at -41 feet. The ledge in these borings appears to be mostly cemented coralline debris. The coral is on the order of 40 feet thick over coralline gravel to about -98 feet from which depth the conditions begin to correlate with those described for the boring within the channel.

Further to the southwest, at the bridge where Ala Moana Boulevard crosses the canal, the -30 ledge is defined by four borings at elevations ranging from -32 to -35 feet overlain by fill (eight feet thick on the banks of the canal) over lagoonal deposits. The depth of water in the canal here is about 12 feet. The coral ledge is five to eight feet thick but in one boring is not well cemented. Coralline gravel and sand occur beneath the ledge to at least -60 feet. The presence of the coral ledge indicates that the canal does not overlie the old Ala Wai Drainage at this location.

The boundary between the -30 ledge and the -15 ledge extends roughly across the middle of Quad B-5. North of this boundary, the -15 ledge occurs fairly consistently except where it is cut by the Kaheka Channel.

On the east end of the block bounded by Atkinson Drive, Mahukona Street, and Kona Street, the -15 ledge occurs at elevations ranging from -18 to -22 feet beneath lagoonal deposits and a surface 7-foot fill layer. This ledge is on the order of 12 feet thick. It is underlain by coralline debris and coral sand to about -114 feet where a cemented sand layer (seven to twelve feet thick) is encountered. Below this layer, from about -124 feet to -234, coralline debris with some partially cemented zones and some alluvial layers occurs, followed by alluvium to at least -259 feet. In some of the borings at the east end of this site, a 10- to 15-foot layer of alluvium occurs at about -95 feet. Five of the nine borings within this block define the upper coral ledge. However, in borings within 150 feet from Mahukona Street, the upper ledge is not found. In two of these borings, a poorly developed layer of cemented coralline debris is found deeper--at about -32 feet--and in the other two borings no ledge is encountered at all. The deposits encountered at depth in these borings are correlatable with that described for the east side of this site.

On the opposite (southwest) side of Mahukona Street, at the east end of Ala Moana Center, a deep alluvial channel is defined by two borings. It is interpreted that the absence of the coral ledge described in the preceding paragraph is related to this channel. The channel probably eroded out the coral ledge, but since the area was on the outer edge of the channel the underlying deposits were not eroded. In the two borings within the channel deposits, below the fill (eight feet thick) and lagoonal material, decomposed cinder sand mixed with black clay and coral fragments extends from -29 to -60 feet. From -60 to -86 feet coralline gravel occurs, followed by soft gray clay (low-energy alluvial deposits) to about -100 feet. Below -100 feet, coral sand and gravel, and alluvium, are interlayered to at least -136 feet. Based on the information available landward of this area, it appears that this channel is the continuation of the Kaheka Channel (described in Quad A-5 and discussed below). The deposits in this channel are found to extend deeper than -136 feet north of Makaloa Street and therefore may be expected to extend to even greater depths in the vicinity of Ala Moana since it is further seaward.

The estimated course of the Kaheka Channel through the Ala Moana area is shown on the geologic map (Plate II) (see also subsurface section C-C' (Plate V)). The southwest boundary of the channel is well defined by five borings which describe the upper coral ledge at elevations ranging from -20 to -22 feet. This ledge varies in thickness from 6 to 12 feet. It is underlain by sand and coralline debris and a layer of cemented coralline debris, which is on the order of five to eight feet thick, and occurs at elevations ranging from -33 to -41 feet. Below this ledge, conditions are similar to those described for the area to the northeast of the channel, i.e., dominated by coralline debris and sand with some layers of alluvium.

At the northwest corner of this quad, the Kaheka Channel is further defined on Kaheka Street between Kapiolani Boulevard and Makaloa Street (see also Quad A-5). On the east side of Kaheka Street, the -15 coral is found at elevations ranging from -17 to -20 feet (in 12 borings). The coral is overlain by about five feet of fill, two to three feet of swamp deposits at sea level, and lagoonal deposits from about -2 feet down to the coral. The coral itself is on the order of 15 to 20 feet thick; however, in roughly half of the borings there is a layer of coralline gravel, with some alluvium, which is about five feet thick and which occurs within the coral ledge. Thus there is a second hard layer, within the "ledge", which occurs at about -31 feet. (In one boring, a one foot black sand layer was found at -27 feet within the ledge.) Below the ledge, from about -36 feet, coralline debris and sand with occasional alluvial lenses are found, grading to sand at -70 feet. This sand is cemented from roughly -80 feet to -85 feet, overlying another coral ledge which extends to -110 feet. From this level to at least -205 feet, coralline debris with occasional alluvial lenses (up to 10 feet thick) is encountered.

Apparently, the east bank of Kaheka Channel occurs just to the west of the previous site. On the west side of Kaheka Street, opposite the previous location, the upper coral ledges are absent. Instead, beneath the upper lagoonal deposits, alluvium with cinder layers is found, from about -19 to depths varying from -31 feet to -95 feet. Below the alluvium, coralline debris (with alluvial lenses) occurs to at least -198 feet. This coralline debris is partially cemented in some intervals. Based on the assumption that the surface of the coralline debris, beneath the alluvium, represents the channel bottom, a true slope angle of about 32 degrees was calculated for the average slope of the sides of Kaheka Channel.

QUAD B-6

At the north end of Quad B-6, between Kapiolani Boulevard and Kona Street, within 400 feet on either side of Keeaumoku Street, 13 borings are available. The -15 foot coral ledge is relatively consistent in this area. On the west side of Keeaumoku, eight borings define the -15 foot ledge at elevations ranging from -16 to -20 feet. It is overlain by fill from the surface to sea level and lagoonal deposits from about sea level down to the coral surface. In the upper part of the lagoonal deposits, within a few feet of sea level, these sediments appear to be swamp deposits with pockets of cinders. The thickness of the coral ledge is about 20 feet. However, a relatively consistent uncemented layer is found within this coral from roughly -30 to -35 feet. This uncemented layer is characterized by coralline gravel with some alluvium in a few cases. Thus, the coral here includes a second ledge at about -35 feet. This situation is similar to conditions at the intersection of Kapiolani Boulevard and Kaheka Street in Quad B-5. Below the coral ledge, coralline debris with some cemented zones extends to a coral ledge at roughly -75 feet. This ledge is about 5 to 8 feet thick and is underlain by an alluvial layer from -105 to about -130 feet. From -130 to about -180 feet sand and coralline debris dominate, including some mixed cinder and coral sand from -165 to

-180 feet. Coral with coralline debris is described from about -180 to -240 feet over alluvium to at least -250 feet.

On the east side of Keeaumoku Street, seven borings define similar conditions, characterized by the uncemented layer within the -15 coral ledge. The total ledge thickness is about 20 feet. Below the ledge, coralline debris and sand is found down to a six-foot-thick coral ledge at about -50 feet which is described in about half of these boring logs. This ledge is underlain by coralline debris to -80 feet followed by alluvium with some cemented sand to -100 feet and sand and coralline debris from -100 to at least -207 feet. Within this unit, some cemented material occurs with cemented horizons described in a few borings at -125 feet (10 to 20 feet thick) and -155 feet (5 to 10 feet thick). At -165, a fairly consistent five-foot layer identified either as decomposed tuff or cinder is described.

On the south side of Kona Street, (just east of Keeaumoku within Ala Moana Center) similar conditions occur. However, 200 feet south of Kona Street, the uncemented layer (described above) within the -15 foot coral is not found and the -15 ledge is reported to extend continuously from -20 to -45 feet.

Above the -15 ledge, a fairly recent channel appears to have cut only the lagoonal deposits. In a line extending from the east corner of Keeaumoku and Kona Streets for a distance of roughly 300 feet in a southeast direction, three borings indicate that the upper lagoonal deposits are displaced by mixed cinder and coral sand. This is the only case of the lagoonal material above the -15 coral being displaced by another unit.

Beginning roughly 800 feet south of the boundary of Quad A-6, there are 59 borings available within Ala Moana Center. Most of these borings extend into, but not through, the -15 coral ledge. The upper surface of this ledge is defined at elevations ranging from about -16 to -30 feet, with the coral surface occurring deeper toward the west end of Ala Moana Center. Two borings, at the east side of Quad B-6, extend below the -15 coral. In one, the uncemented layer within the -15 ledge (discussed above), is described and in the other it is not indicated. Below the coral ledge, the conditions are generally correlatable with those discussed in the preceding paragraphs.

Near the southeast corner of Quad B-6, within Ala Moana Park, the log of one boring is available which describes the -30 coral ledge at -32 feet. The coral is overlain by four feet of fill followed by lagoonal deposits extending down to the coral surface. The coral is nine feet thick and underlain by coralline debris to at least -106 feet. A harder zone within this layer is described from -81 to -91 feet.

At the southwest corner of B-6, about 400 feet from the west boundary of the quad and 210 feet south of

Ala Moana Boulevard, one boring is available which encounters the -15 coral ledge at -21 feet with a thickness of 14 feet, underlain by coralline debris with alluvium to at least -47 feet.

QUAD B-7

On the southeast corner of the intersection of Pensacola Street and Kapiolani Boulevard, two borings provide control on the inland margin of the -15 coral ledge (see subsurface section C-C' (Plate V)). At this site, the -15 coral ledge is described at about -19 feet, however the coral here is not as well cemented as is the surface of the ledge in other areas. The coral is at least 24 feet thick and includes an uncemented layer of coralline debris and alluvium from -30 to -35 feet. The coral is overlain by about four feet of fill over lagoonal deposits down to the coral.

Across Hopaka Street, south of the previous site, three borings are available which define similar conditions. Fill (4 feet thick) over lagoonal deposits, overlies the -15 coral ledge at -15 to -17 feet. The coral is about 10 feet thick. In one boring, a 2 1/2-foot layer of cinder sand is described within the -15 ledge.

Further west, in the middle of Quad B-7, 400 to 600 feet south of the Quad A-7 boundary, three borings are available. In two of these borings, the -15 coral is encountered at -25 feet and -20 feet and is at least 12 feet thick. A three-foot cinder layer occurs within the coral at -23 feet. The coral is overlain by about four feet of fill over swamp deposits at about +1 foot grading to lagoonal deposits at about -1 foot. One boring at this site does not describe coral until about elevation -49 feet, extending to at least -63 feet. Between the coral surface and the overlying lagoonal deposits, a 15-foot layer of cinder occurs. Apparently, a small channel occupied this location and eroded out the coral.

South of this area, about 250 feet west of the intersection of Piikoi Street and Ala Moana Boulevard, one boring occurs which encounters the -15 coral ledge at -27 feet, on the order of 10 feet thick. This ledge includes a five-foot-thick uncemented layer from about -31 to -35 feet. Below this level, coralline debris and sand dominate the strata to about -108 feet followed by alluvium (with coral gravel) to -156 feet. This overlies coralline debris to -165 feet over a coral ledge which extends to at least -190 feet.

In the area of the tennis pavillion in Ala Moana Park, six borings occur within Quad B-7. The layer of lagoonal deposits here is characterized by a large amount of coralline gravel, making it somewhat more competent than in other areas. The fill over the lagoonal material is three to five feet thick. The -15 coral ledge is encountered here at depths ranging from -19 to -25 feet. However, the thickness of the coral was not determined in most cases. The coral in this area is not well cemented. In one boring, no coral ledge was encountered until -35 feet, with more or less cemented coral extending to at least -91 feet.

QUAD B-8

At the extreme southeast corner of this quad, one boring is available which encounters 3 feet of fill over lagoonal deposits to -52 feet, where coral is encountered. It is not clear why the upper coral ledges are not found here. This boring occurs slightly seaward of the estimated boundary between the -15 and -30 coral ledges. Coralline debris is found within the lagoonal deposits and this material may be representative of an uncemented area within either the -15 or the -30 ledge. The coral (with some coralline debris) extends from -52 to -142 feet where lagoonal deposits are encountered, extending to at least -148 feet.

Very little control is available within this quad, however, it is predicted from data discussed for Quad A-8, that the HIC Channel continues across this area (see the geologic map (Plate II)). It is possible that the boring described in the preceding paragraph encounters the seaward extension of the HIC Channel, however, surrounding information does not provide any support for this idea.

At the intersection of Ward Avenue and Auahi Street, one boring encounters the -15 coral at -22 feet, at least 8 feet thick, overlain by lagoonal deposits and about 3 feet of fill.

Based on the information available, it is estimated that the boundary between the -15 coral and the -30 coral is roughly along Ala Moana Boulevard in this quad.

QUAD B-9

At the east boundary of Quad B-9, five borings are located on the south side of Auahi Street. At this location fill extends from the surface (about +5 feet) to sea level, followed by lagoonal deposits which extend down to the -15 coral ledge which is found here at elevations ranging from -17 to -21 feet. The coral ledge thickness is on the order of 10 to 20 feet and the coral is underlain by coralline debris and sand to at least -50 feet.

