THE GEOLOGY OF FORD ISLAND, O‘AHU, HAWAI‘I

A THESIS SUBMITTED TO THE GRADUATE DIVISION OF THE
UNIVERSITY OF HAWAI‘I IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE (PLAN B)

IN

GEOLOGY AND GEOPHYSICS

MAY 2010

By
Elaine Lampitoc

Thesis Committee:

Scott Rowland, Chairperson
John Sinton
Henrieta Dulaiova

We certify that we have read this thesis and that, in our opinion, it is satisfactory in scope and quality as a thesis for the degree of Master of Science (Plan B) in Geology and Geophysics.

THESIS COMMITTEE

____

Chairperson

____

____

Abstract

Ford Island is located in the middle of Pearl Harbor and as with the island of Oʻahu, the coastal geology was affected not only from the changes in sea level but with the uplift of the island. Ford Island's geology was also affected by the addition of ocean dredge material to the north and southeastern sides of the island.

Various publications were reviewed to compile the best available geologic information required for constrained input parameters of a hydrological model. These publications indicate that Ford Island's geology consists of, from oldest to youngest (1) basalt (the main Koʻolau volcano, at a depth of approximately 134 m below present sea level), (2) approximately 131 m of coralline limestone (interbedded with volcanic ash, lagoonal deposits, and alluvium), and (3) approximately 3 m of fill material (topsoil from when the island was planted in sugarcane as well as material dredged from Pearl Harbor in order to enlarge the island). The first and third units are well studied and understood but it is the second unit, the coralline limestone with its interbedded lagoonal deposits, volcanic ash, and alluvium that makes the island's geology complex from the perspective of hydrological studies. The publications provide information based on which we were able to describe the shallow subsurface of Ford Island better, and an interpretation of Ford Island's geologic history is also presented in this paper. However, deeper borings are necessary to confirm the subsurface geology at Ford Island.

1. Introduction

This thesis is a compilation of geologic information published about Ford Island from 1903 up to the most recent in 2009. Together, these papers reflect not only the evolution in our understanding of geologic processes on Oʻahu and in Hawaiʻi, but also changes that Ford Island itself has undergone. The original motivation for this work was to provide the best available geologic information about the island to constrain the input parameters of a hydrological model.

Ford Island lies in the middle of Pearl Harbor on Oʻahu, Hawaiʻi (Figure 1). It is named after Dr. Seth Porter Ford, a Honolulu physician who obtained the island in 1866 after his arrival in the Hawaiian Islands in 1851. Its traditional name is Mokuʻumeʻume, meaning "Island-of-attraction" because of a Hawaiian ceremony that was held there; however it was also known as an island of strife because it was a center of contention over certain fishing rights among former chiefs. Figure 2 presents a historical depiction of Ford Island, which was labeled Moku‘ume‘ume and was approximately 1.4 km^2 (Sterling and Summers, 1978; Department of the Navy, 2003). Other known names were Marin’s island because Don Francisco de Paula Y Marin first owned it in 1810. Marin also raised sheep, goats, and rabbits on the island where they flourished causing the island to also be known as Rabbit Island or Little Goat Island (Dorrance, 1991; Golob, 1996). An aerial photo of Ford Island is shown in Figure 3.

There are different accounts of who owned the island after Dr. Ford. Dorrance (1991) stated that his son, Seth Porter Ford Jr., took possession of the island in 1885 and that in 1891 he sold the island to the John ‘I‘i estate. In 1899, O‘ahu Sugar Company leased Ford Island from the ‘I‘i estate and developed it into a sugar cane plantation (Dorrance, 1991). Another account (Golob, 1996) is that in 1891, the Honolulu Plantation purchased the island and leased it to the O‘ahu Sugar Company from 1906 to 1917. From 1899 to 1917, approximately 1.3 of the 1.4 km^2 were plowed and cultivated in sugarcane (Department of the Navy, 2003).

A survey of the island of O‘ahu was done in 1873 for defense possibilities by the U.S. Army’s Major General John M. Schofield and Lieutenant Colonel Burton S. Alexander (Department of the Navy, 1945). Their report recommended that Pearl Harbor be ceded to the United States, together with a buffer of 6 to 8 km back from the shoreline, and that it be deeded free of cost to the United States in return for allowing Hawaiian sugar to enter the U.S. mainland duty-free. Schofield and Alexander stated that Ford Island would be excellent to accommodate a depot of naval stores and equipment (Horvat, 1966).

On January 30, 1875, the Reciprocity Treaty was signed and it went into effect in 1876. The treaty gave free access to the United States market for sugar and other products. On October 20, 1887, King Kalākaua ratified an amendment to the Reciprocity Treaty granting the United States “exclusive rights to enter the harbor of Pearl River…and to establish…a coaling and repair station for the use of vessels of the United States, and to that end the United States may improve the entrance to said harbor and to all other things needful to the purpose aforesaid.” (Department of the Navy, 1945; Van Dyke, 2008).

In preparation for World War I, the Navy selected Ford Island as a site for land-based guns to defend the harbor. In 1916, the War Department acquired two small parcels of land from the ‘I‘i Estate. The parcels were used as casements for two batteries of six-inch rifled guns and were located on the southwest and northeast corners of the island (Dorrance, 1991). In 1917, Captain John Curry arrived in Hawai‘i to command the 6th Aero Squadron and after looking for suitable facilities on O‘ahu, he recommended that the 6th Aero Squadron be situated at Ford Island. Captain Curry drew up plans for a base to be built on Ford Island and began to make arrangements to purchase the island from the ‘I‘i estate (Curry, 1924). In 1917, the United States purchased the island for a sum of $236,000 (Yates, 1936; Golob, 1996).

The O‘ahu Sugar Company surrendered its leasehold to Ford Island in late 1917 to complete the sale and the island was used by both the Army and the Navy (Dorrance, 1991). During the 1930s, dredge and fill operations extended Ford Island’s surface from 1.4 km^2 to 1.8 km^2 as shown on Figure 4 (Cohen, 1981; Department of the Navy, 2003). However, by 1935, the island became too crowded for joint Army and Navy operations so the Army and Navy made a deal. The Army would give Ford Island as well as North Island (in San Diego) to the Navy, in exchange for a Naval field in Sunnyvale, California (Dorrance, 1991). In 1936, the Army transferred its air force to Hickam field, leaving the Navy in control of Ford Island (Golob, 1996). On December 7, 1941, the Japanese attacked Pearl Harbor destroying not only the ships that were anchored near the island but also many of the aircraft on Ford Island itself (Dorrance, 1991). In 1962, the Navy officially decommissioned the air station at Ford Island (Golob, 1996). In 1996 the island was connected to shore via a causeway. Today, Ford Island is occupied by Navy Officers’ housing as well as the U.S.S. Oklahoma and Utah Memorials, the U.S.S. Missouri Museum, and the Pacific Aviation Museum.

Ford Island (Figure 1) is located in the central portion of Pearl Harbor, Hawai‘i at approximately 21°21′ north latitude and 157° 57′ west longitude. Pearl Harbor consists of three main lochs: (1) West Loch, (2) Middle Loch, and (3) East Loch. Ford Island today is roughly 2 km long in a NE-SW direction by 600-850 m wide in a NW-SE direction, and has an area of 1.8 km^2. The elevation ranges from sea level to ~8.5 m above sea level on the NE coast. Most of Ford Island is relatively flat and lies less than 6 m above sea level.

The median rainfall for the region is approximately 0.050-0.076 m/year. Occasional heavy precipitation during the times of southerly wind (Kona storms) may cause heavy flooding on Ford Island because much of the soil is impermeable, and the island is essentially flat. The wet season spans between November and April. Winter and early spring temperatures range from highs of 24 to 26° C in the daytime to lows of between 10 to 15° C in the nighttime. Daytime high temperatures of 31 to 32° C are common during the summer afternoons. During this season, low temperatures range from 22 to 24° C (Earth Tech, 2003).

2. Summary of Previous Studies

In general Ford Island's geology has been described as a mostly-drowned, flat ridge between two drowned river valleys. These valleys were cut into a sequence of sediments and coralline limestone that developed on the flank of the Koʻolau volcano as it eroded and subsided. How our understanding of both Ford Island's geology and southeast Oʻahu's geology as a whole has developed to its present state is the topic of the following portion of this paper. This will be achieved via brief summaries of significant previous works dealing with the geology of southeast Oʻahu, followed by a summary and characterization of the whole story. Measurements were most commonly reported in Imperial units in these reports; however, for the purpose of this paper, they have been converted to SI units.

In many of the reports, Ford Island's geology, if it is mentioned specifically at all, occurs within discussions of the coastal plain. Bates and Jackson (1984) define the coastal plain as a low, broad plain that has its margin on an oceanic shore and its strata either horizontal or very gently sloping toward the water, and that generally represents a strip of recently prograded or emerged sea floor. The following sections describe the coastal plain, specifically on Oʻahu's south side.

2.1 Branner (1903)

The first publication I will discuss is *Notes on the Geology of the Hawaiian Islands* by J. C. Branner, published in the American Journal of Science in October 1903. J. C. Branner was a geologist at Stanford University in California. It is Branner's description of Pearl Harbor's origin and geology that provides information related to the geology and formation of Ford Island as it was understood in the early 20th century.

Branner (1903) stated that the “harbor has been formed by the depression beneath the sea of a small group of dendritic valleys previously carved by subaerial erosion on horizontal beds of rocks.” He also explained that the various rocks at Pearl Harbor consist of alternate beds of volcanic tuff and coral rocks; and that the coral rocks are not necessarily all coral but include mixtures of shells and other fragmental calcareous materials. In order to better understand the geology of Pearl Harbor, Branner imagined the island of O‘ahu elevated by 15 to 22 m, with the original rock beds restored across the channels and the streams flowing across the land. He indicated that “In the course of time these streams would all cut steep-sided gorges, and where the gorges, by bends of streams, approached each other the watershed between the two streams would be lowered below the general land surface. Such a place would eventually be an isolated bit of high land and after depression would form an island, such as we have in Mokuumeume”. Branner (1903) also stated that “A depression of the island would back the sea into the valleys”, which are now the three lochs (West Loch, Middle Loch, and East Loch). Figure 5 is an excerpt of a figure that was presented in Branner (1903); Ford Island is labeled “Mokuumeume” and the shoreline looks different than it does today.

2.2 Martin and Pierce (1913)

The next publication I will discuss is *Water Resources of Hawaii*, a report that was prepared by the United States Geological Survey (USGS) in cooperation with the Territory of Hawai‘i. The USGS and the Territory of Hawai‘i entered into a cooperative agreement in 1910 as a result of several bills that Congress passed in 1895 to gauge streams, determine the water supply of the United States, and prepare reports to best utilize the water resources. The report was written by W. F. Martin and C. H. Pierce, engineers for the USGS, and presents the results of measurements taken from 1909 to 1911 to study the flow of certain streams and ditches in the Territory of Hawai‘i.

Five islands were discussed in the report: Kaua‘i, O‘ahu, Moloka‘i, Maui, and Hawai‘i. For each island, Martin and Pierce (1913) provided a description of its general location and geological history. Their description of O‘ahu’s geologic history is pertinent to my study area because of its discussion on the coastal plain (along the southern margin of O‘ahu). The coastal plain of O‘ahu consists of limestone; and calcareous and non-calcareous sediments. They described this coastal plain as mainly consisting of uplifted coral, especially on the south side. They stated that the distribution of coral below and above sea level was one of the principal evidences of long periods of subsidence followed by later upheaval; and the fact that well borings show hard coral being encountered at 244 m below sea level lead to the conclusion that the islands had been depressed by 200 to 250 m (Martin and Pierce, 1913).

Martin and Pierce (1913) were able to obtain the Geological Survey records of wells from the Honolulu Plantation Company, Oʻahu Sugar Company, Ewa Plantation Company, and Waialua Agricultural Company which they used to analyze the underground water pumped for irrigation. However, there were no geologic logs for wells located on Ford Island in the report. Of the well logs presented in the report, the nearest well to Pearl Harbor and Ford Island belonged to the Honolulu Plantation Company in ʻAiea and its geologic log is presented in Table 1. The report did not provide any figures showing the actual well locations so the distance from Ford Island could not be determined from this report; however, additional information on this well is presented in another report which will be discussed in further detail.

Table 1: Geologic Log of Honolulu Plantation Well No. 5 in Field No. 16, at New Puuloa Camp, ʻAiea (Martin and Pierce, 1913)

Depth (meters below ground surface)	Description
0 – 74.7	Coral
74.7 – 88.4	Brown clay
88.4 – 97.5	Coral
97.5 – 100.6	Clay
100.6 – 111.3	Coral
111.3 – 117.3	Clay
117.3 – 134.1	Coral
134.1 – 150.9	Clay
150.9 – 156.9	Coral
156-9 – 167.6	Clay
167.6 – 187.5	White clay
187.5 – 211.8	Clay
211.8 – 214.9	Gray rock
214.9 – 222.5	Blue clay
222.5 – 230.7	Brown lava
230.7 – 233.8	Clay
233.8 – 242.9	Red lava
242.9 – 243.8	Hard blue lava

2.3 Davis (1915)

In September 1915, *A Shaler Memorial Study of Coral Reefs* by W. M. Davis was published in the American Journal of Science. W. M. Davis was a professor at Harvard University from 1878 to 1912, and after his retirement, he lectured at universities and continued researching and writing, mainly focusing on coral reefs. With a liberal grant from the Shaler Memorial Fund of Harvard University and a subsidy from the British Association for the Advancement of Science, Davis (1915) was written. The purpose of the study was to test the various theories for the formation of coral reefs. Figure 6 presents a diagram showing the successive stages in the development of an uplifted reef enclosed by a barrier reef. The diagram is useful because Martin and Pierce (1913) described the coastal plain (which Ford Island is a part) of O‘ahu as uplifted coral. Figure 6 actually can be used to describe the different events that occurred on O‘ahu. In stage one, there is a young volcano such as the Ko‘olau volcano. Stage two shows erosion of the volcano occurring and in stage three, the island is subsiding and a coral reef is forming. Stage four shows continued subsidence and in stage five, the coral is uplifted. Limestone erosion occurs in stage six and stage seven shows the barrier reef forming on the eroded limestone.

This article was also useful for my study because it dedicated a section to the elevated reef of O‘ahu, the top of which is at an altitude of 6 to 7 m, and which is broadest along the western part of the southern coast, where Ford Island and Pearl Harbor are located. Davis (1915) stated that "…the record of "coral" in borings at a depth much greater than that at which corals can grow has been taken to prove that the reef grew upwards as the island sank…" However, the term "coral" in well logs was often used to describe any limestone fragments that had been brought to the surface and may not be an accurate description (Davis 1915). This information is helpful in interpreting well logs because caution is to be used wherever "coral" is mentioned and additional careful comparison with nearby borings and/or wells is necessary. The article concurred with Branner (1903) that the lochs of Pearl Harbor were drowned valleys.

2.4 Pollock (1929)

In 1928, J. B. Pollock, a professor at the University of Michigan at Ann Arbor, wrote a paper on his observations of Pearl Harbor during a visit from 1922 to 1924. This paper, *The Origin of Pearl Harbor, Island of Oahu*, was published in 1929 by the Michigan Academy of Science, Arts, and Letters. From 1922 to 1924, Pollock conducted an intensive study of coral reefs, both fossil and living. Based on his observations, Pollock disagreed with the previous studies by Branner (1903) and Davis (1915) that Pearl Harbor was a result of dendritic valleys formed by subaerial erosion and later drowned by island subsidence. Instead, Pollock (1929) concluded that based on the original shape of the harbor (Figure 7), the land forms in Pearl Harbor were actually marine deposits shaped by tidal currents and wave erosion and former sea levels. Basically, Pollock (1929) indicated that (1) the 150 m contour line represented the original shape of Pearl Harbor and (2) the current shape of Pearl Harbor is not due to drowned valleys but is a result of how the reefs grew and were effected by waves, tides, and former sea levels.

Pollock (1929) also dedicated a section of the paper describing Ford Island's geology as consisting of (from oldest to youngest):

Calcium carbonate: A product of living plant and animal organisms. The calcium carbonate is thin strata of calcareous rock sloping gently downward toward the shore. The calcareous rock is composed of sand, coral fragments, some shells, and other kinds of animal remains. Pollock (1929) described the coral on the shore cliffs which appeared in position as if in place where it grew and others were wave-washed fragments.

Volcanic tuff: Strata of volcanic tuff comprise the low cliffs on the southeast side of Ford Island. The tuff at Ford Island is of the same origin of the tuff on the eastern shore of Pearl Harbor which was "formed mainly of the tuff thrown out by explosive eruptions from the Salt Lake Crater" and carried to the region by the strong trade winds which blow from northeast to southwest. The tuff varies in thickness, ranging from 0.05 m to more than 0.15 m.

Clay-like earth: Varies in color from a distinct red to a very dark color. Pollock stated that the materials composing the clay-like earth were derived from two possibilities: (1) the decay of tuff layers which originated from the Salt Lake craters and/or (2) since the clay-like earth are submarine deposits, the material "may have originated in silt brought down by erosion of the mainland by tropical storms."

2.5 Stearns and Vaksvik (1935; 1938)

The next two reports I will discuss were written by H. T. Stearns and K. N. Vaksvik, a geologist and artesian-well engineer, respectively, for the USGS, who prepared the reports for the office of the Commissioner of Public Lands' Division of Hydrography, Territory of Hawai‘i.

These two reports are:

- *Geology and Ground-Water Resources of the Island of Oahu, Hawaii* (1935)
- *Records of the Drilled Wells on the Island of Oahu, Hawaii* (1938)

Stearns and Vaksvik (1935) was prepared in cooperation with the USGS to investigate and report on the water resources of Hawai‘i. In 1928, the Territorial Legislature appropriated funds for the collection of artesian-well data and a geologic investigation of the island of O‘ahu. The purpose of the report was to interpret the data collected on the artesian wells of O‘ahu and describe the geologic conditions that determine the occurrence of high-level ground water. At the time the report was written, the need for water at high levels was increasing because irrigated areas were expanding and land development was growing. In addition to the data interpretation of artesian wells, Stearns and Vaksvik (1935) also described the coastal plain and the formation of the caprock in better detail. These descriptions are important in understanding the geology of Ford Island.

According to Stearns and Vaksvik (1935), the coastal plain reaches a maximum width of nearly 10 km at Pearl Harbor and consists primarily of reef limestone and non-calcareous marine sediments. Figure 8 presents a cross section of the Ko‘olaus and shows the coastal plain on the south side of O‘ahu. Based on well logs, the coastal plain sediments reach a thickness of at least 365 m, part of which is above sea level. However, when studied closely, the coastal plain shows several terrace levels and unconformities indicating that it is a product of several sea level changes rather than a single emergence. The terrace levels are evidence of the emergence and submergence of the shore lines through time, the shore lines were named and are presented in Table 2.

Table 2: Shore Lines of O‘ahu (Stearns and Vaksvik, 1935)

Shore Line Name	Meters above or below present sea level
Olowalu	+ 76.2
Kahuku	+ 16.8
Kahipa	- 91.4
Ka‘ena	+ 28.9
Lā‘ie	+ 21.3

Shore Line Name	Meters above or below present sea level
Wai‘alae	+ 12.2
Waipi‘o	- 18.2
Waimānalo	+ 7.6

Stearns and Vaksvik (1935) discuss the origin of Pearl Harbor based on studies by Branner (1903), Davis (1915), and Pollock (1929); and summarize its geologic history with the following sequence (shown on Figure 9):

1. Deposition of calcareous and non-calcareous sediments in the high sea levels preceding the Waipio stand approximately 350,000 years ago.
2. Recession of the sea to the Waipio stand, about 18 m below present sea level.
3. Cutting of wide valleys by streams in the approximate position of the present lochs and formation of soil on interstream areas.
4. Deposition of tuff by eruptions at Salt Lake craters.
5. Erosion of tuff and continued removal of interstream divides.
6. Submergence by the +7.6 m Waimanalo sea and drowning of valleys to form the ancestral Pearl Harbor Lochs.
7. Growth of irregular reef patches on former stream divides and deposition of non-calcareous sediments near shore.
8. Recession of ocean to present level, causing the exposure of irregular patches of reef where former divides existed.
9. Widening of lochs by wave action, especially near their heads, where soft silts occurred instead of hard limestone, and formation of deltas at the mouth of each valley.

It was during the first of these events, the deposition of the sediments, that the caprock began to form. During later times, the caprock would have been stripped and restored as erosion and re-deposition occurred. Stearns & Vaksvik (1935) considered Ford Island to be part of the caprock. They described Ford Island specifically as consisting essentially of consolidated calcareous marine sediments lying below tuff from Salt Lake.

Stearns and Vaksvik (1938), *Records of the Drilled Wells on the Island of Oahu, Hawaii*, is significant because it includes a description of all of the wells on O‘ahu as of March 1938, as well as all available well logs. It is in this publication that a location was provided for the Honolulu Plantation well in ‘Aiea previously described by Martin and Pierce (1913); the well was approximately 3.5 kilometers from the center of Ford Island (Figure 10). Six wells are listed for Ford Island: 219, 220, 221, 222, 223, and 224; and they are shown on Figure 10 and presented in Table 3. Wells 219 and 220 were once known as Pumping Station 11 which was used by the Oahu Sugar Company. Unfortunately, no well log data for the Ford Island wells were presented in the 1938 publication; and at the time of the report, all six wells were not in use. The geologic logs nearest to Ford Island were that of Well 170 at the Navy Yard and Well 218-1 on Pearl City Peninsula (shown on Figure 10). Their logs are presented in Table 4 and Table 5, respectively.

Table 3: Ford Island Wells (Stearns and Vaksvik, 1938)

Well ID	Location and Owner	Diameter (meters)	Altitude (meters)
219	Near northern end; U.S. Navy	0.3	6.4
220	About 45 meters south of well 219; U.S. Navy	0.3	6.4
221	About 122 meters southwest of well 220; U.S. Army	0.3	5.5
222	About 61 meters south of well 221; U.S. Army	0.3	5.5
223	Under wind direction indicator on flying field; U.S. Army	0.3	6.1
224	Near the army fire station at Luke Field; U.S. Army	0.2	3.6

Table 4: Geologic Log of Well 170 (Stearns and Vaksvik, 1935)

Depth (meters below ground surface)	Description
0 – 30.48	Coral slab
30.48 – 39.62	Clay material
39.62 – 45.72	Coral reef
45.72 – 76.20	Sticky clay
76.20 – 94.49	Sandy clay
94.49 – 118.87	Sticky clay
118.87 – 143.87	Sandy clay
143.87 – 165.20	Sticky clay
165.20 – 171.60	Coral
171.60 – 177.09	Clay
177.09 – 193.55	Hard rock
193.55 – 195.07	Water rock

Table 5: Geologic Log of Well 218-1 (Stearns and Vaksvik, 1935)

Depth (meters below ground surface)	Description
0 – 7.3	Adobe, soil, small coral, sand, shell gravel, etc.
7.3 – 9.1	Fine sand mixed with clayey mud
9.1 – 10.4	Clay, sand, and gravel
10.4 – 13.4	Clay with grit and some sand
13.4 – 14.3	Fine sand and some mud
14.3 – 18.6	Clay and grit
18.6 – 25.6	Very compact sand and clay
25.6 – 26.2	Hard cemented gravel and sand
26.2 – 30.8	Cemented sand
30.8 – 45.1	Sand with clayey mud, some thick, hard cemented streaks
45.1 – 45.4	Gravel and cemented gravel
45.4 – 45.7	Hard cemented gravel

2.6 Stearns (1939)

Stearns (1939) is *Geologic Map and Guide of the Island of Oahu, Hawaii*. Stearns (1939) provided a geologic map that shows three main geologic units on Ford Island (Figure 10) which are (from oldest to youngest):

Consolidated calcareous marine sediments (Pls): These consist primarily of emerged coral reefs with finely laminated lagoon limestone, lithified beach deposits, and consolidated beach deposits that may have formed at the present stand of sea level. This unit is extremely permeable because of primary and secondary cavities, and yields brackish water.