South of this location, on the east side of the intersection of Ahui Street and Ala Moana Boulevard, nine borings encounter the -30 coral ledge at about -31 feet beneath lagoonal deposits. This ledge is on the order of 10 to 14 feet thick; however, in a few of the borings the ledge material was described as coralline debris rather than coral ledge. The coral is underlain by coralline gravel.

In one boring, a second coral layer was encountered from -86 to -106 feet. Three deep borings here indicate a thin basalt flow at about -105 feet, about 12 feet thick, which is underlain by coralline debris to at least -142 feet.

To the west of this area, good control is available in the southwest quarter of this quad. Three borings are located southwest of Ilalo Street, on the northwest side of Ohe Street. Conditions here are relatively consistent, with the -30 coral ledge occurring from -46 feet to at least -56 feet, underlain by coralline debris extending below -78 feet. The ledge is overlain by lagoonal deposits and a surface unit of about five feet of fill. (Two other borings on this site occur within Quad C-9 and are discussed in that section.)

North of this site, along the west side of Cooke Street between Ilalo Street and Ala Moana Boulevard, three borings are available. The conditions described are similar to those in the previous paragraph, however, at the corner of Cooke and Ala Moana, the coral occurs considerably higher, at about -31 feet. In addition, in one boring, a coral ledge is described at -5 feet. This is interpreted to be an occurrence of the modern reef. (This area was under water prior to filling.)

West of these areas the coral occurs at considerably greater depths, apparently having been eroded by a small channel. In a path running roughly from the corner of

Keawe Street and Ala Moana Boulevard through the corner of Ilalo and Coral Streets to the south boundary of the quad, eight borings describe this channel (see the geologic map (Plate II)). Outside of the channel, coral is encountered at elevations ranging from -32 feet to -44 feet. This coral is about 20 feet thick and underlain by coralline debris to at least -90 feet. However, within the channel the coral surface is encountered at elevations ranging from -58 feet to -68 feet and is overlain by cinder sand. Lagoonal deposits overlie the cinder at about -40 feet and therefore postdate the channel. Within the channel the coral is not well cemented and grades to coralline debris which extends to at least -123 feet. No control is available in the north half of this quad to indicate where this channel comes from.

Based on the small amount of available data, it appears that the boundary between the -30 coral ledge and the -15 coral in this quad runs roughly along Ala Moana Boulevard.

QUAD B-10

At the southwest end of Pier 2, extremely variable conditions are found. Two borings, each drilled in over 20 feet of water, encountered soft lagoonal deposits with coralline gravel to -100 feet, where alluvium was found. The alluvium extends to at least -135 feet, grading into basalt and coral boulders at about -120 feet. In contrast, within 100 feet to the east of these borings, the -30 coral ledge is encountered beneath the lagoonal deposits at an elevation of -37 feet, extending to at least -58 feet. It is likely that this area has been dredged in the past, accounting for this abrupt cutoff of the coral ledge. The area to the east of Pier 2 and seaward of Ala Moana Boulevard is essentially all reclaimed land. This area has been filled (probably hydraulically) only within the past 50 years or so.

QUAD C-1/D-1

In Quad C-1, at the east end of the project area on the south side of the Ala Wai Canal, control is available on the -15 ledge east of Kaiulani Avenue. On the northeast side of the corner of Tusitala and Kapili Streets, two borings indicate coral at -24 feet which is about 11 feet thick, and underlain by a 6-foot layer of less cemented material which overlies a second coral layer at -42 feet, which is about 20 feet thick. This occurrence of an uncemented layer within the coral ledge is similar to that described in Quads B-5 and B-6. The ledge is underlain by partially cemented sand to about -87 feet where a thin layer of alluvium is encountered over basalt at about -90 feet extending to at least -113 feet.

Just east of the intersection of Tusitala Street and Liliuokalani Avenue, two borings found coral at -24 feet, extending to about -50 feet where sand was encountered to at least -70. The ledge here includes some poorly cemented zones--probably indicative of an area within the reef where the coral was not well developed. It should be noted that this area of Waikiki probably was characterized by relatively brackish water, which would not tend to encourage well-developed coral. The coral unit is overlain by fill (five feet thick) over lagoonal deposits.

Further east, roughly 150 feet from this site, borings are available on both sides of the intersection of Ala Wai Boulevard and Ohua Street. Similar conditions occur here, with the -15 coral ledge found at about -22 feet and extending to at least -36 feet overlain by fill and lagoonal deposits.

At the intersection of Cleghorn Street and Liliuokalani Avenue, on the north corner, information is available from the log of Well No. 21 (Stearns & Vaksvik, 1938). At this location, sand and coral gravel (probably lagoonal) is found over the -30 coral which is found at -33 feet. This coral is about 22 feet thick overlying sand to -98 feet where basalt is encountered. This basalt layer is post-erosional and is tentatively correlated to the Kaimuki flow described in Quad B-1 on the north side of Ala Wai Golf Course. In this quad, it is about 47 feet thick and underlain by a succession of alluvial layers (ranging to 65 feet thick) and coral ledges. Coral ledges occur at -150, -380, -450, and -520 feet. Basalt is also encountered at -725 and was drilled to -845. Stearns and Vaksvik (1938) have interpreted this lower basalt to be Koolau basalt.

No other control is available in this quad. Based on this information, the boundary between the -15 and -30 coral ledges is interpreted to extend across the southwest corner of the quad, occurring just north of Well No. 21.

In Quad D-1, at the southeast corner of the project area, control is available on both the -15 and -30 coral ledges. Two borings in Honolulu Zoo are available on the east side of Quad D-1 roughly 1000 feet south of Quad C-1. These borings revealed a hard layer, not identified as to rock type, at -19 to -26 feet. This layer is interpreted to represent the -15-foot ledge. Lagoonal deposits and a 7-foot fill layer occur over this ledge.

Roughly 700 feet south of this location, in the area of the Kapiolani Bandstand, coral is encountered at about -33 feet under lagoonal deposits. The thickness of this coral was not determined.

To the west of this area, control is available on Kuhio Avenue within about 200 feet of the east end of Kuhio. At this location, coral is found at -28 and -33 feet with a thickness of at least 24 feet. This coral is overlain by lagoonal deposits, coralline gravel, and sand with an alluvial lens from -18 to -25 feet.

About 400 feet west of this location, (between Kuhio Avenue and Kaneloa at the end of Wai Nani Way) two borings are available which penetrate to basalt. In this case, coral occurs at -26 feet near Kaneloa and at -40 feet near Kuhio Avenue. The thickness of the coral in each boring is about 10 feet. Lagoonal deposits are found over the coral here. Partially cemented sand and gravel underlie the coral to about -65 feet where alluvium with basalt gravel occurs, followed by Kaimuki(?) basalt rock which is described at elevations ranging from -70 to -75 feet and drilled to about -88 feet.

Roughly 200 feet west of this location, on the northwest end of the block enclosed by Ohua, Kuhio, Paoakalani, and Kalakaua Avenues, the -30 coral is encountered consistently at about -34 feet (11 borings). Coral thickness varies from 10 feet to more than 41 feet underlain by coral gravel and sand. In one case, in the center of the block, cemented sand was found from -35 feet to -41 feet in place of the coral. The materials overlying the coral are lagoonal deposits with a larger fraction of coralline gravel than usual for Waikiki. This material is therefore somewhat more competent than the lagoonal deposits found elsewhere within the project area. Kaimuki(?) basalt is found beneath this site at about -93 feet and was drilled to -102 feet.

To the south of this site, three borings are available at the southwest corner of the intersection of Lemon Road and Kapahulu Avenue. Here, the -30 coral occurs consistently at about -36 feet and is at least 12 feet thick, overlain by coralline gravel and lagoonal deposits. Further seaward, on the west corner of Kapahulu Avenue and Kalakaua Avenue, coral is encountered at -41 feet, with a thickness of 13 feet. This coral is underlain by coral gravel to -93 feet where the Kaimuki(?) basalt is encountered. The basalt was drilled to -104 feet.

Based on this data, the boundary between the -15 and -30 ledges appears to cut diagonally across this quad, as shown on the geologic map (Plate II).

QUAD C-2

About 150 feet east of the intersection of Uluniu and Prince Edward Streets, on the north side of Prince Edward, two borings are available which encountered the -30 coral at about -35 feet. The coral thickness here ranges from 12 feet to over 14 feet. This coral is overlain by lagoonal deposits with coral debris and a layer of beach sand occurring over the lagoonal material from the surface to about 2 feet below sea level. The coral is underlain by coral gravel to at least -85 feet.

Opposite this site, on the east end of the block bounded by Kuhio Avenue, Uluniu Street, Prince Edward

Street, and Kaiulani Street, four borings are available. The cores and samples from these borings were examined by the writer. The borings encountered about four feet of fill over beach sand extending to about -3 feet, over a one-foot coral ledge. This is underlain by lagoonal deposits to -35 feet where an alluvial layer is found which appears to include decomposed reworked tuff. This layer is about three feet thick and overlies a well cemented unit composed of coralline debris, sand, and marl with zones of algal coral (coralline algae). This unit extends to -45 feet where a 4-foot pillar coral ledge (*Porites compressa*), infilled with brown silt is found. *Porites compressa* generally occurs in large clusters in the backreef environment and in smaller clusters in the fore reef. Its continuity on this site suggests that this area was back reef at the time of formation of this coral. Below this pillar coral unit, coralline debris, sand, and marl are found--well cemented from -49 to -69 feet and grading to uncemented from -60 to 70 feet. At this depth, a well cemented sand with some coralline debris (probably beach sand) occurs. This material grades into less cemented debris from about -75 to -85 feet. Slightly cemented beach sand extends from -85 feet to -105 feet, including pockets of alluvium from -95 feet down. From -105 to the Kaimaki(?) basalt surface at -110 feet, coral debris, alluvium and basalt boulders were encountered. The basalt extends to at least -115 feet.

On the southwest corner of Uluniu and Prince Edward Streets, two borings were available. The -30 coral is encountered, below lagoonal deposits, in one boring at -45 feet, however, no coral is encountered below the lagoonal material to at least -51 feet in the other boring, which is about 80 feet south of Prince Edward Street. The deposits encountered in this second boring from -36 to -51 feet are alluvial. This probably represents a small channel which occurred within the reef.

Further seaward, within the block enclosed by Koa, Uluniu, Kalakaua, and Kaiulani Streets, coral is found at about -45 feet and is roughly eight feet thick. However, the coral does not occur consistently here, and in some areas is not found. In its place, cemented sand generally occurs. Below the coral unit, sand and coralline debris are encountered down to the Kaimuki(?) basalt at about -105 feet at the east end of the block and as deep as -135 feet at the west end. This basalt is at least 10 feet thick at this site.

Within about 400 feet of the intersection of Kaiulani Avenue and Kalakaua Avenue, conditions are more or less consistent, with the -30 coral ledge occurring at elevations ranging from -37 to about -45 feet. This coral is overlain by fill and beach sand from +7 to -2 feet, a coral layer from -2 to -7 feet and lagoonal deposits with some coralline gravel and sand down to the coral surface.

However, about 400 feet west of the intersection, the subsurface conditions change dramatically. The uppermost coral level is not encountered until -67 feet and further west the coral is not encountered at all. A deep alluvial channel referred to herein as the Kaiulani Channel cuts through the subsurface strata here to a depth of about -172 feet. Within the channel in this immediate area (just west of Kaiulani Avenue), are found low-energy lagoonal-type deposits with some coralline gravel to about -80 feet, underlain by soft organic silts and alluvium to -140 feet, and cinders and organic silt to the top of Kaimuki(?) basalt at -172 feet. Basalt was drilled to -182 feet.

Based on the data available, this channel is at least 400 feet and probably on the order of 500 feet wide. It extends to the northeast as shown on Plate II and control on the channel (four borings) is also available on the west side of the intersection of Kanekapolei Street and Ala Wai Boulevard (see Sample Boring I (Figure 5) and subsurface section C-C' (Plate III)). The logs of these borings disclose soft organic silts with peat layers to about -135 feet. Some coralline sand and gravel occurs in the upper 70 feet. Also, in one boring, a 6-foot-thick partially cemented coral debris layer was found at -56 feet, and a similar 4-foot layer was found at -122 feet. Based on the coral description, it is unclear whether it is actually in-place coral or recemented coralline debris and sand. The evidence of the surrounding stratigraphy (low-energy deposits and channel environment) suggests that coral could not thrive here, and it is therefore likely that this hard ledge is cemented coralline debris. With the exception of these cemented layers, the low-energy organic silt and peat deposits extend to the top of a fairly continuous partially cemented coralline debris layer at -135 feet, which is on the order of about 10 feet thick. This ledge overlies basalt gravel and boulder alluvium which extends to the top of the Kaimuki(?) basalt at elevations ranging from -142 to -187 feet. The basalt is drilled to a maximum of 15 feet below the rock surface. It is probable that the basalt reported further east, in Quads C-1 and C-2, was eroded down by the channel and that this basalt--at about -90 feet outside the channel and at -142 to -187 feet in the channel--is the same flow.