Honolulu volcanic series (Qht): This unit consists primarily of basic vitric-crystal-lithic tuff, with a matrix of palagonite and glass. The beds of tuff are consolidated; gray, lavender, and brown; bedded; slightly permeable; and contain angular fragments of Koolau and post-Koolau basalt, limestone, and other accidental lithics. The tuffs commonly are cemented by calcite.

Artificial fill composed of marine deposits (Rf): This unit consists of permeable marine mud with shells, coral, and other calcareous marine organisms dredged from the ocean floor of Pearl Harbor. The unit is brown to white in color.

As shown on Figure 10, the surrounding areas of Pearl Harbor also encounter the same geologic units as well as consolidated or non-consolidated non-calcareous sediments and the Koʻolau basalt.

2.7 Palmer (1946)

In 1946, *The Geology of the Honolulu Ground Water Supply* by H. S. Palmer was published. This report provided a non-technical description of the geologic nature and hydraulic working of the main ground water system of the Honolulu area. It is a revision of a previous report, *The Geology of the Honolulu Artesian System* published in 1927. The 1946 publication was prepared under a cooperative agreement between the University of Hawai‘i and the Board of Water Supply, City and County of Honolulu.

In this report, Palmer describes the coastal plain and caprock, shown on Figure 11. According to Palmer (1946), the coastal plain is underlain by the caprock; and the caprock consists of sediments (volcanic ash, volcanic tuff, coral sand, coral gravel, and clay). Because Ford Island is located within the caprock and coastal plain, this report essentially describes the materials that compose Ford Island as well, and agrees with the findings of previous reports.

2.8 Wentworth (1951)

Geology and Ground-water Resources of the Honolulu-Pearl Harbor Area, Oahu, Hawaii, was prepared for the Board of Water Supply, City and County of Honolulu to further investigate the rock structures and ground-water conditions in the Honolulu and Pearl Harbor watersheds. It was written by C. K. Wentworth, a geologist who had made various geologic studies both in Hawai‘i and on the continental United States, in 1951. This report re-iterates the geology of the Honolulu-Pearl Harbor area discussed in the previous studies.

2.9 Visher and Mink (1964)

The next report I will discuss is *Ground-Water Resources in Southern Oahu, Hawaii* by F. N. Visher and J. F. Mink written in 1964. The report is part of a series of comprehensive investigations by the USGS in a cooperative program with the Hawai‘i Division of Hydrography, Department of Public Lands, Hawai‘i Economic Planning and Coordination Authority, and the City and County of Honolulu. Today, the Department of Public Lands is composed of two state departments, the State of Hawai‘i Department of Water and Land Development and the Department of Land and Natural Resources. The purpose of the study was to investigate the basal groundwater supply in southern O‘ahu; determine the geologic and hydrologic conditions that control its quality and availability; and to obtain information on the amount of water that can be developed in the area.

Visher and Mink (1964) stated that the coastal plain of O‘ahu was built after the cessation of major volcanic activity; is underlain by terrestrial and marine sedimentary deposits and by lava flows and pyroclastic deposits of late volcanic activity. The term late volcanic activity in now referred to as rejuvenation-stage activity. The sediments that constitute the bulk of the coastal plain form a relatively impermeable wedge (i.e., the caprock) over highly permeable lavas. Geologically, Ford Island is part of the coastal plain.

2.10 Stearns and Chamberlain (1967)

In October 1964, H. T. Stearns and T. K. Chamberlain obtained a grant from the National Science Foundation to drill a series of deep holes on the edge of the Ewa Coastal Plain, O‘ahu, Hawai‘i (Figure 12) in order to obtain what they hoped would be complete sections of the upper crust. In 1967, Stearns and Chamberlain published the following article in Pacific Science, *Deep Cores of Oahu, Hawaii and Their Bearing on the Geologic History of the Central Pacific Basin,* which documented their results. The Ewa Coastal Plain was selected because it is the widest coastal plain in the Central Pacific Basin.

This paper also provided additional information about the geology of Ford Island because Ford Island is part of the Ewa Coastal Plain. Two holes were drilled (Ewa 1 and Ewa 2) as part of this study and their borelogs are presented in Table 6 and Table 7. The borelogs from Ewa 1 and Ewa 2 were used to reinterpret well logs for nearby wells which had been previously reviewed in Stearns and Vaksvik (1938).

Ewa 1 was drilled as far seaward as possible, opposite of Ewa Beach Park, on the western side of Pearl Harbor’s navigation channel. Basalt bedrock was encountered beneath 327 m of interbedded coral reefs, lagoonal muds, sands, and soils. The terrace at Ewa 1 is flat, low emerged coral reef partially covered with a thin discontinuous soil layer at approximately 2 m above mean sea level.

Table 6: Geologic Log of Ewa 1 (Stearns and Chamberlain, 1967)

Depth (meters below ground surface)	Description
0 – 0.61	Loose coral and sand
0.61 – 12.74	Reef limestone
12.74 – 13.35	Tuff (?)
13.35 – 50.29	Reef limestone
50.29 – 50.60	Brown mud with fragments of coral
50.60 – 50.90	Brown compact mud
50.90 – 61.87	Reef limestone
61.87 – 63.70	Beach rock

Depth (meters below ground surface)	Description
63.70 – 76.20	Brown mud
76.20 – 82.30	Reef limestone
82.30 – 86.26	Brown mud
86.26– 88.39	Altered reef limestone
88.39 – 94.79	Reef limestone
94.79 – 95.71	Muddy limestone
95.71 – 96.01	Brown mud
96.01 – 100.89	Reef limestone
100.89 – 101.50	Gravel (?)
101.50 – 102.72	Reef limestone
102.72 – 106.07	Reef limestone
106.07 – 106.68	Reef limestone
106.68 – 108.20	Reef limestone
108.20 – 109.12	Limey mud breccia
109.12 – 110.64	Brown mud
110.64 – 110.95	Gray sand
110.95 – 113.08	Calcareous mud
113.08 – 114.60	Reef limestone
114.60 – 116.74	Calcareous mud
116.74 – 120.09	Reef limestone
120.09 – 122.22	Mud and coral fragments
122.22 – 125.58	Brown mud
125.58 – 126.49	Reef limestone
126.49 – 132.59	White limy mud
132.59 – 135.33	Reef limestone
135.33 – 138.07	Brown mud and limestone fragments
138.07 – 141.43	Gray mud
141.43 – 141.58	Organic mud
141.58 – 143.87	Gray mud
143.87 – 150.27	White mud
150.27 – 151.49	Reef breccia (?)
151.49 – 174.35	Reef limestone
174.35 – 175.26	Brown mud and lime
175.26 – 178.31	White mud and lime
178.31 – 179.83	Reef limestone
179.83 – 181.97	White limy mud
181.97 – 185.62	Greenish mud
185.62 – 188.06	White mud
188.06 – 191.72	Green and black mud
191.72 – 192.33	Lignite
192.33 – 193.55	Gray-green mud
193.55 – 196.90	Gray mud
196.90 – 201.17	Dark gray mud
201.17 – 203.61	Green and black mud
203.61 – 205.98	Black sand
205.98 – 206.20	Fine sand
206.20 – 209.09	Gray mud

Depth (meters below ground surface)	Description
209.09 – 215.19	Tan mud
215.19 – 221.59	White mud
221.59 – 221.71	Brown mud
221.71 – 221.89	Gray mud
221.89 – 224.18	Reef limestone
224.18 – 232.87	White mud and limestone nodules
232.87 – 241.40	Reef limestone
241.40 – 247.19	Gray mud
247.19 – 248.72	Reef limestone
248.72 – 259.38	Gray mud
259.38 – 261.52	Olive black mud
261.52 – 283.77	Gray and black mud
283.77 – 287.12	Olive black mud
287.12 – 288.95	Gray mud
288.95 – 289.56	Basaltic sand
289.56 – 294.44	Gray mud
294.44 – 298.40	Brown mud
298.40 – 298.86	Brown sand
298.86 – 299.16	Brown clay
299.16 – 299.92	Brown sand and gravel
299.92 – 302.06	Brown mud
302.06 – 309.37	Gray mud
309.37 – 317.91	Tan and gray mud
317.91 – 321.26	Brown sand
321.26 – 323.55	Conglomerate
323.55 – 326.75	Brown clay
326.75 – 328.42	Weathered basalt
328.42 – 331.71	Basalt
331.71 – 331.93	Basaltic clinker
331.93 – 334.37	Basaltic clinker
334.37 – 337.41	Pahoehoe

A few hundred meters south of the West Loch shoreline is the location of Ewa 2 which is shallower than Ewa 1. Ewa 2 was drilled to half the depth than Ewa 1, and approximately 158 m of sedimentary rocks, similar to Ewa 1 (interbedded coral reefs, lagoonal muds, sands, and soils), were penetrated before reaching the basement basalts. The ground level at Ewa 2 is approximately 6 m above mean sea level. As shown in Figure 12, all of the borings encounter basalt and at Ewa 1, Well 272, and Ewa 2, reef limestone, calcareous sediments and non-calcareous sediments were all encountered above the basalt. Ewa 2 and Well 271 are actually located in approximately the same position in the coastal plain as Ford Island which is not shown in the figure but would be where the "RB" in "HARBOR" is on the figure. At Ewa 2 and Well 271, basalt was encountered at approximately 160 m and 100 m, respectively; and since Ford Island is located approximately in the same position within the coastal plain, it could be assumed that basalt would be encountered within this range.