At the Ala Wai Canal, the west edge of the canyon occurs roughly 100 feet west of Kanekapolei. Control available at the west corner of the intersection of Walina Street and Ala Wai Boulevard indicates conditions which are again consistent with those generally found in Waikiki outside of the alluvial channels. Lagoonal deposits with some sand and coral gravel are found to about -30 feet, overlying a coral ledge which is on the order of 15 feet thick. This coral layer overlies coral sand and gravel with a few alluvial lenses (about 5 feet thick) down to Kaimuki(?) basalt, which occurs at elevations ranging from -94 to -102. The basalt was drilled to a depth of six feet.

About 350 feet south of Ala Wai Boulevard on this same block, the log of Well No. 23 (Stearns & Vaksvik, 1938) describes coral and coral mud (presumably lagoonal deposits) from the surface to -398 feet where it becomes interlayered with alluvial layers up to 50 feet thick. "Lava sand" (assumed to be basalt cuttings) is reported from -666 to at least -715 feet. This basalt is assumed to be Koolau basalt.

Further west, at the west corner of Nahua Street and Ala Wai Boulevard, the coral occurs at about -35 feet and is about 10 to 13 feet thick. Here, the coral is overlain by a cemented sand layer which extends from about -28 feet to the top of the coral. In one boring, a 10-foot-thick alluvial lens occurs below the coral. In general, coralline gravel occurs between the coral ledge and the Kaimuki(?) basalt surface, which was found ranging from -90 to -97 feet. The basalt was drilled to a depth of 10 feet. In one case, a 7-foot layer of cemented coral sand occurs immediately over the basalt.

QUAD C-3

At the east boundary of Quad C-3, at the south corner of the intersection of Waikolu Way and Seaside Avenue, five borings define lagoonal deposits extending to about -32 feet, and in one boring, a coral gravel layer from -24 to -30 feet. At about -32 feet, a 10-foot layer of alluvium is encountered, underlain by cemented sand and coral gravel to the top of the -30 coral ledge, which occurs at elevations varying from -46 to -50 feet. This coral extends to at least -58 feet. In three older borings at this site, coral is reported immediately below the alluvium at elevations ranging from -33 to -40 feet (2 to 9 feet thick), however, the evidence of more recent borings indicates that this ledge is actually a well cemented sand layer which was mis-identified as coral.

At the north boundary of this quad, on the north side of Kuhio Street, between Launiu and Kaiolu Streets, three borings describe the characteristic channel deposits of the alluvial channel referred to previously as the Launiu Channel. These sediments are dominated by alluvial silts with a number of layers of cinder or basaltic sand and gravel on the order of 5 to 15 feet thick, inter-layered with the alluvium. A black and white sand unit (basalt and coralline sand) about 20 feet thick, occurs at roughly -90 feet. This unit is also found at similar elevations in the borings on Ala Wai Boulevard, which penetrate this channel (see Quad B-3). Control in this area extends down to -131.5 feet, but fails to reach the bottom of the channel sediments (see section C-C' (Plate V)). The sediments in this channel are generally loose and soft. The channel deposits underlie a surface fill layer and lagoonal deposits which extend from sea level to about -25 feet.

Additional control on this channel is available on Kalia Road, near the existing shoreline. One boring between Beach Walk and Lewers Road encountered fill (four feet thick) over beach sand (four feet thick) over lagoonal deposits to -45 feet. Fine grained sand extends from -45 to -94 feet, followed by sand and coralline debris to -107, alluvium to -118, and sand from -118 to at least -123 feet. No coral ledge was found here, and it is likely this entire section is composed of deposits related to the Launiu Channel. About 400 feet east of Lewers, on Kalia Road, one boring encountered similar conditions with no coral ledge found at elevations above -95 feet.

On the west side of Saratoga Road, roughly 250 feet south of Kalakaua Avenue, 10 borings describe coral at about -40 feet. The coral is overlain by lagoonal deposits and about five feet of alluvium immediately over the coral. In general, this ledge is about five feet thick and includes some zones of coralline debris. The coral is underlain by coralline debris and sand with a few pockets of alluvium to at least -64 feet.

In the southwest corner of this quad, at the extreme southeast corner of Fort DeRussy about 100 feet west of the line of Saratoga Road, the upper coral ledge is missing in two borings and occurs at levels ranging from -49 to -57 feet in three other borings. The upper materials over both areas include about five feet of fill/beach sand and lagoonal deposits from sea level to about -35 feet. In these borings, the coral has been displaced by brown alluvial silt with coral gravel which extends as deep as -95 feet. It appears that this alluvium was deposited in a minor stream channel which cut the reef here. This channel probably is related to the Launiu Channel which is defined further east.

QUAD C-4

At the northeast corner of Quad C-4, about 250 feet south of the intersection of Kuhio and Kalakaua Avenues, four borings are available which penetrate to a maximum depth of about -109 feet. In this area, the surface unit of fill and beach sand extends to roughly -2 feet, followed by lagoonal sediments with coral gravel to about -29 feet. In three of the borings, a unit of cemented (beach?) sand is encountered at about -30 feet, with a thickness ranging from 3 to 5 feet. This unit includes pockets of alluvial silt near -34 feet. The coral ledge in this area occurs at elevations ranging from -36 to -38 feet. Coral thickness ranges from 2 to 25 feet, and the ledge is underlain by coral gravel and coral with occasional pockets of alluvium to the depths explored. The alluvial pockets are extremely local and cannot be traced from one boring to the next. At depth, coral ledges are indicated in two borings from -80 to -95 feet, and in two borings at -107 feet, at the termination depth of the boring.

Further southeast in the center of this quad, over 30 borings are available to define the subsurface conditions at the seaward end of Fort DeRussy. At the northwest side of this area, from 100 to 500 feet southeast of DeRussy Way, conditions are extremely consistent, with lagoonal deposits occurring at about -4 feet beneath a surface unit of fill and beach sand. The -30 coral ledge occurs at about -37 feet and is generally covered by a thin veneer (up to 2 feet thick) of alluvial silt and coral gravel. The coral thickness ranges from 12 to 19 feet. Coralline gravel and sand underlie the coral ledge to at least -128 feet. In one boring, an alluvial lens occurs within the coral gravel from -66 to at least -73 feet.

These same conditions dominate most of the area at the southeast corner of this quad, with coral thickness ranging from 7 to 14 feet. In addition, poorly defined coral ledges are indicated at -85 feet and -120 feet.

Further west, roughly 300 feet northwest of the seaward end of DeRussy Way, borings are available which define the -30 coral ledge at elevations ranging from

-34 to -39 feet. The thickness of the ledge here varies from 13 to 29 feet and the ledge is underlain by coralline gravel and sand to at least -94 feet. In one boring, the coral ledge was not well defined, occurring as coral gravel probably representing a localized poorly cemented part of the reef. The ledge in this area is overlain by coralline gravel and sand. This material has a somewhat larger gravel fraction than the lagoonal deposits which normally occur over the upper coral in Waikiki, although it still appears to have a lagoonal origin--possibly grading to back reef deposits.

On the northeast corner of the intersection of Ena Road and Ala Moana Boulevard, four borings are available which define the coral ledge at varying levels from -26 to -34 feet. (Most of this site occurs within Quad B-4 and is discussed in detail in that section.) Similarly, one boring at the west boundary of Quad C-4, south of Ala Moana Boulevard, is part of a group of borings which occurs in Quad C-5 and is discussed below.

<u>QUAD C-5</u>

About 400 feet south of the intersection of Hobron Lane and Ala Moana Boulevard, the coral is well defined by four borings (one of these borings is just inside Quad C-4 but discussed here). The -30 coral ledge is encountered at elevations ranging from -37 to -40 feet with a thickness of 8 to 13 feet. In general, the coral here is overlain by fill and sand to an elevation of -6 feet, and lagoonal clay and coralline gravel from about -6 feet to within about 10 feet of the top of the coral ledge. Immediately over the coral a relatively soft alluvial layer occurs which ranges from 3 to 10 feet thick. In addition, in one boring, a 4-foot thick coral ledge is found at about -24 feet. This ledge is not found in the adjacent borings and probably represents an isolated coral head. Beneath the -40 ledge, the materials are characterized by coralline debris with some coral. These boring logs suggest ledges at the -82 to -85 foot range and at about -120 feet.

Roughly 650 feet southeast of the Ala Moana Bridge, over the Ala Wai Canal, one boring is available in Ala Wai Harbor. At this location, coral occurs at about -39 feet with a thickness of at least 7 feet. The coral is overlain by lagoonal deposits.

At the west boundary of this quad, roughly 1000 feet south of Quad B-5, one boring is available (in 8 feet of water) which describes coralline debris from -8 feet to -44 feet where the -30 coral ledge is encountered which is at least 6 feet thick.

<u>QUAD C-6</u>

A total of 9 borings are available within this quad. These borings were completed for the "Comprehensive

Plan for Ala Moana Reef" (1960) previous to the construction of Magic Island. Therefore, all of these borings were completed offshore and do not reflect the fill which has been placed since 1960.

In general, with the exception of dredged areas, the bottom offshore is characterized by a coral ledge which is found at elevations ranging from -1 to -12 feet which represents the modern reef. (In order to avoid masking other units, the occurrence of the modern reef is not shown on the geologic map.) The thickness of this reef is highly variable, ranging from 7 to 28 feet and including numerous zones of coralline debris and sand. Dredged areas where the modern reef has been removed include the area within about 300 feet offshore of Ala Moana Beach (also extending this line across Magic Island), and in the Ala Wai Channel to within about 100 feet east of Magic Island. The area along Ala Moana Beach was originally dredged to provide a channel to connect Kewalo Basin with Ala Wai Yacht Harbor, but this channel was subsequently closed.

Below the modern reef, coralline debris and lagoonal deposits generally extend to the -30 coral ledge which occurs at elevations ranging from -31 to -45 feet with a thickness of at least 10 feet. Within this quad, two isolated occurrences of a coral ledge at -21 feet were described. These occurrences probably represent either individual coral knolls or dredged levels. As shown on the geologic map (Plate II) the -30 coral ledge is not found in a line extending southwest from the mouth of the Ala Wai Harbor. Three borings indicate either alluvium or low-energy lagoonal-type deposits within this zone below the modern reef. This is interpreted to represent the offshore continuation of the Kaheka Channel.

QUAD C-7

Adjacent to the tennis pavilion in Ala Moana Park, one boring encounters the -30 coral ledge at -33 feet with a thickness of at least 4 feet. The coral is overlain by lagoonal deposits and a 1 1/2-foot fill layer. (Other borings at this site are also discussed under Quad B-7).

Just offshore of Ala Moana Beach, similar conditions are found with the -30 ledge being encountered at -39 feet with a minimum coral thickness of 11 feet. A two-foot layer of alluvium occurs immediately over this ledge.

Further offshore (beyond 400 feet), the modern reef is encountered at elevations ranging from -1 to -9 feet with variable thickness from 3 to 17 feet. Coralline gravel and lagoonal deposits occur below the modern coral down to the -30 ledge. In one boring, a 4-foot coral layer was found at -20 feet. The -30 ledge is found at elevations ranging from -38 to -40 feet. The thickness of this coral is about 15 feet and it is underlain by coralline debris and sand to at least -87 feet. In one boring, 1200 feet offshore, the -30 ledge is not encountered to at least -50 feet. In this case, coralline gravel occurs in this interval.

QUAD C-8

Eight borings are distributed within this quad providing control on the offshore conditions. The modern reef is encountered at elevations ranging from -2 to -12 feet with thicknesses ranging from 4 to over 30 feet. Dredged areas, where the upper coral has been removed, include the area within 400 feet of Ala Moana Beach, and the Kewalo Channel. Below the upper coral, coralline debris and lagoonal deposits generally occur down to the -30 ledge. In two borings, a coral unit is encountered at about -22 feet, representing either a coral knoll or a dredged depth. The -30 ledge is encountered at elevations ranging from -37 to -44 feet with variable thicknessess ranging from 2 to at least 14 feet. This ledge includes numerous zones of uncemented coralline debris. Another coral ledge is defined in one boring at -79 feet with a thickness of at least 21 feet.

QUAD C-9

Relatively little control is available within this quad. At the southwest end of the channel leading into Kewalo Basin, on the west side of the channel, two shallow borings are available which define a coral level (presumably the modern reef) at -11 feet. This reef is overlain by about 15 feet of miscellaneous fill material over about 7 feet of sand and coral gravel. The reef is about 14 feet thick and underlain by coral gravel to at least -37 feet.

North of this site, near the north corner of the intersection of Olomehani and Koula Streets, one boring indicates fill from the surface to about -1 foot, with coralline gravel extending to a coral ledge which occurs at -19 feet. This coral extends to at least -42 feet.

On the north side of Kelikoi Street, within 300 feet west of Ohe Street, two borings occur within this quad (the rest of this site is discussed under Quad B-9). In these borings, 5 to 14 feet of fill is described over lagoonal deposits down to coral at about -46 feet which is at least 5 feet thick.

QUADS D-6/D-7/D-8

Control within these quads extends only about 400 feet south of their north boundaries. Five borings occur across this area. The modern reef is found at elevations ranging from -12 to -16 feet with thicknesses on the order of 4 to 17 feet. It is particularly significant that no coral of the -30 ledge is encountered in these borings to the -50 foot depth of exploration. The interval below the modern reef is characterized by coralline debris sand, shells, and silt. This area apparently defines the seaward limit of the -30 coral with the deposits encountered probably representing the fore reef-zone of the -30 coral reef.

CHAPTER IV

GEOLOGY

Based on the subsurface conditions delineated in Chapter III, age relationships can be established between some of the geologic units in the study area. From this information, a partial understanding of the geologic history of the area can be developed. The purpose of this chapter is to present the age relationships where they have been defined and to discuss the implied relationships between units where the available information is not definitive. This information is summarized at the end of this chapter in a geologic model presenting a possible explanation of the sequence of events which produced the conditions found in the project area.

GEOLOGIC SETTING

The project area is located on the coastal plain of southeastern Oahu. This plain has been built on the eroded flanks of the Koolau Volcano which forms the eastern half of the island. The major activity of the Koolau Volcano ceased roughly 2 million years ago (Macdonald & Abbott, 1970) and since that time the dominant geomorphic processes have been erosion and redeposition. The coastal plain is the product extensive accumulations of alluvium, derived from the erosion of the volcano, interbedded with coral reefs and associated deposits. In addition, less than one million years ago (Macdonald & Abbott, 1970), the post-erosional Honolulu Volcanic Series began, producing numerous cinder and tuff cones, and basalt flows which became interlayered with the coastal plain deposits.

Most of the coastal plain developed during the Pleistocene epoch when the sea level was fluctuating a great deal. These changes in sea level have been related to the the effects of the various glacial stages, which produced changes in the amount of water in the oceans, depending on how much water was being held up in the glacier ice. During interglacial periods, the sea level rose above the present level, followed by a regression of the sea to well below the present level during the glacial stages. These cycles of advance and retreat of the sea have produced reef deposits at varying levels--in some cases above the present sea level. During periods of low sea level, alluvial channels and erosional surfaces have developed which extend well below existing sea level.

Within the project area, there are numerous coral ledges at depth, which are apparently related to a number of different cycles of transgression and regression of the sea. Due to the limited control on the deeper ledges and the high degree of complexity of these units, the geologic discussion presented herein is limited to the upper coral ledges and related units. Of particular significance in this discussion is the Waimanalo stand of the sea, first described by H.T. Stearns (Stearns & Vaksvik, 1935). This sea stand is found up to a maximum elevation of about +25 feet. Corals which grew during this time occur widely and probably account for much of the emerged reefs of southern Oahu (Macdonald & Abbott, 1970). The upper surface of much of the coral of this age, in particular in the project area, occurs at elevations of about five feet above sea level. The corals of this level have been dated by the uranium-thorium method and yielded relatively consistent ages on the order of 120,000 years before present (Veeh, 1966, and Ku, et al., 1974). Stearns (1974) has tentatively assigned this sea stand to the Illinoian/ Wisconsinan interglacial period (Sangamon), and proposed that it was preceded by and followed by regressions of the sea level--possibly to as low as -300 feet or more. The regression preceding the Waimanalo stand is named the Waipio Low and the regression following Waimanalo time is named the Mamala Low. In a relatively recent paper, Stearns has proposed a number of minor transgressions during the Wisconsinan (Stearns, 1974). However, the general picture is that one last great regression of the sea--the Mamala Low--with minor fluctuations, occurred between the Waimanalo High Stand and modern times. As discussed below, it appears that the Waimanalo transgression, the subsequent Mamala regression, and the return to the modern sea level have had the dominant influence on the geology of the area disclosed in this study.

At the west end of the project area (Plate I), where the landward boundary intersects the coastline near the Aloha Tower, about a mile of coastal plain occurs between the project area and the Koolau Range. However, Koolau basalts crop out within a quarter mile to the north of the northeast corner of the area.

Post-erosional vents which occur in the vicinity of the area (shown on Plate I) include, on the north side of the area, the tuff cone of Punchbowl and the cinder cone of Rocky Hill. In addition, within two miles north of Rocky Hill, the three cinder cones of Tantalus, Round Top, and Sugarloaf occur. Further east, just north of the northeast corner of the project area, the Sugarloaf lava flow is well exposed in Moiliili Quarry. To the east of the project area, the flows of the Kaau(?), Mauumae, and Kaimuki eruptions are found, and to the southeast is the Diamond Head tuff cone. All of these vents have contributed to the geologic history of the project area. To put these events in perspective, in time, relative to the various advances and regressions of the sea, they are listed in Table 1 on the following page (modified from Macdonald & Abbott, 1970). These events are presented in their order of occurrence, from oldest to youngest, opposite the type of features in the project area which are associated with them.

GEOLOGY OF PROJECT AREA

The geologic units within the project area include deposits ranging in age from Koolau basalts to the fill deposits of Magic Island placed since 1960. The units are discussed below more or less in order of age.

KOOLAU BASALTS (Quads A-1/B-1, A-5, A-6, A-7, A-10, C-1, C-2)

Basalt, tentatively identified as Koolau basalt, is encountered in a number of deep wells in the project area. At the northeast corner of the area, it occurs at -75 feet and is found at progressively greater depths both to the northwest and southwest. At the east end of Waikiki, it is found at roughly -700 feet and at the west end of the project area Koolau basalt is found as deep as -992 feet. This unit presumably represents the eroded surface of the basaltic bedrock which formed the original Koolau volcano. As much as 833 feet of interlayered coralline deposits and alluvium occur between the Koolau basalt and the post-erosional lava flows of the Nuuanu Volcanics (the deepest post-erosional flow in the area). The deepest coralline

TABLE 1

GEOLOGIC EVENTS WITHIN THE PROJECT AREA

EVENT	FEATURE WITHIN PROJECT AREA
Koolau Volcanics	Basalt bedrock
Cycles of regression & transgression of sea level	Interlayered coral & alluvium
Nuuanu (Luakaha & Makuku) Volcanics	Lava flows
Rocky Hill Volcanics	Lava flow
Kaau Volcanics	Lava flow(?)
Mauumae Volcanics	Lava flow
Waipio Low Sea Stand (-300 feet?)	Erosion of coastal plain
Diamond Head Volcanics	Reworked tuff
Kaimuki Volcanics	Lava flow
Punchbowl Volcanics	Lava flow
Waimanalo High Sea Stand (+25 feet)	+5 Coral Ledge -15 Coral Ledge -30 Coral Ledge
Mamala Low Sea Stand (-300 feet?)	Erosion of coastal plain
Round Top Volcanics	Cinder
Tantalus Volcanics	Cinder
Sugarloaf Volcanics	Lava flow
Present Sea Level	Modern Reef & Lagoonal Deposits

deposits encountered occur at -782 feet. This thickness of deposits indicates that some subsidence of the Koolau volcano has occurred--particularly in order to account for coral at such a great depth.

NUUANU BASALT (QUAD A-10)

Two lava flows have been identified in Nuuanu Valley by C. K. Wentworth (as reported by Winchell, 1947). These are named for the Laukaha and Makuku tuff cones from which they originated. Within the project area, post-erosional basalt is found in Quad A-10 which is tentatively assigned to these Nuuanu Volcanics (Stearns & Vaksvik, 1938). The elevation of the top of this basalt (or basalt boulders presumably related to it) has been found at -76, -81, -102, -114, and -143 feet. These occurrences are closely spaced and inconsistent, with the -81 occurrence less than 150 feet from the -143 occurrence. The thickness of the basalt, where determined, ranges from 35 feet (at -114) to 45 feet (at -143). At the -81 occurrence, basalt was drilled to -105 without penetrating the lower surface of the flow. However, at the -76 occurrence, the flow is only 11 feet thick and at -102 feet--only 2 feet thick. It is possible that the two Nuuanu flows partially overlap here and that the upper Makuku flow (-76, -81, and -102) has been removed by erosion, or was never deposited, at the locations where only the lower Luakaha flow (-114 and -143) is encountered.

ROCKY HILL BASALT (Quads A-5, A-6)

Rocky Hill is a cinder and spatter cone which is located just northeast of Punahou School. It has been assigned by Stearns to an age corresponding to the Kaena stand of the sea (Stearns & Vaksvik, 1935). The Kaena Sea Stand is the high stand which preceded the Waipio Low. A lava flow which apparently issued from Rocky Hill is found at depths ranging from -43 feet to -81 feet in Quads A-5 and A-6. It has a thickness of 40 and 10 feet, respectively. This basalt is also encountered in borings north of the project area and its surface elevation rises toward Rocky Hill. This flow is overlain by the +5 coral ledge (discussed below) which formed during the Waimanalo stand of the sea.

Although there is not sufficient evidence to clearly identify the age of this flow, one observation is that its stratigraphic position, compared to that of other flows, suggests the possibility that it may be younger than Kaena. Two blocks landward of the project boundary, the Rocky Hill flow is overlain by only seven feet of Waimanalo coral. This stratigraphic position is similar to that of the Kaimuki basalt further east, which has been clearly identified to have formed above water--presumably during the Waipio Low (see below). This similarity is by no means conclusive but suggests that the assignment of Rocky Hill basalt to the Kaena High Sea Stand should be reconsidered.

KAAU AND MAUUMAE BASALT (Quad A-1/B-1)

At the northeast corner of the project area, three post-erosional basalt flows are encountered overlying one another and separated by five-foot layers of alluvium. The surface of these flows occurs at roughly +25 feet, +5 feet, and -17 feet. The upper flow is tentatively identified as part of the Kaimuki basalts, discussed below. The lower of these two flows is assumed to be Kaau basalt which flowed down from Kaau Crater in the back of Palolo Valley, however, it could also be from the Mauumae vent. The basalt flow above it, at +5 feet elevation, is probably from the Mauumae vent on the lower end of the ridge just east of the mouth of Palolo Valley. This flow was previously exposed in the now covered Kapahulu Quarry near the intersection of Kapahulu Avenue and Harding Avenue. In that outcrop, it was overlain by four to eight feet of Diamond Head tuff, which was in turn overlain by Kaimuki basalt, capped by Waimanalo coral, thus clearly establishing its age relationship as pre-Waimanalo (Macdonald & Abbott, 1970). In addition, this Mauumae basalt showed crudely developed pillow structure suggesting that it was erupted either below sea level or into some other wet environment. On this basis, it has been assigned to the Kaena High Sea Stand.

An additional occurrence of these lower flows (either Kaau or Mauumae) may be a two-foot layer of boulders found at the east side of Kaimuki High School.

Also, basalt boulders found at -40 feet and -60 feet in the Manoa-Palolo Stream Channel may be related either to these flows or to the Sugarloaf flow.

WAIPIO LOW SEA STAND

The Mauumae volcanics are apparently the last geologic event affecting the project area preceding the regression of the sea which Stearns has correlated with the Illinoian glaciation. It has been determined that, during this regression, the sea level dropped below elevation -110 feet (Lum & Stearns, 1970). This regression has been named the Waipio Low by Stearns (Stearns & Vaksvik, 1935). No doubt erosion became more prevalent during this period, due to the lowered stream base, and deep channels were probably cut into the existing coastal plain by the streams. The alluvial deposits described at depth, in Chapter III, reflect this period of erosion. The subsurface sections (Plates III, IV, and V) show an indication of the extent of alluvium below the upper coral ledges.

KAIMUKI BASALT AND DIAMOND HEAD TUFF (Quads A-1/B-1, C-1, C-2, D-1)

The eruptions of Diamond Head and the Kaimuki shield apparently occurred during the Waipio Low (Stearns & Vaksvik, 1935). Diamond Head tuff occurs immediately under Kaimuki basalt in the old Kapahulu Quarry. In addition, alluvium with tuff is described underlying the +5 coral ledge in the vicinity of King Street and University Avenue (see subsurface section A-A' (Plate III)). However, no other evidence of the Diamond Head eruption is found in the project area. This is probably related to the fact that tuff, when decomposed, is similar in appearance to alluvium, and in many cases may have been described simply as brown silt.

Following the eruption of Diamond Head, the basalt flows of the Kaimuki shield were extruded. As mentioned previously, the Kaimuki basalt is found as high as +25 feet at the northeast corner of the project area. In Kapahulu Quarry, the Waimanalo Coral is described directly overlying the Kaimuki flow (Macdonald & Abbott, 1970). Similarly, a basalt flow can be traced along Kapahulu Avenue in Quad A-1/B-1. It occurs progressively deeper, with its surface elevation occurring at -5 feet at the corner of Date Street and Palani Street. In most instances where this basalt is found, it is immediately overlain by the +5 (Waimanalo) coral ledge. The maximum determined thickness of this flow is 75 feet. Based on its relationship to the overlying coral, this flow is correlated with the Kaimuki basalt flows. (This correlation is not definitive and there is a remote possibility that this basalt is from the older Kaau or Mauumae vents.)