Table 7: Geologic Log of Ewa 2 (Stearns and Chamberlain, 1967)

Depth (meters below ground surface)	Description
0 – 3.05	Artificial fill
3.05 – 5.73	Calcareous soil
5.73 – 11.13	Brown sandy soil
11.13 – 14.02	Gray marl
14.02 – 31.09	Reef limestone
31.09 – 35.97	Reef detritus
35.97 – 36.58	Brown sand
36.58 – 37.19	Coarse calcareous sand and gravel
37.19 – 39.32	Brown mud
39.32 – 42.98	Indurated limy mud
42.98 – 49.07	Brown mud
49.07 – 49.38	Brown silt and sand
49.38 – 49.68	Brown mud
49.68 – 50.29	White mud
50.29 – 55.47	Reef limestone
55.47 – 56.08	Limestone fragments in brown mud
56.08 – 56.14	Black organic mud
56.14 – 58.52	Brown mud
58.52 – 59.13	Fine sand
59.13 – 60.66	Brown mud
60.66 – 62.18	Muddy fine sand
62.18 – 63.40	Gravel and sand
63.40 – 72.85	Brown mud
72.85 – 73.46	Gravel and sand
73.46 – 80.01	Brown mud
80.01 – 80.16	Sand and gravel
80.16 – 81.69	Brown mud
81.69 – 82.60	Coarse sand
82.60 – 83.52	Brown mud
83.52 – 87.17	Brown and white mud
87.17 – 87.78	Brown mud
87.78 – 88.39	Fine sand
88.39 – 89.61	Brown mud
89.61 – 90.53	Fine sand
90.53 – 91.44	Brown mud
91.44 – 91.74	Brown sand
91.74 – 93.57	Brown mud
93.57 – 94.49	Fine sand
94.49 – 99.36	Brown mud
99.36 – 100.58	Brown sand
100.58 – 103.33	Brown mud
103.33 – 104.85	Brown sand

Depth (meters below ground surface)	Description
104.85 – 116.13	Brown silt and mud
116.13 – 121.92	White and gray marl
121.92 – 126.49	Brown limestone
126.49 – 127.41	Brown marl and limestone
127.41 – 128.02	Brown and gray marl
128.02 – 129.54	Gray limestone
129.54 – 130.45	Gray brown marl
130.45 – 133.50	Brown mud (soil)
133.50 – 136.25	Gray marl
136.25 – 140.82	Brown mud (soil)
140.82 – 148.13	Brown muddy sand
148.13 – 152.10	Brown gray marl
152.10 – 153.62	Brown silty mud
153.62 – 157.58	Red basaltic, residual soil
157.58 – 163.07	A‘a basalt
163.07 – 165.20	A‘a clinker (soil)

The geologic history of the Ewa Coastal Plain was summarized by Stearns and Chamberlain (1967) with the following sequence:

1. Prolonged weathering and erosion of Ko‘olau basalts result in the formation of thick soil deposits, deep incision of stream valleys, and deposition of stream cobbles, pebbles, and basaltic sand along the coast.
2. Gradual submergence and accumulation of thick deposits of shallow marine lagoonal sediments (typical lagoonal-deltaic sedimentary facies) creates swampy conditions.
3. Submergence continues, the water deepens and the lagoonal deposits are superseded by calcareous muds and coral debris.
4. Growth of corals is followed by progradation of the land, the coral reef facies is shifted seaward.
5. Continued progradation of the land brings basaltic river sands and silts and organic muds into the area. Swampy conditions resume and peat deposits accumulate (represented by lignite and soils found at approximately 190 m below mean sea level).
6. Sea level rises following the deposition of the lignite and coral facies shift landward. Calcareous mud containing coral debris accumulates and is followed by the growth of coral reefs approximately 15 m thick.

7. On top of the reef is calcareous mud followed by brown mud and sands and soils, indicating a progradation of the lagoonal facies.
8. The coral reef facies is shifted landward and thick coralline limestone reef accumulates.
9. The growth of the reef is followed by a progradation of the lagoonal facies. Brown lagoonal mud accumulates and is capped with bedded beach rock.
10. Above the beach rock is another reef limestone section indicating a migration of the coral facies landward again.
11. The coral reef facies advances inland and reef is formed making up the present surface of the Ewa Plain.

2.11 Foote *et al.* (1972)

In 1972, the *Soil Survey of the Islands of Kauai, Oahu, Maui, Molokai, and Lanai, State of Hawaii* was published. It was written by D. E. Foote, E. L. Hill, S. Nakamura, and F. Stephens of the United States Department of Agriculture's Soil Conservation Service. The survey was done in cooperation with the University of Hawai‘i Agricultural Experiment Station to learn more about what kinds of soil are on the islands, where they are located, and how they can be used.

As a result of the survey, general soil maps were made for each of the five main islands. Foote *et al.* (1972) stated that the coastal plains on O‘ahu formed from coral reefs and alluvial sediments; and the coral reefs formed in shallow water at a time when sea level was higher. Ford Island is included in the general soil map for O‘ahu and the general soil map for Ford Island indicated Ford Island was a coral outcrop, consisting of coral or cemented calcareous sand.

2.12 Munro (1981)

The next report I will discuss is *The Subsurface Geology of Pearl Harbor with Engineering Application* by K. Munro. Munro (1981) is a masters thesis that was submitted to the University of Hawai‘i at Manoa and describes the subsurface conditions and geology of a specific area of Pearl Harbor. The study area covered approximately 8 km^2, from the northeastern tip of East Loch to Makalapa Crater. The report analyzed investigations commissioned by landowners and conducted by commercial soil engineers. The soil descriptions in the report were separated into five categories based on geologic source: volcanic material, lagoonal deposits, alluvium, coralline material, and fill. The report essentially re-iterates what had previously been published about the geology of the area.

2.13 Macdonald, Abbott, and Peterson (1983)

Volcanoes in the Sea: The Geology of Hawaii was written by G. A. Macdonald, A. T. Abbott, and F. L. Peterson. The first edition was printed in 1970 and the second edition in 1983. Macdonald *et al.* (1983) is a non-technical text intended for persons with little or no previous training in geology. It provides a general overview of the geology of Hawai‘i.

Macdonald *et al.* (1983) re-iterates information from previous studies; however, it describes the geologic history of the Pearl Harbor area as “complicated”. As did many previous publications reviewed here, Macdonald *et al.* (1983) discussed the rise and fall of sea level as well as island subsidence. Specifically for the area in consideration here, as the island of O‘ahu sank by more than 360 m, a broad bay developed on the south shore (Pearl Harbor) with a barrier reef across its mouth. The text also described how sinking rates varied and when there was greater sinking, there was reef development in the bay; and when there was lesser sinking, the bay was completed sedimented (creating swampy conditions). Macdonald *et al.* (1983) also stated that during the Waipi‘o low stand, sediments and the barrier reef were exposed causing valleys to be cut to the ocean. The text re-iterated Stearns and Vaksvik (1935) that the valleys were narrow at the coast due to resistant coral and broad inland due to the sediments being more easily eroded. Macdonald *et al.* (1983) concluded its summary on Pearl Harbor’s geologic history with Pearl Harbor being a valley system that eventually drowned by rising sea level.

2.14 Ogden (1993)

In 1993, Ogden Environmental and Energy Services Co., Inc. completed a site inspection for the Ford Island landfill, located on the island’s southwestern side (Figure 13). Ogden Environmental and Energy Services Co., Inc. was an environmental engineering consultant that is now known as AMEC. The site inspection was conducted to document whether contamination existed at the site and to develop recommendations if no further action, further investigation, and/or removal actions were needed.

According to Ogden (1993), Ford Island’s geology at the landfill (southwest end of the island) consists of limestone and fill. The coralline limestone is semi-lithified to lithified and contains volcanic fragments, indicating that volcanism and coral deposition occurred together. The fill overlying the limestone is approximately 4.5 to 9 m thick and consist of silts, clays, sands, and gravel.

2.15 Erkelens (1995)

In support of the re-development of the northeastern side of Ford Island, an archaeological study was completed by C. Erkelens in 1995. Eight trenches, averaging 5 m in length and 0.08 m in depth, were dug and investigated (Figure 14). According to Erkelens (1995), all trench profiles displayed similar stratigraphic sequences, with six layers. Below are brief descriptions of the layers (from bottom to top), along with Erkelen's geologic interpretations:

Limestone bedrock: The limestone bedrock is white to pink in color and very hard to crumbly depending on the state of decomposition. The limestone bedrock was a result of the coral reef growing over the basalt bedrock of O‘ahu, although that basalt bedrock is nowhere exposed on Ford Island or in the dug trenches (Erkelens, 1995).

Slightly plastic, terrigenous clay: The clay is dark reddish brown with strong crumb structure and very hard consistency. The clay does not contain coral nor other marine derived sediments. The clay reflects a low energy environment deposition resulting in slow accumulation and silting in of the Pearl Harbor basin (lagoonal deposits). As a result of sea level change or a change in the rate of alluvial deposition from the surrounding hillsides, the limestone reef was overlain by terrigenous sediment.

Coarse coralline sand: The coarse coralline sand is gray to light or pinkish gray, 0.01 to 0.015 m thick with well rounded gravel, pebbles, and cobble-sized pieces of coral. This layer was formed from decomposed coralline bedrock that eroded from a higher elevation nearby and was later re-deposited above the non-marine, terrigenous sediments (Erkelens, 1995).

Slightly plastic, silty clay: The slightly plastic, silty clay is reddish brown, 0.002 to 0.007 m thick, intermixed with coarse sand- to gravel-sized particles of coral. Its base is distinct. This deposition regime was of higher energy than that of the slightly plastic, terrigenous clay below. Erkelens (1995) indicated that rainfall was of sufficient magnitude that the flow of muddy water from the surrounding hillsides had sufficient energy to erode the coralline gravel size fraction. This alluvial flow then retained enough energy to transport these large coralline particles in suspension with the terrigenous sediments to the center of Pearl Harbor. The result was a homogenous mixture composed of coralline sediments and terrigenous silt derived from alluvial erosion of the hillsides (Erkelens, 1995).

Slightly plastic, silty clay: This slightly plastic, silty clay is dark red, 0.01 m thick and has fine to medium-sized coral sand particles mixed in the clay. This layer is similar to the layer immediately below except the particle size is finer indicating a slight decrease in the transport energy.

Silty clay loam: The silty clay loam is dark reddish brown with a strong fine crumb structure. After the slightly plastic, silty clay was deposited, a subsequent drop in sea level led to a carving of river valleys and left Ford Island as a plateau of high, dry land in the center of the Pearl Harbor basin. When sea level later rose to its present height, the flooded river valleys became lochs and the waters of Pearl Harbor surrounded the central basin plateau of Ford Island (Erkelens, 1995). The silty clay and loam are mostly the result of the island being plowed for sugarcane cultivation.

Erkelens (1995) provided detailed descriptions and interpretations for the stratigraphy at the northeastern side of Ford Island. The various soil type descriptions seem to be consistent with previous studies; the sands and clay that overly the limestone could be the fill as described in Ogden (1993). What is interesting to note is that the trenches indicate encountering coralline limestone (Figure 14). The trenches averaged 0.8 m in depth indicating the coralline limestone ranges from approximately 5 to 7.5 m above mean sea level since Ford Island averages an elevation of 6 m above mean sea level with the highest point being 8.5 m above mean sea level.

2.16 Department of the Navy (2002)

In 2002, an environmental impact statement prepared for the development of Ford Island was finalized for the Department of the Navy. The report stated that the perimeter of the island, especially the northern and eastern shorelines, was composed of material dredged from the ocean or hauled from nearby areas. The rest of the report re-iterated the geologic material that was described in previous publications.

2.17 Department of the Navy (2003)

In 2003, the Department of the Navy prepared an Archaeological Monitoring Plan in support of development projects on Ford Island. Archaeological monitoring at Ford Island is due to early reports of human burials in limestone crevices. The purpose of the plan was to establish procedures to support various projects where ground disturbance was anticipated and described various excavation trenches in addition to the trenches described by Erkelens (1995). Ford Island's geology was summarized to be "a terrigenous core encircled by coral limestone, which has been uplifted and exposed in areas." The plan stated that the limestone crevices described in early reports of human burials were likely cracks or caverns in a karst limestone environment previously located along the original shoreline (Department of the Navy 2002).