It is probable that this basalt continues seaward under the Ala Wai Golf Course. Based on this assumption, the basalt flow found beneath the east end of

Waikiki (Quads C-1, C-2, and D-1) at elevations ranging from -70 feet (near Kuhio Avenue and Paoakalani Avenue) to -135 feet (Kaiulani Avenue and Kalakaua Avenue), is tentatively identified as Kaimuki in origin. (A K/Ar age determination is currently underway for a sample of this basalt to verify this identification). The thickness of this flow, as determined at one location in Quad C-1, is 47 feet. This basalt is generally overlain by a thin boulder alluvium covered by up to 30 feet of cemented sand (possibly beach sand). This sequence of deposits appears to have been laid down during the transgression of the sea from the Waipio Low to the Waimanalo Stand. Above the sand, cemented coralline debris occurs, overlain by the -15 and -30 (Waimanalo) coral ledges which are discussed below.

PUNCHBOWL BASALT (Quad B-9)

In Quad B-9, on the west side of Kewalo Basin, a 12-foot thick basalt flow is found with a surface elevation of about -105 feet. This flow occurs 0.6 miles from the nearest known occurrence of the Nuuanu basalt and 0.9 miles from the nearest location of the Rocky Hill flow. However, it is directly seaward of Punchbowl Crater. Although Punchbowl is for the most part, a tuff cone, at least one lava flow has been identified as having issued from this crater (lava flows also crop out within the crater). This flow was encountered in the excavation for the Board of Water Supply building north of the corner of Beretania and Alapai Streets (Winchell, 1947) and in cuts for the Lunalilo Freeway. It is also encountered in Well Group 88 (Stearns & Vaksvik, 1939) and ranges from about 15 to 35 feet thick with a surface elevation of roughly +10 feet. (It is noteworthy that this basalt is immediately overlain by coral--presumably Waimanalo.) Based solely on the location of the basalt in Quad B-9 relative to this known Punchbowl flow, the B-9 basalt is tentatively correlated with Punchbowl. However, it remains possible that it could have originated from one of the Nuuanu vents or from Rocky Hill.

WAIMANALO HIGH SEA STAND

Following the Waipio Low, the sea trangressed to above the present sea level. This high stand of the sea, named by Stearns, the Waimanalo Stand, has been traced to an elevation as high as +25 feet, and this level is generally regarded as the maximum elevation to which this sea stand reached. As discussed previously, this stand has been dated to have formed roughly 120,000 years before present. Extensive coral growth occurred during this high sea stand, probably as a result of the warmer climate of the interglacial stage.

Within the project area, the uppermost Waimanalo coral generally occurs at about +5 feet, and it has a maximum reported occurrence of +10 feet within this area. Further inland, this coral can be traced to higher elevations.

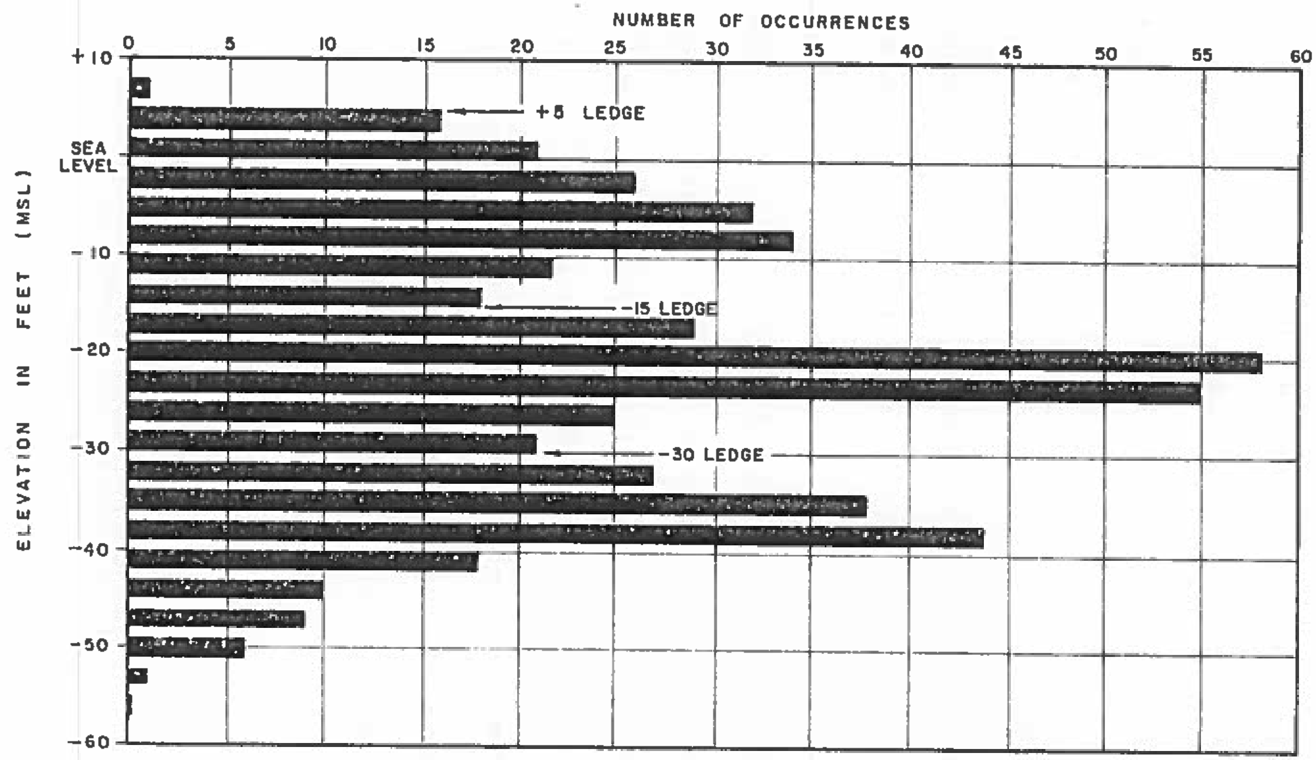
It occurs at about +20 feet in the floor of Moiliili Quarry, just north of the project area (Stearns & Vaksvik, 1935).

There are three coral levels within the project area all of which appear to have formed during the Waimanalo High Sea Stand. These include the -15 ledge, seaward of the already mentioned +5 ledge, and the -30 ledge which is seaward of the -15 ledge. These ledge elevations are nominal elevations which generally reflect the highest elevation at which the ledge is found.

The nominal elevations for the three ledges were determined from the frequency diagram (Figure 6). This diagram presents the number of borings (in the project area) in which the surface of an upper coral ledge was encountered at a given elevation. Upper coral ledge surfaces encountered between -60 and +10 feet are included in this diagram. To facilitate presentation, the number of occurrences are summed for successive three-foot elevation intervals and plotted. To avoid confusion in the interpretation of this diagram, the occurrences of coral ledges where they have been eroded by known channels are not included. Similarly, the occurrences of the modern reef are excluded. A total of 511 occurrences of coral are reflected in this diagram.

From this diagram, three peaks, or levels of most frequent coral occurrence, can be identified at -8, -20, and -38 feet. The highest occurrence of a given coral ledge is generally the most useful for discussion of its geologic significance and the agents which contributed

FIGURE 6



OCCURRENCES OF CORAL LEDGES Vs. ELEVATION

NOTE: BASED ON 511 BORINGS IN WHICH UPPER LEDGES WERE ENCOUNTERED. DATA ON MODERN REEF LEVEL IS EXCLUDED.

to its growth and/or erosion. Therefore, the nominal elevation for each ledge indicated in Figure 6 was chosen at the minimum occurrence level above the peak for that ledge.

Although all three of the coral ledges appear to be Waimanalo in age, the age of the individual ledges relative to one another is not clear. Stratigraphic evidence is one source of information but it is frequently ambiguous. For example, the -15 ledge appears to overlie the -30 ledge at a few locations, however, in many other cases, the -15 ledge is continous to well below the level of the -30 ledge.

Coral type also provides some clues. Three types of coral have been identified in the cores and are significant with respect to the reef environment which they represent. Therefore, the presence of these corals at a given location allows for some inferences to be drawn regarding the environment in which they formed. These types are algal coral (or calcareous algae), Porites lobata (an encrusting coral), and Porites compressa (a branching coral). Generally, the algal coral and Porites lobata occur in the high-energy reef flat, in or near the zone of wave action. The algal coral is particularly indicative of the high-energy algal ridge of the reef. Porites compressa, however, is a more fragile coral and is more common in low energy lagoonal and backreef areas (Maragos, 1973). These corals are relatively easy to differentiate in rock cores and provide some indication of possible relationships between ledges which differ in coral types.

In the following discussions, an attempt is made to interpret the relationships between these levels but it should be understood that these relationships are tenuous. Radiogenic dating is currently under way on coral from each of these levels, and it is hoped that this dating will provide more definitive data on the relationships. The general succession of the ledges as presently envisioned is reflected in subsurface section A-A' (Plate III).

+5 Coral Ledge (Quads A-1 thorugh A-10, B-1, B-2, C-1)

The range of actual surface elevations of the +5 coral are shown on Figure 6 and generally the surface of this ledge grades deeper toward the seaward side of the ledge. The lateral distribution of this ledge over the project area is shown on the geologic map (Plate II). Although the thickness of the +5 coral is quite variable, it is generally on the order of about 20 feet thick and overlies coralline gravel and/or alluvium.

Cores of this ledge which have been examined by the writer, from Quads A-2 and A-9, indicate that the upper part of this ledge is characterized by algal coral, two to seven feet thick, overlying *Porites lobata*. This indicates that the +5 ledge is not simply a seaward, deeper water, occurrence of the +25 sea level. Rather, it suggests that as the sea receded from the +25-foot stand, it paused at about +5 feet (or slightly above) long enough to encourage the growth of the high energy-loving algal coral and Porites lobata. It may be that the +25 reef was planed off somewhat prior to the growth of the +5-foot coral or that the +5 ledge established itself on the fore reef coral rubble of the +25 reef. The cores observed tend to support the latter hypothesis but the number of cores available are not sufficient to be definite on this point.

In any case, the sea stood at this +5 level long enough to form the +5 coral ledge and a deposit of beachrock at its landward margin. This beachrock is encountered on King Street near University Avenue with its upper surface occurring at about +3 feet (See subsurface section A-A' (Plate III)).

The available stratigraphic evidence indicates that the relationship between the +5 coral ledge and the -15 coral ledge (discussed below) is that the -15 ledge developed after or possibly simultaneous with the +5 ledge. There are no instances in the data where the +5 ledge overlies either the -15 or -30 ledge.

At the seaward edge of the +5 ledge, the coral generally drops off abruptly to the -15 ledge, however, the -15 ledge is not well developed at this boundary. It appears that this zone is dominated by coralline rubble--possibly the fore reef of the +5 ledge. At its west end in Quads A-9 and A-10, the +5 ledge occurs at relatively deep levels--ranging from -10 to -14 feet. The ledge here may have been eroded to this level--either during modern sea level or during the stand which formed the -15 ledge.

As discussed previously, this ledge stratigraphically overlies the Rocky Hill basalt, the Nuuanu basalt (by about 100 feet), the Kaau and Mauumae basalts, and Diamond Head Tuff. In addition, it immedately overlies the Kaimuki basalt and the Punchbowl basalt (north of the project area).

<u>-15 Coral Ledge</u> (Quads A-2 through A-10, B-1 through B-10, C-1, C-2, D-1)

The -15 coral ledge, although not as well developed as the +5 ledge, occurs consistently in the study area. The range of elevations of the surface of this ledge are indicated on Figure 6, and they generally grade deeper in a seaward direction. The lateral distribution is shown on the geologic map (Plate II). The thickness of this ledge ranges from roughly 10 to 20 feet. In most cases, this ledge is underlain by coralline debris with some cemented layers.

Only one set of cores for this ledge was available for examination by the writer. These cores disclosed <u>Porites lobata</u> at the top of this ledge, extending for a depth of about 10 feet. This suggests that this ledge was within the high energy zone a few feet below sea level during its formation.

The fact that the -15 ledge is not found under the +5 ledge indicates that it postdates or is contemporaneous with the +5 ledge. However, the presence of well developed *Porites lobata* on this ledge suggests that the -15 ledge was formed in relatively shallow water--shallower than the 20-plus feet of water which characterized the area during the formation of the +5 ledge. Therefore, this ledge probably postdates the +5 ledge. Furthermore, since the -15 ledge is overlain by lagoonal deposits, it must have been deposited either during the regression from the Waimanalo Stand to the Mamala Low or during the transgression to the modern sea level. However, it is not likely that the *Porites lobata* would thrive in a lagoonal environment such as existed during the transgression to the modern sea level. In summary, although the evidence is far from definitive, it appears that the -15 ledge was formed shortly after the +5 ledge during a pause in the regression of the sea from the Waimanalo High Stand to the Mamala Low Stand.