The plan described trenches that were excavated in 2002 for the construction of the Navy Lodge and trenches that were excavated as part of the aviation gasoline pipeline investigation which was ongoing at the time (Figure 15). The trenches that were excavated for the Navy Lodge foundation on the northern side of the island were generally 1 m wide and between 0.4 to 1.2 m deep. The stratigraphy consisted of three layers (from bottom to top):

Limestone bedrock: The limestone bedrock is very pale brown and was encountered approximately 0.9 m deep.

Silty clay: The clay is dark reddish brown and was encountered at depths of 0.45 to 0.9 m.

Coral fill: The coral fill is light gray and 0.45 m thick.

A trench was also excavated for the Navy Lodge drain line and was 2 m deep. This trench was similar in stratigraphy as the trenches for the foundation with the exception of the second layer (silty clay). This layer was 0.8 m thick at the southern end.

In addition, seven trenches were excavated around the island as part of an aviation gasoline pipeline investigation. The excavations were described in the plan and ranged from 2 m to 2.5 m deep. At the northwest corner, the excavation profiles consisted of two main layers: (1) loamy sand with gravel on the bottom and (2) fill soils with gravel (dredge fill material) on top. On the northeast end of the island, the 2 m deep trench revealed only fill soils with a buried asphalt layer at approximately 0.24 m deep.

On the south end of the island, excavation profiles the two layers consisted of (1) limestone with silty clay, and (2) fill.

2.18 Earth Tech (2003)

The Navy has an environmental restoration program that focuses on the clean-up of Navy properties due to historical site practices (i.e., sandblasting of lead based paint, burn and disposal pits, etc.). From 1999 to 2003, Earth Tech, a private environmental consulting company based in Honolulu, conducted an investigation at Ford Island to characterize the nature and extent of contamination at potential release locations (i.e., transformers, fuel pipelines, etc.). As part of this investigation, 244 surface soil and 85 subsurface soil samples were collected around the island prior to the installation of 45 monitoring wells. The locations of the borings/monitoring wells are shown on Figure 16.

During the 1930s, enough material was dredged from Pearl Harbor both to enlarge the island from 334 acres to 441 acres, and to fill in some low areas where construction was to take place (Cohen, 1981). The fill material is therefore thickest around areas of construction and where the shoreline has been reclaimed. Based on samples collected from 0 to 0.15 m below ground surface, most of the fill consists of silt, sand, and graded coral gravel. The subsurface geology consists of lagoonal deposits, coralline debris, weathered volcanic material, and fill materials.

2.19 Geolabs (2006a and 2006b)

Geolabs, Inc. is another Honolulu-based geotechnical engineering and drilling services company, and in 2006 they completed geotechnical investigations for housing developments on the northeastern and southern sides of Ford Island.

The investigation consisted of three borings on the northeastern side and four borings on the southern side. Borings are shown on Figure 16. The boring logs completed for this investigation were used in developing a cross section, cross section location is shown on Figure 17 and is presented in Figure 18. The borings on the northeastern side of the island were drilled to a maximum depth of 6.5 m below the ground surface and encountered only severely fractured, highly weathered coral. Above the coral is a fill layer consisting of very stiff clayey silt on the order of 0.5 to 1.5 m thick.

The four borings on the south side of the island were drilled to depths of 6.25 to 6.5 m. Borings 1 and 4 only encountered coralline detritus consisting of loose to medium dense silty coralline gravel. Borings 2 and 3 only encountered medium hard to hard coral. 1 to 2.4 m of coral fill was found above the coralline detritus in the four south-side drill holes. Overlying the fill is a concrete pavement slab, on the order of 0.127 to 0.178 m thick.

2.20 Fletcher *et al.* (2008)

A summary of the geology of Hawaiian reefs is presented in *Coral Reefs of the U.S.A.*, (Fletcher *et al.*, 2008). Fletcher *et al.* (2008) also discuss the environmental history of the reefs in Hawai‘i and the uplift of O‘ahu. Fletcher *et al.* (2008) stated that Hawai‘i volcanoes are too heavy for the underlying lithosphere to support without bending. Isostatic subsidence over the hot spot leads to plate flexure, a process responsible for an arch of uplifting lithosphere in an aureole surrounding the depression. As an island moves off the hot spot, it evolves from a regime of subsidence to one of uplift as it passes over the flexing arch (Fletcher *et al.*, 2008).

Uplift of O‘ahu is thought to be responsible for the high elevation of the fossil coral limestone such as the Ka‘ena reef. However, another reason for the high position is actually a combination of slow uplift and high sea level (Fletcher *et al.,* 2008).

As the Pacific Plate flexes downward the volcanic pile subsides and an island-wide rise in relative sea level occurs. This is significant in understanding the geology of Ford Island because in addition to the Pleistocene oscillations of sea level, plate flexure also affects the stratigraphy of the reefs. During high sea levels, there is new reef accretion and flooding of older limestone units; whereas low sea levels expose the reefs to subaerial dissolution and erosion (Fletcher *et al.*, 2008).

2.21 Kleinfelder (2009)

In 2009, Kleinfelder completed a geotechnical investigation for the National Oceanic and Atmospheric Association (NOAA) Pacific Regional Center which is to be completed on Ford Island in Summer 2010. As part of this investigation, 3 soil borings were drilled on the northwest side of the island. The boring depths ranged from approximately 9.75 to 16 m. Additionally, 5 shallower and narrower holes were cored, the depths ranged from approximately 2 to 3 m below ground surface. Borings are shown on Figure 16.

Beneath a 0.152 m concrete slab at the site, the boring logs describe 4 main subsurface units, from bottom to surface: (1) alluvial deposits, (2) sandstone, siltstone, coral formations, (3) coralline sands and gravels, and (4) fill. Specific details of each unit are described below.

Alluvial deposits: The alluvial deposits consisting of stiff to hard silts and clays were encountered. The unit extended to the maximum depth explored, approximately 30 m below ground surface.

Sandstone, siltstone, and coral formations: Above the alluvial deposits, sandstone, siltstone, and coral formations were encountered. This layer ranges from 6 to 21 m in total thickness. In general, the siltstone and sandstone encountered were severely fractured, moderately to highly weathered, and soft to medium hard. A void measuring approximately 0.10 m thick was encountered at approximately 6.4 m deep in the cemented sandstone in boring KB-1.

Coralline sand and gravel: This unit consists of medium dense to dense gravelly and silty sands and sandy gravel. This layer ranges from about 2.7 to 6 m thick and consists of silty clay estuarine deposits, coralline detritus, and weathered calcareous sandstone. It also contains shell fragments.

Fill layer: Beneath the concrete slab, at borings KB-1 and KB-2, the fill consists of 0.3 to 0.6 m of silty sand and gravelly sand material with loose to dense consistency. To the north of the concrete slab at KB-3, the fill consists of sandy clay with some silt with very stiff consistency.

In addition to the geotechnical investigations done by Kleinfelder (2009), a deep well is currently being installed near the location of the new NOAA facility (Well 2157-05). The well, which is expected to be completed by Summer 2010 will support the future NOAA facility and is more than 390 m deep. The drill log for the first 390 m which was originally drilled in 2005 is presented here in Table 8. The drill log was also used in the development of the cross-sections presented in Figure 18 and Figure 19. Unfortunately, above the pāhoehoe, the log described the overlying material as “salt” and it is unclear if the log was supposed to say “silt” or if it actually meant salt.

Table 8: Drill Log for Well 2157-05

Depth (m below ground surface)	Description
0 – 3.05	Calcareous sand and gravel
3.05 – 6.10	Brown to gray calcareous clayey silt with some sand and gravel
6.10 – 24.38	Dark gray to dark brown salt/clay grading to clayey salt with streaks of basaltic pea gravel
24.38 – 134.11	Dark gray to dark brown salty clay salt with streaks of basaltic pea gravel
134.11 – 166.12	Gray, brown and reddish brown weathered basaltic cinder with coarse sand to gravel sized with some interbedded silt layers (Pahoehoe)

Depth (m below ground surface)	Description
166.12 – 193.55	Dark brown to reddish brown Pahoehoe, cuttings are angular and coarse sand to gravel sized
193.55 – 207.26	Dark brown to black cinders of Pahoehoe origin
207.26 – 227.08	Dark gray to reddish brown Pahoehoe with some white secondary mineralization
227.08 – 251.46	Dark brown to dark gray basaltic cinders
251.46 – 268.22	Dark brown to black pahoehoe
268.22 – 284.99	Brown to reddish brown weathered cinder
284.99 – 316.99	Dark brown to dark gray
316.99 – 320.04	Brown to reddish brown cinders
320.04 – 330.71	Gray to dark gray Pahoehoe
330.71 – 341.38	Gray to dark gray Pahoehoe
341.38 – 390.14	Primarily dark gray Pahoehoe with several a‘a layers, cuttings are cingular, some secondary white mineralization in some spaces

3. Synthesis of Previous Studies

The summaries presented in section 2 provide various descriptions of not only the geology of Ford Island (i.e., the various rock types and their distribution) but also the genesis of the island as part of the formation of Pearl Harbor and the coastal plain. Here I will synthesize the summaries from section 2, beginning with the formation of Pearl Harbor.

3.1 Geologic History of Pearl Harbor and Ford Island

Pearl Harbor’s geologic history begins in the Pleistocene, long after the island of O‘ahu was created by the Wai‘anae and Ko‘olau volcanoes, when the Ko‘olau volcanics ended approximately 2.1 million years ago (Ozawa *et al.*, 2005) and eustatic sea level was approximately 25 – 50 m higher that it is today (USGS, 2010). The island of O‘ahu was already subsiding and was experiencing stream and wave erosion. Sediments were deposited from streams and coral reefs grew around the island. Figure 20 shows oxygen isotope data (Shackleton *et al.*, 1990) that indicate alternating warm and cool periods for the last 2.6 million years. This curve is used as a proxy for sea level because the warm and cool periods correspond to the high and low sea level stands, respectively; (known as marine isotope stages [MIS]). Figure 20 also shows major geologic events associated with Pearl Harbor. Based on the oxygen isotope data, from 2.1 million years ago until 470,000 years ago, eustatic sea level fluctuated. As eustatic sea level dropped, the coral reefs were exposed creating hard-pan limestone and the streams formed valleys. As sea level rose, coral reefs continued to grow around the island

and sediments continued to be deposited. There was also rejuvenation-stage volcanism occurring on O‘ahu with the eruptions from Makalapa crater taking place 470,000 ± 60,000 years ago (Ozawa *et al.*, 2005; Figure 21). 470,000 years ago, eustatic sea level was approximately 80 m lower than it is today (Berné, 2004) which would indicate that the Makalapa volcanic ash and lapilli were deposited subaerially over the reefs and sediments. Eustatic sea level was higher 400,000 years ago, approximately 20 m higher that it is today (Hearty, 2002). This sea level is represented as MIS 11 and correlates to what is commonly referred to as the Ka‘ena highstand. If the Makalapa eruptions instead occurred 400,000 years ago (just younger than the uncertainty given by Ozawa *et al.*, 2005), then the volcanic ash and lapilli were deposited submarinely, when the island was submerged. At the same time, uplift was occurring at a rate of 0.020 ± 0.003 m/kyr on O‘ahu (Hearty, 2002). All of these events, sedimentation, reef growth, and volcanism, built what is now a coastal plain composed of calcareous and non-calcareous sediments and tuff.