The relationship between the -15 ledge and the -30 ledge is not at all clear. As mentioned previously, in a few cases ranging from Quad A-5 to D-1, the -15 ledge appears to overlie a ledge at about -30 feet, however, in most cases there is no evidence of this and the -15 ledge is continuous to below -30 feet. Unfortunately, there are not any cores available for examination in the cases where the two distinct ledges are found. Generally, where the two ledges appear superimposed, the -15 ledge is thin--5 to 10 feet thick--and separated from the -30 ledge by 5 to 10 feet of coralline debris and sand. The implications of this question are further discussed below.

-30 Coral Ledge (Quads B-2 through B-10, C-1 through C-8, D-1 through D-7)

The -30 coral ledge appears to be a more complex feature than the +5 and -15 ledges. The upper surface of this ledge grades from -30 feet at its landward boundary to below -50 feet near the existing shoreline. The lateral distribution of this ledge is shown on the geologic map (Plate II). The thickness of this ledge is quite variable, ranging from less than 5 feet to over 30 feet.

Two sets of cores of this ledge, from Quads C-1 and C-2, have been examined by the writer. The upper surface of the ledge at these locations ranges from -38 to -40 feet. These cores indicate that the -30 ledge includes an upper layer of cemented coral rubble which is on the order of 7 feet thick and includes some zones of algal coral (coralline algae). This material overlies a five-foot layer of *Porites compressa* which has been infilled with alluvial silt. The *Porites* overlies a definite unconformity. The material below the unconformity includes a well cemented coralline debris and marl capped with a thin (less than one foot) layer of algal coral. The *Porites* appears considerably less weathered than the material below the unconformity.

The elevation of this unconformity is about -50 feet. Based on these conditions, the -30 ledge is interpreted to be composed largely of cemented coralline rubble, produced at two widely spaced points in time, with a period of coral growth in between. The events which appear to have formed this ledge are the following:

1. The cemented coralline rubble below the unconformity was deposited during the transgression from the Waipio Low Stand to the Waimanalo High Stand.
2. The presence of algal coral capping the coralline rubble suggests that there may have been a brief pause in the advance of the sea to permit the coral growth.
3. The sea level then advanced well past this elevation. The *Porites compressa* is a coral which thrives below wave base in the relatively low-energy lagoonal, backreef or forereef areas. The layer of this coral found in the -30 ledge probably did not grow until the sea level was considerably above the surface of the unconformity.
4. Based on the contrast in decomposition (i.e., apparent time interval) across the unconformity, this coral probably did not grow until after the sea had transgressed to the +25 maximum and then dropped back to the +5 or -15 level. Therefore, it may be seaward (fore reef) reflection of one of these ledges rather than representing a separate time period of coral growth.

5. As regression continued, the *Porites compressa* became infilled with alluvium. With further regression, as the sea level dropped to near the elevation of this ledge, coralline debris with some algal coral was deposited.
6. The sea level then regressed below the level of the -30 ledge, the coralline debris became cemented, and alluvium was deposited over the ledge. This alluvium probably contained a substantial amount of reworked tuff which had been eroded from Diamond Head. (Such an alluvial layer occurs frequently over the -30 ledge).

There are a number of significant factors which are implied by this sequence. The -30 ledge may be largely mis-identified as a coral growth feature. It may actually be, for the most part, accumulated coralline debris which has been subsequently cemented. The fact that algal coral is found both at the top and bottom of this ledge may indicate that the sea paused briefly at this locale both on the way up and during its regression. Since most cementation occurs in the vicinity of sea level, the extensive degree of cementation found in this ledge may be the result of the sea level pausing twice at this level.

A reef coral, interpreted to be a pause in the advance from the Waipio Low, has been observed on Kauai by D. Cox (Stearns, 1966) at -60 feet and reported by Ruhe, *et al*. (1965) at -40 feet which supports this hypothesis. Stearns also described a planing off of the Bellows Field Dune formation found in cores from Waimanalo, Oahu (Lum & Stearns, 1970). He named this pause the Olomana Shoreline, at about -30 feet, after a beachrock which was found over the dune formation at -30 feet. These various pauses probably reflect the fact that during transgression, the sea was not advancing at a uniform rate and that numerous pauses were taking place.

Within the project area, cemented sand (possibly beachrock) has been described in a few locations at roughly -30 feet (see subsurface sections A-A' and C-C' (Plates III and IV)). However, this beachrock occurs on top of the -30 ledge and therefore was probably deposited during the pause at this level during the regression from the Waimanalo Stand.

The presence of dense, well developed *Porites compressa* within the -30 ledge is evidence, although tenuous, that a barrier reef may have been forming at this time in the vicinity of the present shoreline. Thus the viability of the *Porites compressa* would be explained by the fact that it was growing in its favored environment, the back reef. Furthermore, the fact that this coral is infilled with alluvial silt rather than sand or coral gravel supports the idea that it formed in a back reef rather than fore reef environment. The postulated evidence of a barrier reef offshore becomes more significant in discussions below, where this barrier reef becomes a platform from which the modern reef developed.

MAMALA LOW SEA STAND

After the deposition of the top part of the -30 ledge, the sea level appears to have receded as much as 300 feet below the present sea level in response to the Wisconsinan glaciation (Stearns, 1974). Erosion dominated this period due to the rapidly lowered stream base. During this time, extremely deep alluvial channels dissected the coralline reefs of the project area to depths of over 200 feet below existing sea level. Subsurface section C-C' (Plate V) shows cross sections of most of the channels which have been found in the project area. In addition, subsurface section B-B' (Plate IV) depicts a section roughly parallel to the Kaheka Channel and shows the typical variation in distribution of alluvial deposits and gives an idea of the depths of these features.

The alluvial channels encountered in the project area include, from west to east:

Unnamed Channel	Quad B-9
HIC Channel	Quads A-8, B-8
Unnamed Channel	Quad B-7
Kaheka Channel	Quads A-5, A-6, B-5, B-6, C-5, C-6
Makiki Channel	Quads A-4, A-5, B-4

Old Ala Wai Drainage	Quads B-3, B-4, B-5, C-5
Unnamed Channel	Quad B-3
Launiu Channel (ancient Manoa Stream Channel)	Quads A-2, A-3, B-2, B-3, C-3, D-3
Kaiulani Channel/Manoa-Palolo Channel and Old Manoa-Palolo Drainage	Quads A-1/B-1, A-2/B-2, C-1, C-2, C-3, D-2, D-3

The specific conditions encountered in each channel are discussed for the various quads in Chapter 3. However, a few general characteristics of these channels are as follows:

1. The maximum depth of down-cutting extends below -200 feet.
2. The channels are relatively straight, oriented perpendicular to the coastline, and steep sided, i.e., they have youthful characteristics.
3. The sediments in the bottom of the channels are of relatively high energy types with some boulder alluvium. However, above this alluvium the deposits for the most part are low-energy, estuarine-type sediments with some land-derived alluvium and coralline debris. Some peat layers occur within the low-energy alluvium.
4. Starting upward from about -80 feet, the channels generally include deposits of cinder sand, with the exception of the Kaiulani Channel which has no cinder deposits.

5. The channel deposits do not extend above the top of the coral ledges.
6. Some of the smaller channels apparently were only tributaries to the larger channels and did not cut as deep as the larger channels.

The geologic history reflected in these characteristics indicates that the sea dropped quickly to the Mamala Low Stand and that downcutting of the streams across the project area was very pronounced. The erosional force of this downcutting is indicated by the fact that the Kaiulani Channel apparently cut 60 to 80 feet into the Kaimuki basalt flow.

As the sea began to readvance from the Mamala Low to the present sea level, on the order of 40 feet or so of boulder alluvium was deposited before the advancing sea began to encroach upon and drown the channels within the study area. This caused the low-energy estuarine-type deposits to become dominant. Of course, erosion was still taking place above sea level, reworking the uplifted coral such that layers of alluvium with coralline gravel and sand were also being deposited in the channels.

<u>TANTALUS-ROUND TOP CINDER</u> (West half of Project Area)

At about the time that the channel deposition reached roughly -80 feet, cinder eruptions began to take place within the watersheds of all of the channels (except the Kaiulani Channel). These eruptions are reflected in the substantial deposits of cinder sand which are characteristically found in the channels. Presumably, the source of the cinders was the Tantalus-Round Top eruptions.

The Tantalus-Round Top vents occur north of the project area. Previous workers have indicated that these were essentially simultaneous and that they took place when the sea level was at or near its present level (Stearns & Vaksvik, 1935). However, the fact that cinders are found as deep as -80 feet in the alluvial channels indicates that at least the beginning of these eruptions took place prior to the rise of the sea up to its present level. This is supported by the fact that these channels were evidently buried by lagoonal deposits prior to the present sea level.

The Tantalus/Round Top eruptions cover a large portion of the western part of the project area with a thin blanket of cinder sand. The distribution of the cinder would initially be controlled by vent orientation and wind direction, with wind direction becoming more significant at increasing distances from the vent. Assuming that northeast tradewinds prevailed at the time, the cinder would be concentrated southwest of the vents. This appears to be the case to a great extent. However, much of the cinder was reworked and ended up in the channels. See subsurface section C-C' (Plate V) which indicates the extent of the cinder.

At the time of these eruptions, it appears that Kaiulani Channel drained only Palolo Valley--thus accounting for the absence of cinders in this channel since Palolo Valley is well to windward of the Tantalus/Round Top vents. At this time, Manoa Stream apparently was channeled down Launiu Channel (see the geologic map (Plate II)).

SUGARLOAF BASALT (Quads A-2/B-2)

The Sugarloaf basalt flow is found near the northeast corner of the project area in Quads A-2/B-2. This flow originated from the vicinity of the Tantalus-Round Top vents and then cascaded over the cliffs on the west side of Manoa Valley and flowed down the valley, terminating within the project area as shown on the geologic map (Plate II). This flow apparently pushed the Manoa Stream Channel over to the east side of the valley, causing it to join Palolo Channel just north of Quad A-1, forming Manoa-Palolo Channel (Stearns & Vaksvik, 1935).

As discussed in Chapter III (Quads A-2/B-2) the Sugarloaf basalt overlies the +5 coral ledge, but it is also found extending well below the level of this coral in Quad A-2/B-2. This is interpreted to indicate that the basalt flowed down and presently occupies the ancient channel of Manoa Stream here. The orientation of this flow relative to the Launiu Channel, found further seaward (described in Chapter III), indicates that the ancient Manoa Stream Channel drained through the Launiu Channel. The Launiu Channel contains cinder deposits as high as elevation -36 feet. It is interpreted that the time that the highest cinders in Launiu Channel were deposited coincides with the time that the Sugarloaf flow took place. This flow presumably cut most of the sediment flow off from Launiu Channel and pushed the Manoa Stream drainage over to the Palolo drainage. Based on orientation, it appears that Palolo Stream at this time was draining through Kaiulani Channel. The fact that no cinder deposits are found in Kaiulani Channel suggests that the Sugarloaf flow was the last event of the Tantalus group of vents. If further cinder eruptions had taken place from these vents after the Manoa drainage had been routed through Kaiulani Channel--and surely such eruptions would deposit some cinder in the Manoa watershed--some of this cinder would be expected to be deposited in Kauilani Channel.

MODERN REEF AND LAGOONAL DEPOSITS

The indications (discussed above under -30 coral ledge) that the Porites compressa of the -30 ledge formed in a back reef or lagoonal environment implies that a barrier reef may have occurred seaward of the existing shoreline prior to the Mamala regression. This barrier need only have been at -30 to -35 feet in order to protect the Porites compressa which occurs at -40 feet. As the sea readvanced toward the present sea level, this coral bench could then have become recolonized with coral, thus providing the foundation for the modern reef. The existence of this bench appears to be requisite in view of the apparently rapid advance of the sea to the modern sea level. The low-energy deposits found in the channels indicates that drowning of these channels was relatively rapid. It is not likely that coral growth could keep up with such rapid advance. Therefore, as the sea neared the existing sea level, the corals must have colonized a pre-existing bench. This idea is somewhat supported by the presence of a -30 ledge beneath the modern reef off Ala Moana Beach.

As the modern reef grew vertically, in response to the rising sea level, it continued the formation of a barrier reef. The present distribution of the modern reef is shown on the project area map (Plate I). The modern reef also occurs to the west of Kewalo Basin beneath fill and also beneath the Magic Island fill. This reef occurs fairly consistently offshore, with the exception of the area seaward of Kaiulani Avenue. It may be that the Kaiulani Channel--which was apparently the last of the deep channels which was active in the Waikiki area--induced a brackish water condition offshore here, discouraging coral growth.