Eustatic sea level dropped to approximately 106 m below present during the Waipi‘o lowstand (approximately 350,000 years ago; Gavenda, 1992). After the formation of the coastal plain, the drop in eustatic sea level during the Waipi‘o lowstand led to streams to cut three valleys across it. These valleys were probably carved by a combination of subaerial dissolution of the limestone as well as mechanical erosion. Approximately 125,000 years ago, eustatic sea level was approximately 7 m higher than it is today (MIS 5e). The rise in sea level is known as the Waimānalo highstand and uplift was occurring at a rate of 0.024 ± 0.003 m/kyr (Hearty, 2002). The reef that has been mapped on Ford Island and on the coastal plain has been attributed to the Waimānalo highstand. Approximately 12,000 years ago, eustatic sea level was approximately 106 m below present, this lowstand was known as the Mamala Low (Gavenda, 1992). Sea level rose to its present stand, submergence occurred, causing the valleys to be flooded, forming what is today Pearl Harbor. The streams that cut the valleys also crossed each other leaving a piece of land to be surrounded by water, Ford Island.

Figure 22 presents a graph from an article by McMurtry *et al.* (2010) that plots coral age vs. elevation. McMurtry *et al.* (2010) is a somewhat controversial article that presents data supporting the idea that O‘ahu has been experiencing uplift for the last 500,000 years at a constant rate of 0.06 ± 0.001 m/kyr, suggesting that elevated reefs are at their current location because of uplift and not because of high sea levels. The graph (and field evidence) also mean that older reefs are topographically above younger reefs which might contradict their expected superposition positions. Further discussion on this article is presented in section 4.

3.2 The Present Geology of Ford Island

Ford Island's surface geology consists almost entirely of artificial fill from two sources: (1) topsoil from when sugarcane was planted and (2) dredged material from the harbor. From 1899 to 1917, 1.3 km^2 of Ford Island's original 1.4 km^2 were plowed for sugarcane cultivation, which disturbed the original surface geology. The topsoil from sugarcane cultivation consists of loamy silts and clays. In the 1930s, material dredged from the harbor was added to the shoreline to increase the size of the island from 1.4 km^2 to 1.8 km^2 (Figure 16). The dredged material consists of clays, silts, sands, gravel, shell fragments, and coralline detritus. Prior to the fill being added, the surface geology was mapped by Stearns (1939) as shown on Figure 10. Today, most of Ford Island has been developed and the majority of its surface area is concrete or asphalt.

Previous studies and bore logs indicate that the subsurface geology consists of coralline limestone, tuff, and other various deposits related to marshes, lagoons (i.e., shale), and streams (alluvium). Based on the borelogs, I will describe the subsurface geology as it varies on different parts of the island. In each case, the rocks are described from oldest to youngest:

North: On the northwest side, where there is one deep drill hole (Well 2157-05), pāhoehoe and ʻaʻā lavas are found from ~390 m to as high as 130 m below the surface (Table 8). Above this is approximately 127 m of clay and basaltic gravel, but unfortunately, the logs do not differentiate these into layers. The drill log for Well 2157-05 did not describe any coral; however, the log mentions "salt", it is unclear if it meant to say "silt" or if the description of salt was actually coral. Above the gravel is approximately 3 m of coralline sand. On the northeastern side of the island, the deepest drill hole extended only to 6.5 m below the surface. Coral is at this depth and overlain with approximately 0.3 to 1.5 m of fill. One borelog, which also extended to a depth of 6.5 m indicated coral detritus and alluvium at that depth. The coral detritus and alluvium are overlain by approximately 6 m of coral and 0.5 m of fill. The north side received approximately half of the ocean dredge material as shown on Figure 16 and the northernmost boring extended to a depth of approximately 4.5 m and consisted entirely of fill.

South: On the southeastern side, boreholes extended to a depth of approximately 5.5 m. At this depth, limestone and coral gravel were encountered and is overlain with approximately 1 m of tuff. Approximately 0.3 to 1.2 m of fill and concrete overlie the tuff. The artificial fill dredged from Pearl Harbor extends as deep as 3.5 m in the southeast. On the southwestern side of the island, the deepest drill hole extended to 6.5 m. At 6.5 m below the surface, there is basalt gravel overlain by approximately 1.5 m of fill. Other drill holes at the same depth encountered coralline detritus (ocean dredge material) overlain by 1.5 to 5 m of fill (silty loam). There are areas on the south side where: (1) the coral is overlain by alluvium or (2) the coral is overlain by alluvium, and another coral layer is above the alluvium.

West: Boreholes on the west side extended to a depth of approximately 6 m below the surface. At this depth, coralline limestone is overlain by approximately 2 to 5 m of fill material. Coral detritus (ocean dredge material) was added only along the edges on the west side (Figure 16).

East: The subsurface geology on the eastern side of the island consists mainly of fill because it received approximately half of the ocean dredge material (Figure 16). Unfortunately, the deepest boreholes on the east side (approximately 5 m) do not go beyond the depth of the fill; therefore, what is beneath the fill could not be determined.

4. Discussion and Conclusions

The original motivation for this paper was to provide geologic information about Ford Island that could be used for input parameters of a hydrologic model. As with the island of O‘ahu, the coastal geology of Ford Island was affected not only by changes in sea level but also by subsidence and uplift. Ford Island’s geology was also affected by the addition of ocean dredge material to the north, west, and southeastern sides of the island.

As mentioned earlier, cross-sections were generated (locations shown on Figure 17) and are presented in Figure 18 and Figure 19. Both cross-sections incorporate borelog data from previous studies as well as the deeper part of the log for Well 2157-05. Cross-section A-A' (Figure 18) goes from the Ewa 2 boring (Stearns and Chamberlain, 1967) located across West Loch to the west, to the Honolulu Plantation well located to the east of Ford Island, in Aiea (Martin and Pierce, 1913). However, because most of the borings drilled on Ford Island are so shallow, the only unit that possibly could be correlated across the island was the artificial fill overlying coralline limestone in the shallow subsurface. In the deeper subsurface, there appears to be a correlation between the Ewa 2 boring Well 2157-05, and the Honolulu Plantation Well. The correlation between the Ewa 2 boring and the Honolulu Plantation Well, which are approximately 8 km apart and across Ford Island, is shown in Figure 18.

The layers of coralline limestone beneath Ewa 2 and the Honolulu Plantation wells indicate near-sea-level conditions and the interbedded layers of sands, muds, and clays, indicate subaerial conditions. Because Ford Island is located between these two borings, one would expect similar rocks below it. At least with regard to the deep basalt, there does appear to be a correlation between the Ewa 2 boring (basalt at ~160 m), the Honolulu Plantation well (basalt at ~100 m), and Well 2157-05 on Ford Island (basalt at ~130 m).

I also generated a cross-section using the well information from Stearns and Vaksvik (1938) to see if there is a correlation with the drill log for Well 2157-05 (Figure 19). These extend to approximate depths of 195, 46, and 390 m below the surface, respectively for Well 170, 218-1 and 2157-05. All three encountered basalt at these depths. The difficulty with correlating the data for Figure 18 and Figure 19 is that the descriptions provided in the drill log of Well 2157-05 for the sequence above the basalt are essentially meaningless. The other borelogs were easier to correlate because the logs had distinguishing coral intervals, separated by clays, sands, and mud, but the drill log for Well 2157-05 did not.

Based on the cross-sections, I can interpret that there were times when the island was submerged, and coral reefs grew. When the island was emerged, clays, muds, sands were deposited. Figure 18 indicates that the island was submerged three times and emergent three times. If the subaerial coral on Ford Island is due to the Waimānalo high stand (~125,000 years ago; MIS 5), and the stratigraphy beneath is simple, then the 3 coral layers encountered in the drill holes probably correspond to MIS 7, 9, and 11 at increasing depths, respectively. However, as noted above, McMurtry *et al.* (2010) present data that support the idea that O‘ahu has been experiencing uplift for the last 500,000 years at a rate of 0.06 ± 0.001 m/kyr. If they are correct then elevated reefs did not accrete at highstands but instead reached their current elevation by uplift alone. This might mean that the reefs encountered below present sea level in the Pearl Harbor area (Figure 18 and Figure 19) aren't from the older sea level high stands because these, according to McMurtry *et al*. are all now above present sea level. When would these reefs have grown? Perhaps they are associated with long-lived low stands, a number of which occurred prior to the Makalapa eruption (which overlies them). Clearly the best way to resolve this issue would be to determine the ages of the reefs encountered in the drill holes.

Figure 19 also shows layers of sandy clay interbedded with clays, muds, and sands. These other sediments support Stearns and Vaksviks' theory (re-iterated by Macdonald *et al.*) of softer sediments being the reason for the wide lochs; however, another factor that should be addressed is the effect that fresh water springs had on the shaping of the lochs. Dissolution by fresh water entering either via streams or springs might have widened originally stream-cut valleys. Or, if Pollock (1929) is correct, then Pearl Harbor might have been shaped purely by marine processes followed by dissolution due to the fresh water springs (which are located around Pearl Harbor's perimeter).

In conclusion, Ford Island's geologic history started at the end of the Koʻolau volcanics 2.1 million years ago. Eustatic sea level was approximately 25-50 m higher than today and the volcano was subsiding (Figure 23a). As the island continued to subside, although at a slowing rate, sea level fluctuated, producing interbedded coral and sediment (Figure 23b). The Makalapa crater erupted 470,000 ± 60,000 years ago, depositing ash and lapilli. Sea level was approximately 80m below present at that time and uplift was occurring. During one or more sea level lowstands (MIS 12, 10, 8, or 6), valleys were cut and widened (Figure 23c). Approximately 125,000 years ago, the Waimānalo reef was deposited at a time when sea level was 7m higher than present. Sea level dropped and when it reached present sea level, the valleys were flooded, isolating Ford Island (Figure 23d). Fill was later added to the perimeter of the island.

Ford Island's geology consists of, from oldest to youngest: (1) basalt, (2) coralline limestone (interbedded with volcanic deposits, lagoonal deposits, and alluvium), and (3) fill material (topsoil from when the island was planted with sugarcane as well as material dredged from Pearl Harbor to enlarge the island). The first and third units are well studied and understood but it is the second unit, the coralline limestone with its interbedded lagoonal deposits, volcanic deposits, and alluvium that is complex and requires more investigation. Factors that need to be considered are:

(1) Volcanic deposits from the Makalapa eruption have been dated at 470,000 ± 60,000 years. However, depending on what date is used, the volcanic deposits could have been deposited subaerially (when sea level was low) or submarinely (when sea level was high).

(2) The rate of uplift and how it affected the submergence and emergence of Ford Island. Was uplift really constant as McMurtry *et al.* (2010) describe?

(3) The effect fresh water springs may have had on the coral deposits and possible dissolution occurring. Did they have an effect on the shaping of the lochs in Pearl Harbor? And if they did affect the shaping of the lochs, did the springs also affect the isolation of Ford Island?

There are possible correlations in surrounding wells as shown in the cross-sections presented in Figure 18 and Figure 19. The correlations indicate times of submergence and emergence; however deeper borings are needed on Ford Island to confirm the correlation. Well 2157-05 is the deepest boring on Ford Island to date and probably encountered these interbedded deposits; however, this could not be determined from the drill log because the descriptions could not be correlated with other borelogs. The rest of the borings extend only to shallow depths and do not encounter the interbedded deposits. With that in mind, the shallow subsurface of Ford Island is well understood but deeper borings are necessary to understand the deep stratigraphy and confirm the island's geologic history.

Acknowledgements

I would like to acknowledge and thank Aly El-Kadi, Steve Martel and Ali Fares for reading a previous version of this paper. I would also like to thank AECOM Technical Services and the Department of the Navy for the data and reports referenced in this paper. I would also like to acknowledge Rafael de la Sierra for helping me with the figures.