The barrier formed by the modern reef produced a lagoon behind it in which lagoonal deposits accumulated as the sea level rose. These lagoonal deposits are widespread throughout the project area, overlying the -30 and -15 ledges, the alluvial channels, and the lower, seaward edge of the +5 ledge. In general, any area that was not above existing sea level prior to the transgression to the modern sea level became covered with lagoonal deposits (see the Subsurface Sections, (Plates III, IV, & V) for an idea of the distribution of these lagoonal deposits).

After the sea more or less stabilized at its present level, the lagoon filled up and became a swamp. Swamp deposits, with peat layers are found from just below existing sea level, on top of the lagoonal deposits, to just above sea level. Even into historical time, much of the area seaward of the +5 ledge was dominated by swamp conditions.

The lagoonal deposits generally appear to be one of the most recent units found in the study area (with the exception of man-fill). However, in two locations, Quads A-7 and B-6, deposits of loose silty cinder (in one case mixed with coralline sand) displace the lagoonal deposits (see Section C-C', (Plate V)). One of these deposits is small, about five feet thick, while the other is about 20 feet thick. These are anomalous deposits and it appears that they are the result of reworking of the (Tantalus Group) cinder deposits which occur landward of this area. Cinders are not found elsewhere in the lagoonal deposits and this localized occurrence of the cinders suggests that they are reworked older cinders rather than representing a new eruption.

FILL

The most recent "geologic" event to effect the project area is the placement of fill, by man, to facilitate the development of marginal land for useful purposes. Areas of swamp/lagoonal deposits are generally overlain by about five feet of fill. In addition, some fill has been placed over the modern reef as discussed above.

SUMMARY

In order to summarize the geologic history of the project area which has been developed in this study, the following geologic model (or outline) of the tentative sequence of events has been prepared and is presented on Table 2. Events which are fairly well established are denoted with an asterisk while others are more tenuous. Age dating now in progress should provide more clarification of some of these relationships.

TABLE 2

MODEL OF GEOLOGIC HISTORY OF PROJECT AREA

1. Koolau Volcanic Series*

2. Erosional period accompanied by some sea level fluctuation and development of older coralline deposits*

3. Kaena High Sea Stand*

   a. Ongoing deposition of coralline deposits during this period*

   b. Nuuanu Volcanics

   c. Rocky Hill Volcanics (possibly Waipio in age)

   d. Kaau and Mauumae Volcanics*

4. Regression to Waipio Low Sea Stand*

   a. Ongoing erosion with some deposition of alluvium throughout this period

   b. Diamond Head Volcanics*

   c. Kaimuki Volcanics*

   d. Punchbowl Volcanics*

5. Advance to Waimanalo High Sea Stand*

   a. Deposition of transgressional sequence of deposits--mainly sand and coralline debris

   b. Pause at roughly -50 feet causing cementation of deposits and a thin layer of algal coral

   c. Maximum sea level of +25 feet reached* before extensive coral growth began

6. Regression from Waimanalo High Stand*

   a. Extensive coral growth during +5 sea level*

   b. Further coral growth during -15 pause. Some growth of deeper water coral offshore of this shoreline

TABLE 2. (continued) MODEL OF GEOLOGIC HISTORY OF PROJECT AREA

c. Pause at about -30 feet causing additional cementation of coral rubble and growth of a thin algal coral layer

d. Possible formation of a partial barrier reef seaward of existing shoreline which may have existed at about -35 feet

7. Mamala Low Stand*

a. Erosion of deep channels in coral ledges*

b. Deposition of thin layer of alluvium over coral ledges*

8. Advance to Present Sea Level*

a. Filling of channels with low-energy, estuarine alluvium, and alluvium with coralline debris*

b. With sea level at about -80 feet eruption of Tantalus-Round Top cinder. Continued cinder deposition in channels up to about -30 feet*

c. Modern reef colonizes barrier reef top (6.d) seaward of existing shoreline and begins to grow upward to keep up with sea level rise

d. Sugarloaf, last of Tantalus group of eruptions, fills ancient Manoa Channel, cutting off sediment supply off from Launiu Channel and routing Manoa Stream through Palolo Channel and Kaiulani Channel*

e. Modern reef forms barrier offshore with a lagoon* behind it

f. Lagoon begins to fill with sediments*

9. Present Sea Level*

a. Lagoon fills up and becomes a swamp*

b. Man starts to place fill to reclaim lagoonal/ swamp areas and some areas of the modern reef*

CHAPTER V

ENGINEERING GEOLOGY

As discussed in the preceding chapter, the nature of the data studied for this project leaves considerable room for interpretation of the geologic significance of the various units. However, the original data was specifically aimed at providing a description of the physical properties of the subsurface materials and, as such, it appears to present a reasonably accurate reflection of what is physically there in terms of hardness, compressibility, density, grain-size, etc. That is, where a coral ledge is described, it is definitely a hard layer, regardless of whether it is actually cemented coralline debris, cemented sand, lithified marl, or in-place coral. This subsurface information therefore permits, at the very least, the development of a good understanding of the physical characteristics of the subsurface materials in the project area. This understanding has been utilized in this chapter to develop a general description of the physical nature of the various units (in addition to that presented in Chapter II).

Of course, in practice, the geologic significance of these units will always be of primary importance in any attempt to anticipate the occurrence of a particular layer and to develop an understanding of the total suite of characteristics that can be expected of a given unit.

In this chapter, the various geologic units are generalized according to physical type rather than discussing each individual unit of a given type. For example, the various basalt flows are discussed under the heading "basalt" rather than being discussed separately. Where appropriate, examples of specific units are discussed. For each physical unit, the general distribution of the unit and the internal variation which normally occurs within such a unit is discussed briefly. Engineering characteristics of the units are presented relative to normal engineering parameters. Emphasis in this section is on foundation engineering since most of the available data is directed toward that specialization. The foundation engineering considerations addressed are for relatively large structures greater than three stories. For smaller structures, foundation loads are not usually large enough to cause significant foundation problems. This chapter provides a reasonably complete description of general foundation engineering and engineering geology practice within the study area relative to the various materials which are encountered.

BASALT

Occurrance The post-erosional basalt units found in the project area are generally oriented perpendicular to the coastline. The flows at the east end of the area appear to have come from the Sugarloaf flow via Manoa Valley; from the Kaau and Mauumae flows via Palolo Valley; and from Kaimuki Shield. The Kaau and Mauumae flows generally extend seaward from Palolo Valley, and probably do not occur much further west than the east side of the project area. The Kaimuki flows probably tended to flow westward, around Diamond Head at roughly the northeast corner of the project area and from there to the sea. In the western part of the study area, the post-erosional basalt flows are apparently related to the Rocky Hill, Punchbowl, and Nuuanu volcanics. In these cases, the distribution of the basalt flows is not well known but they extend in general seaward of the vents. In the case of the Koolau basalt bedrock, the lateral distribution of any single flow is not significant. The distribution of the basalt is for the most part a function of the final eroded surface relief of the Koolau Volcano prior to deposition of the sediments which now overlie the bedrock.

The occurrence and thickness of the post-erosional flows vary widely and must be proven out in any particular area by drilling. The thicknesses of the basalt flows recorded in the project area range from less than 5 feet to over 70 feet. Generally, a 10-foot depth of drilling is adequate to prove out the rock for foundation purposes, however, this depends on the magnitude of anticipated foundation loading.

Variation of the rock structure within the basalt flows can be significant. Although dense basalt rock is among the strongest rock there is, such factors as lava tubes and clinker layers and other zones of flow debris and voids can produce local areas of low strength, some of which are virtually impossible to predict. Therefore, for foundation purposes, sufficient density of borings must be drilled in order to provide reasonable control on the continuity of the basalt.

Engineering Characteristics The Sugarloaf basalt, within Quad A-2, and the Kaimuki(?) basalt, within Quad A-1, are the only basalt units within the project area which are near enough to the surface to be utilized for support of shallow foundations. In these areas, spread footings are generally used. The actual compressive strength for dense, unweathered basalt is very high--on the order of 30,000 pounds per square inch (psi) (Krynine & Judd, 1957, p.52)--as compared with concrete which is normally on the order of 5000 psi. However, due to the variations which normally characterize basalt flows, and for structural engineering considerations, allowable foundation bearing pressures on the order of 10,000 to 30,000 pounds per square foot are normally used. For basalt, compressibility of the material is not a factor.

In most of the cases where basalt is encountered within the area of study, it occurs at depth, where it can be used to carry foundation loads only if deep foundations are used. Normal practice in Honolulu in such cases is to use pile foundations, although caissons may be appropriate for special applications. Allowable pile bearing capacities on basalt of up to 200 tons per pile (for 16½-inch octagonal piles) have been used in this area. Such loading is relatively high and makes this type of foundation attractive as compared to the much lower capacities allowable in coral. However, it is frequently necessary to predrill pile locations to get through coral and/or other cemented layers which occur between the surface and the basalt. Without such predrilling, many piles are likely to be broken in attempting to drive the piles through the cemented zones. Where exploratory drilling does not find significant hard zones in the coralline strata, use of the basalt, if available, for a pile bearing layer can be the best approach.

CINDER

Occurrence The deposits of cinder found in the project area are quite variable. In general, two types of cinder deposits are found--clean cinder, and cinder mixed with alluvium. At the east end of the project area, a layer of cinder, generally sand size, blankets the +5 coral ledge and in two cases displaces the lagoonal deposits which occur above the -15 coral. These cinder deposits are probably somewhat reworked by runoff, but particularly in the area where the cinder overlies the +5 ledge, it is relatively clean and free of other alluvial materials. The characteristics of such a clean cinder, where it occurs near the surface, are generally favorable for shallow foundations.

Other cinder deposits in the study area, however, are found to include alluvial lenses or occur as lenses within larger deposits of alluvium. Such cinder has probably been reworked to a considerable extent and can be expected to include a significant fraction of alluvial fines which tend to decrease its suitability for engineering purposes.

The thickness of the cinder deposits is unpredictable at any given site. Although originally laid down in relatively uniform layers, the reworking of the cinder by runoff, etc., can produce cinder thicknesses which vary considerably. Thus, these deposits must be well defined for foundation purposes because the compressibility of underlying units may be critical if the cinder layer is thin and overlies alluvium or lagoonal deposits.

Engineering Characteristics The near-surface cinder deposits which overlie the +5 coral ledge are used in some cases to support relatively light structures on shallow spread or mat foundations. The angle of internal friction for clean cinder is on the order of 30 to 35 degrees. In some instances, the cinder may be slightly cemented, yielding a cohesion in the range of 1000 psf, however, such cementation is variable and should generally be neglected for bearing capacity considerations. For clean cinder, allowable bearing pressures on the order of 3000 to 6000 psf are typical, depending on footing size, embedment, etc. For silty cinder deposits, bearing pressures would be less. The silt has the effect of decreasing the friction angle and such deposits are more likely to have soft alluvial pockets within the cinder. These factors reduce the allowable bearing pressures to about 2500 psf.

Settlement of foundations bearing on cinder deposits should be carefully evaluated. Although the cinder itself will compress relatively quickly in response to foundation loading--generally the compression will take place during construction--pockets of alluvium within the cinder and deposits below the cinder may be compressible and may cause substantial differential settlement of a structure after it is completed. In addition, locally loose zones sometimes occur in otherwise competent material and settlement in such zones can be significant.

In general practice, cinder layers are not utilized as bearing layers for piles. Where these deposits are extensive and thick enough, and relatively clean, they would be suitable for piles; however, their highly variable occurrence at depth discourages such use. For friction piles extending into the deep alluvial channels which contain cinder deposits, the cinder layers can be utilized at least partially for frictional resistance. A friction angle of 17 to 22 degrees is typical between clean sand and concrete (Naval Facilities Engineering Command, NAVFAC DM-7, 1971, Table 10-1). Alluvial silt within the cinder would tend to reduce this value somewhat.

RESIDUAL SOIL AND TUFF

There are no occurrences of residual soil or tuff delineated within the project area which appear to be large enough or continuous enough to be suitable for foundation bearing layers. Some small deposits of decomposed reworked tuff are found and reworked residual soil no doubt accounts for a significant fraction of the alluvial deposits found in the study area. In the reworked condition, however, these materials are more appropriately regarded as dense alluvium.

ALLUVIUM

Occurrence The distribution of alluvium over the project area is extremely variable and predictable only within the well defined alluvial channels. Outside of these channels, alluvial lenses are also common--occurring within cinder units, coral and coralline gravel units, and within lagoonal units. The thickness of these alluvial deposits ranges from one or two feet to tens of feet. The variability of alluvium is also due to the fact that the characteristics of the alluvium within a given alluvial deposit or series of deposits can vary widely in terms of composition, size distribution, and density. For example, a single alluvial channel may include alluvium in which the coarse fraction at one point is predominately dense, medium to coarse cinder sand, and a relatively short distance away, the coarse fraction may be dominated by loose to medium dense coralline gravel.