5. References

Bates, R. L. and J. A. Jackson (editors). 1984. *Dictionary of Geology Terms.* Third edition. Prepared under the direction of the American Geological Institute. Anchor Books, Doubleday, New York, New York.

Berné, S., M. Rabineau, J. A. Flores, and F. J. Sierro. 2004. *The Impact of Quaternary Global Changes on Strata Formation: Exploration of the Shelf Edge in the Northwest Mediterranean Sea.* Oceanography. Volume 17, No. 4: 92-103. December.

Branner, J. C. 1903. *Notes on the Geology of the Hawaiian Islands.* American Journal of Science, Fourth Series, Volume XVI, No. 94. October.

Cohen, S. 1981. *East Wind Rain, A Pictorial History of the Pearl Harbor Attack.* Pictorial Histories Publishing Company, Missoula, Montana.

Curry, J. F. 1924. *The Air Corps in the Hawaiian Islands.* Memorandum.

Davis, W. M. 1915. *A Shaler Memorial Study of Coral Reefs.* American Journal of Science. Fourth Series. Volume XI. No. 237. September.

Department of the Navy. 1945. *Administrative History of the Fourteenth Naval District and the Hawaiian Sea Frontier. vol. 1 (Hawaii, 1945) [This manuscript, identified as United States Naval Administrative History of World War II #121-A, is located in the Navy Department Library's Rare Book Room.]*, Historical Section, Fourteenth Naval District.

Department of the Navy. 2002. *Final Programmatic Environmental Impact Statement, Ford Island Development.* Volume I. Pearl Harbor, Hawaii: PACNAVFACENGCOM. January.

Department of the Navy. 2003. *Final Archaeological Monitoring Plan in Support of Ford Island Development Projects. Ford Island, Pearl Harbor, Oahu, Hawaii, TMK: 9-9 Portion.* Pearl Harbor, Hawaii: Naval Facilities Engineering Command, Pacific. February.

Dorrance, W. H. 1991. *Historic Ford Island, Moku'ume'ume, Historic Structures of Ford Island.* Historic Hawaii. December.

Earth Tech, Inc. (Earth Tech). 2003. *Remedial Investigation, Ford Island, Pearl Harbor Naval Complex, Oahu, Hawaii*. Pearl Harbor, Hawaii: PACNAVFACENGCOM. February.

Erkelens, C. 1995. *Archaeological Study of the Proposed Ford Island Golf Park and Saratoga Boulevard Relocation, Ford Island Bridge Project*. International Archaeological Research Institute, Inc. Prepared for Belt Collins. July.

Fletcher, C. H., C. Bochicchio, C. L. Conger, M. S. Engels, E. J. Fierstein, N. Frazer, C. R. Glenn, R. W. Grigg, E. E. Grossman, J. N. Harney, E. Isoun, C. V. Murray-Wallace, J. J. Rooney, K. H. Rubin, C. E. Sherman, and S. Vitousek. 2008. Geology of Hawaii Reefs, Chapter 11 in *Coral Reefs of the U.S.A.* Springer, p. 435-488.

Foote, D., E. Hill, S. Nakamura, and F. Stevens. 1972. *Soil Survey of the Islands of Kauai, Oahu, Maui, Molokai, and Lanai, State of Hawaii.* U.S. Department of Agriculture, Soil Conservation Service. Washington, D.C.

Gavenda, R. T. 1992. *Hawaiian Quaternary Paleoenvironments: A Review of Geological, Pedological, and Botanical Evidence.* Pacific Science. Volume 46, No. 3: 295-307.

Geolabs, Inc. 2006a. *Geotechnical Engineering Exploration, Ford Island PPV – South, Hawaii Regional Housing Privatization Increment II – Navy Sites, Pearl Harbor, Oahu, Hawaii. W.O. 5657-00(A).* Prepared for Parsons. November.

Geolabs, Inc. 2006b. *Geotechnical Engineering Exploration, Ford Island PPV – North, Hawaii Regional Housing Privatization Increment II – Navy Sites, Pearl Harbor, Oahu, Hawaii. W.O. 5657-00(B).* Prepared for Parsons. November.

Golob, P. 1996. *Isle of Allure, Isle of Strife, For Historic Ford Island: An Era of Tranquillity Draws to a Close.* Hawaii Magazine. February.

Hearty, P. J. 2002. *The Ka'ena Highstand of O'ahu, Hawai'i: Further Evidence of Antarctic Ice Collapse during the Middle Pleistocene.* Pacific Science, Volume 56, Number 1: 65-81. January.

http://hawaii.gov/hawaiiaviaton/hawaii-airfields-airports/oahu-pre-world-war-ii/ford-island

Horvat, W. J. 1966. *Above the Pacific.* Aero Publishers, Fallbrook, California.

Lau, L. S, and J. F. Mink. 2006. *Hydrology of the Hawaiian Islands.* University of Hawaii Press, Honolulu.

Kleinfelder West, Inc. 2009. *Geotechnical Investigation Report for the Proposed NOAA Pacific Regional Center, Ford Island, Pearl Harbor, Oahu, Hawaii*. Prepared for Hellmuth, Obata, and Kassabaum, Inc. April.

Lum, D. and H. T. Stearns. 1970. *Pleistocene stratigraphy and eustatic history based on cores at Waimanalo, Oahu, Hawaii.* Geological Society of America Bulletin, 81:1-16.

Macdonald, G. A., A. T. Abbott, and F. L. Peterson. 1983. *Volcanoes in the Sea, The Geology of Hawaii.* 2nd ed. Univ. of Hawaii Press.

Martin, W. F. and C. H. Pierce. 1913. *Water Resources of Hawaii 1909 – 1911.* U.S. Geological Survey Water Supply Paper 318. Washington: Government Printing Office.

McMurtry, G. M., J. F. Campbell, G. J. Fryer, and J. Fietzke. 2010. *Uplift of Oahu, Hawaii, during the past 500 k.y. as recorded by elevated reef deposits.* Geology, Volume 38, Number 1: 27-30. January.

Munro, K. 1981. *The Subsurface Geology of Pearl Harbor with Engineering Application.* Master's thesis, Univ. of Hawaii, Geology and Geophysics. August.

Ogden Environmental and Energy Services (Ogden). 1993. *Ford Island Landfill Site Inspection Report*. Pearl Harbor, Hawaii: PACNAVFACENGCOM. November.

Ozawa, A., T. Tagami, and M. O. Garcia. 2005. *Unspiked K-Ar dating of the Honolulu rejuvenated and Ko'olau shield volcanism on O'ahu, Hawai'i.* Earth and Planetary Science Letters, 232:1-11.

Palmer, H. S. 1946. *The Geology of the Honolulu Ground Water Supply*. Board of Water Supply, City and County of Honolulu, Honolulu, Hawaii.

Pollock, J. B. 1929. *The Origin of Pearl Harbor, Island of Oahu.* Michigan Academy of Science, Arts, and Letters. Volume X.

Shackleton, N. J., A. Berger, and W. R. Peltier. 1990. *An alternative astronomical calibration of the lower Pleistocene timescale based on ODP Site 677.* Transactions of the Royal Society of Edinburgh: Earth Sciences, 81:251-261.

Stearns, H. T. 1939. *Geologic Map and Guide of the Island of Oahu, Hawaii*. Bulletin 2, Territory of Hawaii, Division of Hydrography, Honolulu, Hawaii.

Stearns, H. T. 1985. *Geology of the State of Hawaii*. 2nd ed. Palo Alto, California: Pacific Books.

Stearns, H. T. and K. N. Vaksvik. 1935. *Geology and Ground-Water Resources of the Island of Oahu, Hawaii.* Bulletin 1. Territory of Hawaii. Division of Hydrography. Honolulu, Hawaii.

Stearns, H. T. and K. N. Vaksvik. 1938. *Records of the Drilled Wells on the Island of Oahu, Hawaii.* Bulletin 4. Territory of Hawaii. Division of Hydrography. Honolulu, Hawaii.

Stearns, H. T. and T. K. Chamberlain. 1967. *Deep Cores of Oahu, Hawaii and Their Bearing on the Geologic History of the Central Pacific Basin.* Pacific Science, v. XXI, no. 2, p. 153-165.

Sterling, E. P. and C. C. Summers. 1978. *Sites of Oahu*. Bishop Museum, Honolulu.

United States Geological Survey (USGS). 2010. *Satellite Image Atlas of Glaciers of the World*. United States Department of the Interior. Fact Sheet FS 2005-3056. May 2005. Revised 2007, 2010.

Van Dyke, J. M. 2008. *Who Owns the Crown Lands of Hawaii?* University of Hawaii Press, Honolulu.

Visher, F. N. and J. F. Mink. 1964. *Ground-Water Resources in Southern Oahu, Hawaii.* Geological Survey Water-Supply Paper 1778. Prepared in Cooperation with the State of Hawaii Department of Land and Natural Resources, Division of Water and Land Development. United States Government Printing Office, Washington.

Wentworth, C. K. 1951. *Geology and Ground-water Resources of the Honolulu-Pearl Harbor Area, Oahu, Hawaii.* Board of Water Supply, City and County of Honolulu: Honolulu, Hawaii.

Yates, W. P. 1936. *Aviation in Hawaii*. Paradise of the Pacific Press: Honolulu, Hawaii.

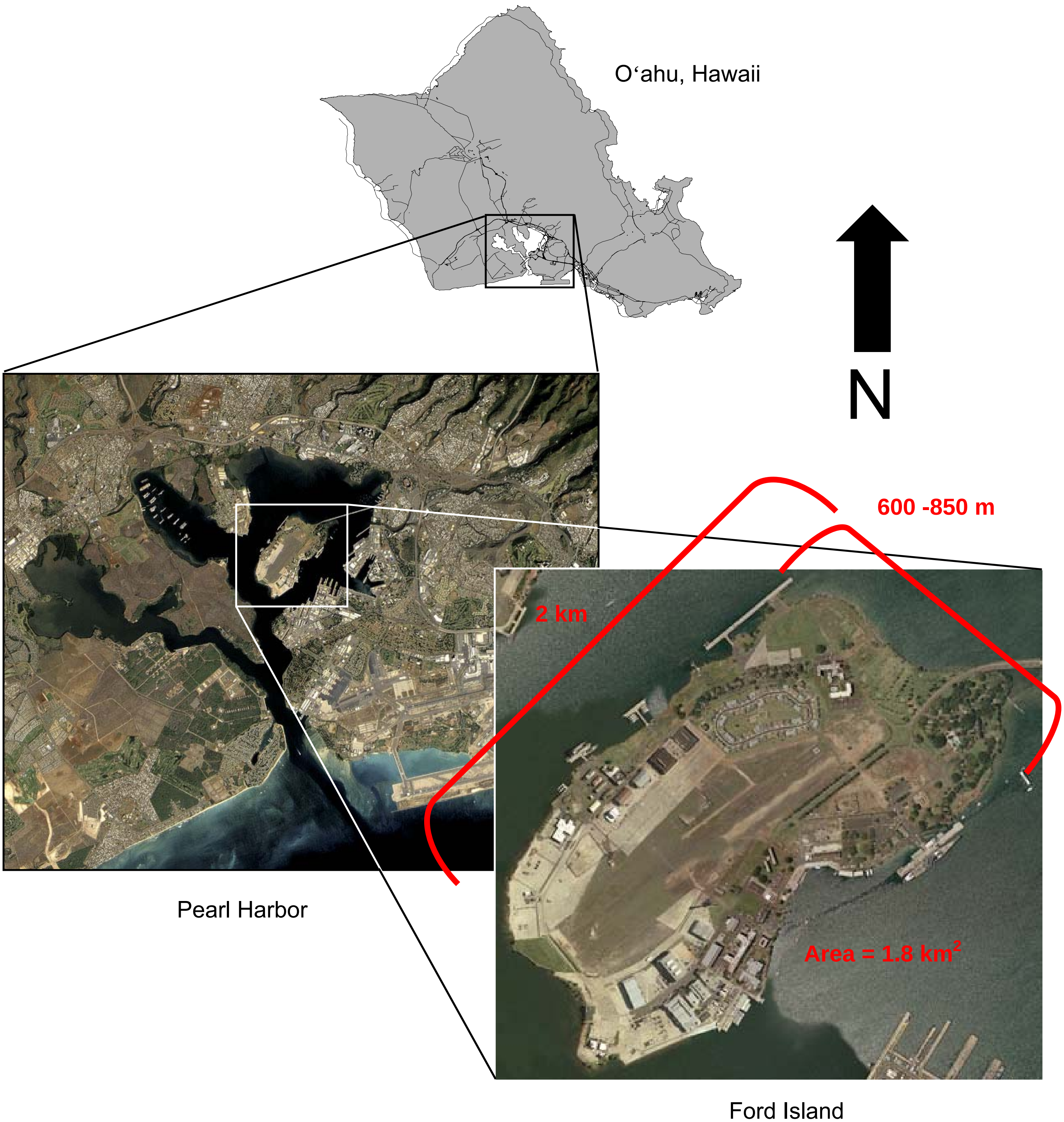


Figure 1: Site Location - Ford Island is located in Pearl Harbor's East Loch on the island of O'ahu. Ford Island is 2 km long in the NE-SW direction, 600-850 m wide in the NW to SE direction, and 1.8 km^2 in size (Source: Google Earth and USGS).