Engineering Characteristics In general, the alluvium falls into one of three categories: over-consolidated, normally consolidated, and under-consolidated. The alluvium which is over-consolidated is presumably the oldest. It probably reaches this state by having been either dessicated or cemented to some extent while it was above sea level during one of the periods of low sea stand. The characteristic of over-consolidated alluvium is that it is consolidated more than would be expected for the overburden weight under which it presently exists. Partially cemented alluvium such as decomposed reworked tuff would fall into this category. Normally consolidated alluvium is that which, upon consolidation testing, exhibits consolidation consistent with its existing overburden pressure. Under-consolidated alluvium such as the more recent, soft, low-energy alluvium that is found within some of the larger channels (for example, Kaiulani Channel) was probably deposited during the last advance of the sea. These materials appear to be less consolidated than would be expected for the existing over-burden pressure. The mechanism for under-consolidation is probably similar to that discussed for the lagoonal deposits (see below).

As is obvious from the forgoing discussion, the strength properties for alluvium can vary widely. Under-consolidated alluvium is not generally suitable for any type of foundation with the exception of light, flexible, one- and two-story structures. Normally consolidated alluvium, in the project area, is usually not regarded as appropriate foundation material because better bearing layers are avail-able. However, in the deep alluvial channels, some support for piling can be developed in layers of over-consolidated (or cemented) alluvium. These materials tend to develop both cohesive and frictional strength but variations in such materials make it inappropriate to cite typical values for strength parameters.

One characteristic that is an important property of alluvium is that, with the possible exception of highly over-consolidated or well cemented alluvium, this unit is compressible. This is significant both for foundations resting on alluvium or for foundations located on other units which overlie the alluvium. In such cases, it is important to perform consolidation testing to evaluate potential settlement.

A special problem in this area is differential settlement. In cases where part of a foundation overlies alluvium and part overlies a more competent unit such as coral, large differential settlements can occur where the foundation portion over the alluvium settles, while the portion of the foundation over the coral remains relatively stationary. This condition can produce structural distress and cracking within a building.

FILL

Fill materials range from well compacted, carefully controlled engineered fill to very soft hydraulically placed fill. In engineered fill, the material may be appropriate for foundation support; however, in general, fill placement is not controlled and any use of fill as a foundation soil requires very thorough exploration of the fill and careful evaluation.

LAGOONAL DEPOSITS

Occurrence Occasional pockets of lagoonal deposits occur within units of coralline debris. However, the most significant accumulation of lagoonal deposits occurs in a laterally consistent layer overlying virtually all units in the project area which occur at or below existing sea level. The low-energy (estuarine) alluvium found in some of the alluvial channels also has properties similar to these lagoonal deposits.

There is not any great areal variation within the lagoonal deposits. The only change generally found within the unit is a consistent tendency for these deposits to grade, with depth, to a larger fraction of coralline debris. Thus, they tend to be softer near the surface than near the bottom of the deposit.

Engineering Characteristics The lagoonal deposits are not suitable for any type of engineering use except for support of very light, flexible structures which can tolerate substantial settlements. These deposits are characterized by loose coral gravel and shells with a soft matrix of gray clay and very fine sand. It appears that the overburden pressure of this material at any point, that is the weight of the overlying material, is supported on the loose, almost honeycomb structure of the coralline debris that occurs within it, so that the fine grained matrix material is essentially unconsolidated "soup".

Although, it cannot provide foundation support, this material is highly compressible and is significant with regard to the problems it can cause. For example, it can substantially increase the load on a pile in excess of its design load. This condition can occur when, in the process of pile driving, the honeycomb structure of the coral gravel becomes disturbed and the material begins to consolidate under its own weight. The consolidation exerts a downdrag force on the pile which is additive to the structural load. This condition can also be induced by the consolidation of compressible soil in response to the loading caused by fill placement. If such additional loading by downdrag is not considered during foundation design, pile overloading may result--either in the form of exceeding the acceptable subsurface bearing capacity or by exceeding the pile structural capacity.

CORALLINE GRAVEL AND SAND (CORALLINE DEBRIS)

Occurrence The most common unit which occurs in the project area is coralline gravel and sand (coralline debris). This material represents the largely uncemented portion of a reef which comprises a large volume of most reefs. As such, the coralline debris generally occurs in relatively thick, wide-spread deposits. However, it commonly includes lenses of softer units such as alluvial lenses or lagoonal deposits. Furthermore, occasional cemented zones also occur within this unit--either cemented sand or cemented coralline debris (cemented sand and cemented coralline debris are grouped under one unit here because of their similar strength properties).

Engineering Characteristics Coralline debris and sand layers are generally not utilized in the project area for foundation design because of their wide variation in strengths and the availability of harder coral ledges or basalt units. However, there is little doubt that in practice many of the piles driven in the area are founded in coralline debris. Furthermore, this unit, where cemented, appears to be frequently mistaken for a coral ledge unit.

The strength properties of coralline debris are difficult to generalize. Where these materials are generally free of fines, strength is derived mainly from friction and the angle of internal friction may range from 20 to 30 degrees or more.

CORAL LEDGES

Occurrence The coral ledge units are the most significant, from a foundation engineering viewpoint, of any of the materials encountered in the project area. Most of the structures in this area are supported by one or another of the coral ledges.

Generally, the coral units occur in ledges with the upper surface of each ledge occurring at a reasonably predictable elevation. However, it should be noted that pockets of sand or coral rubble do occur within the coral ledges and may be significant from an engineering standpoint. As discussed in the preceding chapters, three fairly well defined coral ledges have been described in the project area at nominal elevations of +5 feet, -15 feet, and -30 feet. The surface elevations of the +5 ledge may range from 5 feet above to 10 feet below this level. The surface of the -15 and -30 ledges may occur as much as 15 feet below these nominal levels. However, these variations of the coral surface are gradual and the coral surface elevation at a given site is generally consistent across the site, except at ledge boundaries where coral elevations can be expected to vary abruptly. The vertical variation within each ledge is not as consistent as the upper surface elevation, however, and the thicknesses of the coral ledges can range from a few feet to tens of feet within a few hundred feet laterally. Therefore, it is important to define the thickness of a coral ledge by drilling before using it as a foundation bearing layer.

The thickness of a coral formation can be particularly important in the case of pile foundations where piles are being driven to bearing at the coral ledge. If a ledge is locally thin, albeit strong, and the designated pile blow count is too high, excessive hammering may cause a pile to break through a coral layer that, for properly determined blow counts, would provide an acceptable bearing layer. In other words, it is important to assign design pile driving criteria which will prove out the ledge for the proposed loading, but assigning an excessively high blow count may cause a pile to penetrate through, and break up an otherwise acceptable foundation layer.

<u>Engineering Characteristics</u> Coral ledges in the project area are utilized for foundation support for both shallow and deep foundations. The +5 coral ledge, where it occurs (see the geologic map (Plate II)), is commonly utilized to support spread foundations. Since there is considerable variation in cementation of the coral, depending on coral type (species), extent of infilling and degree of secondary cementation, the bearing pressures used are variable. Typical values for allowable bearing pressures on coral range from 6000 to 12000 pounds per square foot.

Such values are probably conservative; however, because shear strength parameters are very difficult to determine for coral. One of the factors that makes determination of the strength of coral ledges a problem is that coral is difficult to test satisfactorily. Usually the only portion of a core or sample for which a conventional shear

strength test can be expected to be accurate, is the strongest part of the coral. Conversely, the critical portions of the coral unit, that is the weaker portions, do not stay together in a core sample and tend to become disturbed by conventional drive sampling. Therefore, values obtained in testing frequently must be regarded as an upper limit of the strength range of the coral. Typical compressive strengths for the dense testable layers in the -30 coral in Waikiki have been found to range from about 50,000 to 150,000 pounds per square foot. Such strengths are found both in dense, growth-position coral and in well cemented, coralline debris and marl. Obviously, if the entire coral unit could be expected to possesses such strength, much high bearing pressures could be used; however, the weaker zones must be taken into account.
In any case, this unit serves as a relatively high strength bearing layer which generally permits economical foundation design wherever it is available.

An important aspect of coral ledges which must be kept in mind when utilizing them for bearing layers, either for shallow foundations or deep ones, is the possibility of solution cavities. Solution cavities up to tens of feet in height have been found in the +5 coral ledge. In general, such cavities occur in the vinicity of the existing groundwater surface, however, a few deeper cavities have been found in the project area.

Although the cavities which have been found are in the +5 ledge, it is not unlikely that such cavities also exist in the deeper -15 and -30 ledges since these levels have, in the past, been above the water table during lower sea stands. Due to this potential for solution cavities in the coral, sufficient subsurface exploration is necessary to provide enough subsurface information to determine if cavities exist. If cavities are encountered during drilling, steps can then be taken to protect foundations against catastrophic failure. Such failures have occurred in the vicinity of Quad A-2 (see Chapter III). This exploration is particularly critical for spread foundations in the near-surface coral where cavities have been previously encountered.

In the case of pile foundations, the pile driving operation to some extent offers a test of the strength of the coral as the pile is driven, such that if critical cavities were present below the pile tip, the pile would probably break through during driving. Such a "proof load" is not available for spread foundations. One method that is sometimes used to check for cavities beneath planned spread foundations is to probe each footing excavation to a depth of 10 or 15 feet with a jackhammer drill (or similar equipment) prior to footing construction. If cavities are found, they are grouted with a lean grout. The difficulty with the problem of solution in coral formations is that solution is an ongoing process and cavities can conceivably develop under a structure after construction. This is an unresolved problem and the potential time frame of such cavity formation in the project area is not known.

As stated above, pile foundations are commonly used for support of structures overlying the -15 and -30 coral ledges. Generally, the -30 ledge is more consistently suitable as a pile bearing layer than the -15 ledge. However, in either case, a percentage of the piles normally breaks through the planned bearing layer. In such cases, the pile must be either abandoned or driven a considerable distance to a deeper bearing layer. Generally, the percentage of piles which break through is relatively small, about 15 percent, but it can be higher. This is particularly true for sites where the initial subsurface drilling was not extensive enough to adequately define which layers were appropriate for pile bearing and what kind of loading a given layer can carry. In order to examine actual pile foundation characteristics in the project area, the test pile driving records for a few projects have been briefly analyzed to indicate the performance of piles on the -15 and -30 ledges. The pile performance is discussed below. The values referred to, in the following, are for 16½-inch octagonal piles.

-15 Ledge The test pile records of three sites overlying the -15 coral ledge were studied. In the northwest corner of Quad B-3, the -15 ledge was used to support 100 tons per pile. This is a relatively high value for this coral. For this case, the piles generally achieved sufficient resistance on the coral at elevations ranging from -15 to -22 feet with a few extending as deep as -31 feet. Twenty seven percent of the piles broke through the -15 ledge and took up at varying elevations ranging from -79 to -145 feet.

At a site in the east half of Quad B-4, south of the Ala Wai Canal, the -15 ledge was used to support 80 tons per pile. The final tip elevations of test piles ranged from -24 to -32 feet with most of the piles taking up in the interval from -24 to -29 feet. This site is located on the seaward side of the -15 ledge where the ledge elevation determined from borings was about -25 feet. Eleven percent of the test piles broke through the -15 ledge, taking up at elevations ranging from -35 to -54 feet.

At the east end of the project area, in Quad D-1, a site was studied which, based on the borings, appears to overlie the boundary between the -15 and -30 ledges, however, these ledges are very close in elevation to one another at this location. Low capacity 40 tons per pile loading was used here. All of the test piles driven achieved the assigned driving resistance in the -15 and/or

-30 ledges, at elevations ranging from -25 to -31 feet with most stopping in the interval from -25 to -27 feet.

-30 Ledge The records of test pile programs were examined for three sites which overlie the -30 ledge. The results for these sites indicate somewhat more consistent conditions than for the -15 ledge.

At one site on the boundary between Quads B-3 and C-3, 60 tons per pile was supported at elevations ranging from -34 to -50 feet. Most of these piles stopped in the interval between -36 and -45 feet. Twelve percent of the piles broke through this ledge and took up in the vicinity of -77 feet.

In Quad C-3, at a site on the east side of the quad, 75 tons per pile was supported at elevations from -33 to -48 feet. Most of these piles took up between -33 and -38 feet. Ten percent breakthrough of the -30 ledge occurred, with deeper support being achieved at about -90 feet.

In Quad C-2, just south of the Ala Wai Canal, a pile bearing capacity of 100 tons per pile was used. These piles generally took up at elevations ranging from -30 to -39 feet with the majority between -30 and -34 feet. Seventeen percent broke through, finally stopping at elevations ranging from -56 to the basalt surface at -101 feet.

Based on these sites, and a general observation of the reported performance of structures with various pile bearing values, it appears that pile capacities on the coral ledges up to about 100 tons are acceptable depending on the local conditions. In some cases, 100 tons may be too high. However, these coral ledges do not appear to be suitable for loads greater than 100 tons per pile.
For loads in excess of this value, consolidation of the uncemented material beneath and within the ledge evidently becomes significant. Thus for pile capacities in the neighborhood of 100 tons or more, excessive settlement may be experienced.

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