Figure 2: Historical depiction compiled from maps dating from 1875 to 1915 showing Ford Island with its Hawaiian name and various landmarks (Source: Sterling and Summers, 1978).

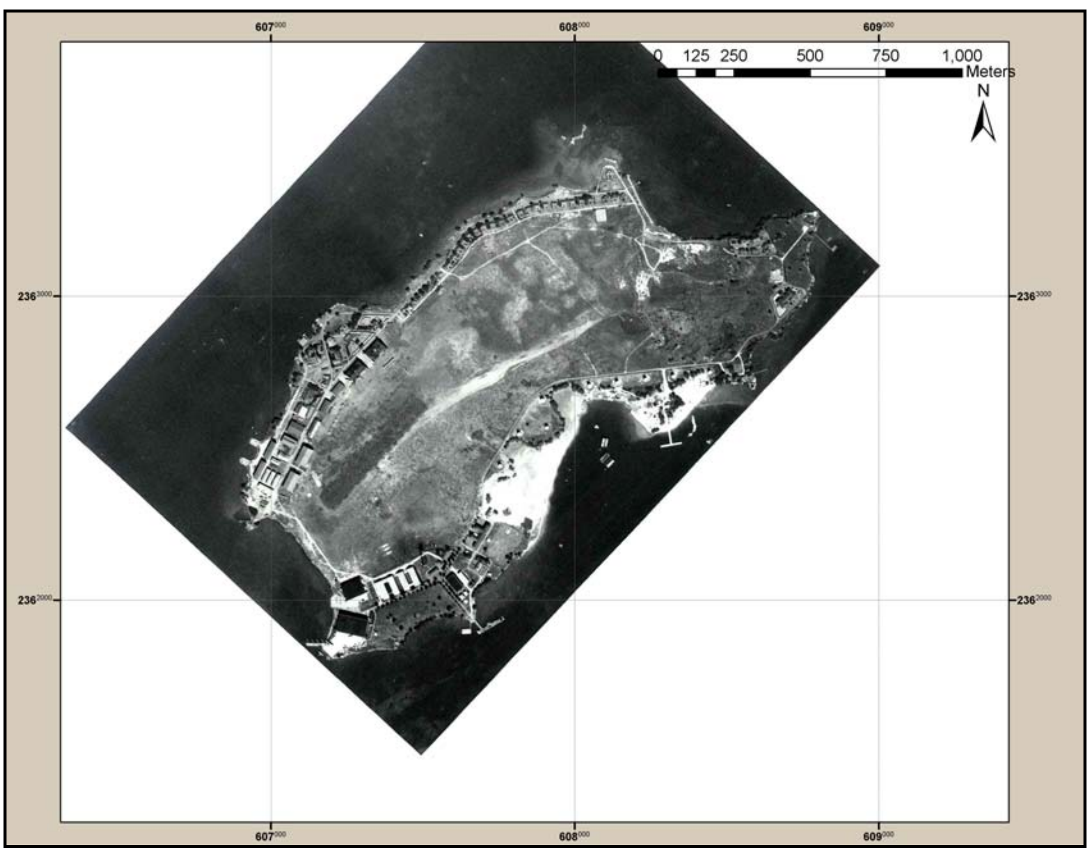


Figure 3: Aerial photo of Ford Island taken ca. 1920 prior to the addition of dredge and fill material in the 1930s. In this photo, the island is 1.4 km^2 in size (Source: Bishop Museum).

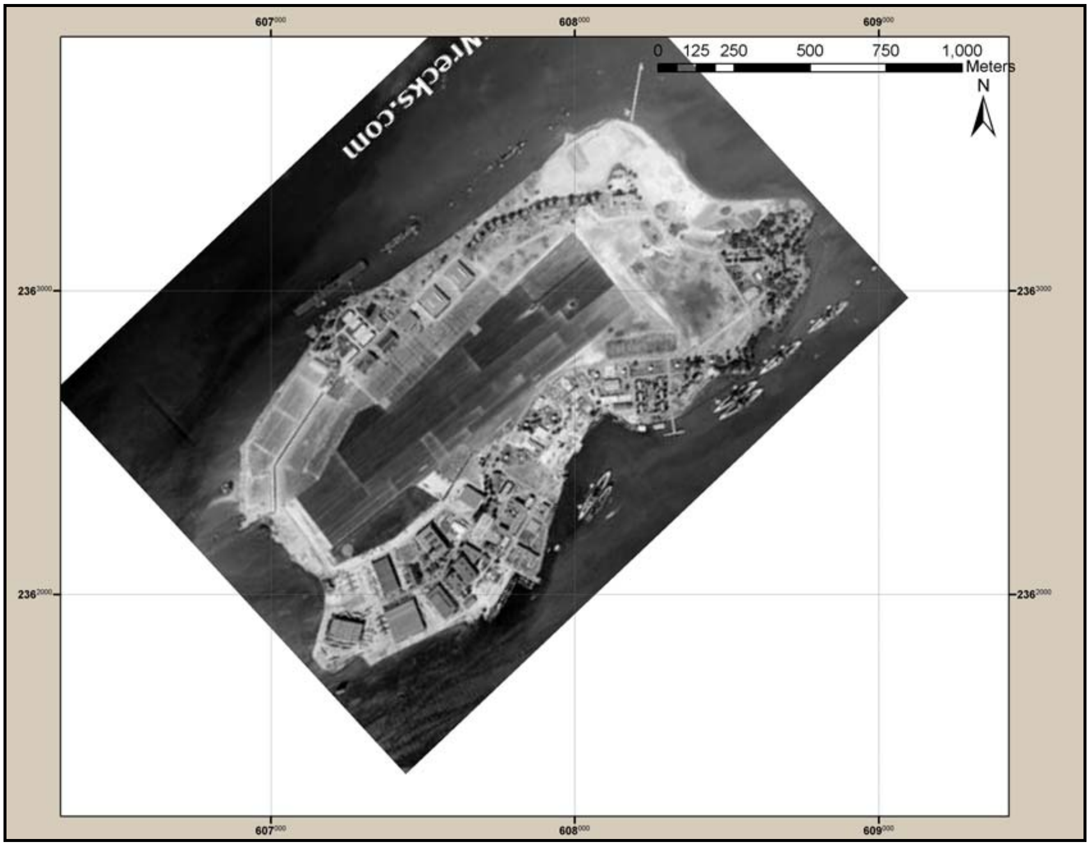


Figure 4: Aerial photo of Ford Island taken in the 1940s. The photo shows the modified shoreline shortly after the addition of approximately 0.4 km^2 of ocean dredge material, increasing Ford Island's size to 1.8 km^2 (Source: www.wrecks.com).

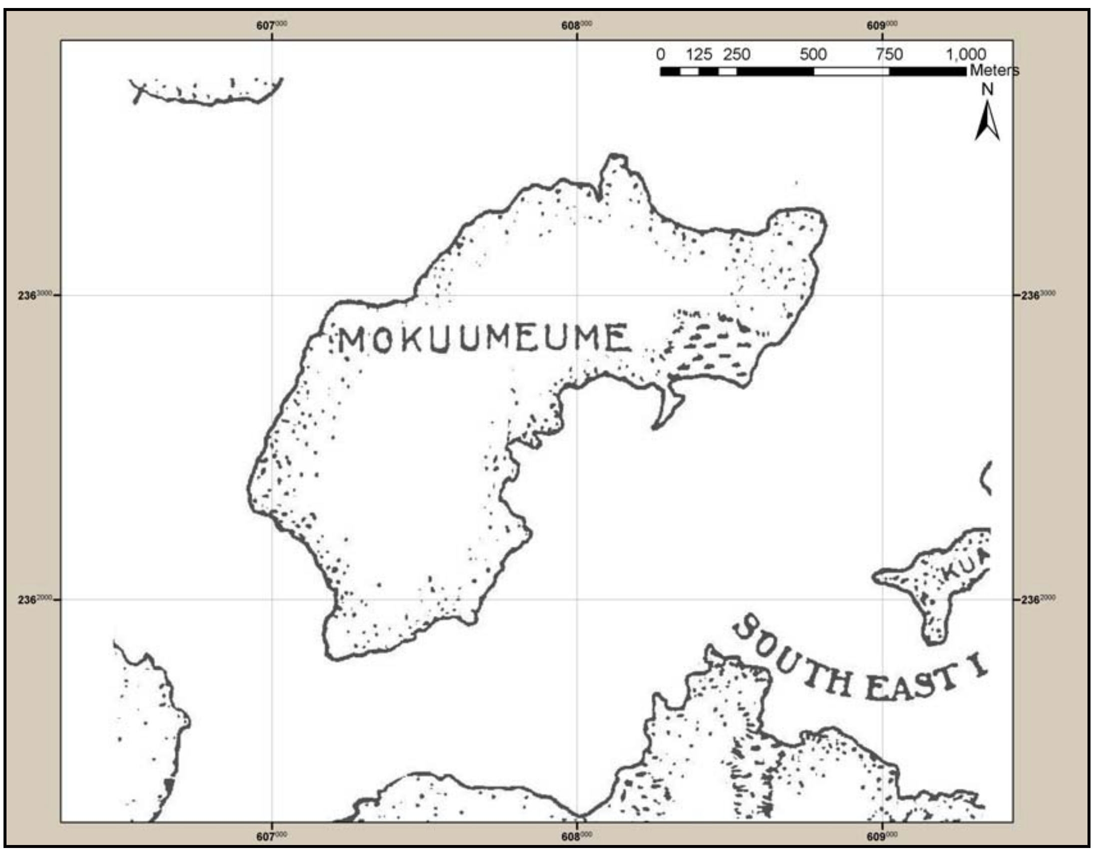


Figure 5: Excerpt from Pearl Harbor map presented in Branner (1903). Ford Island is labeled "Mokuumeume" and the shoreline looks different than it does today (Source: Branner, 1903).

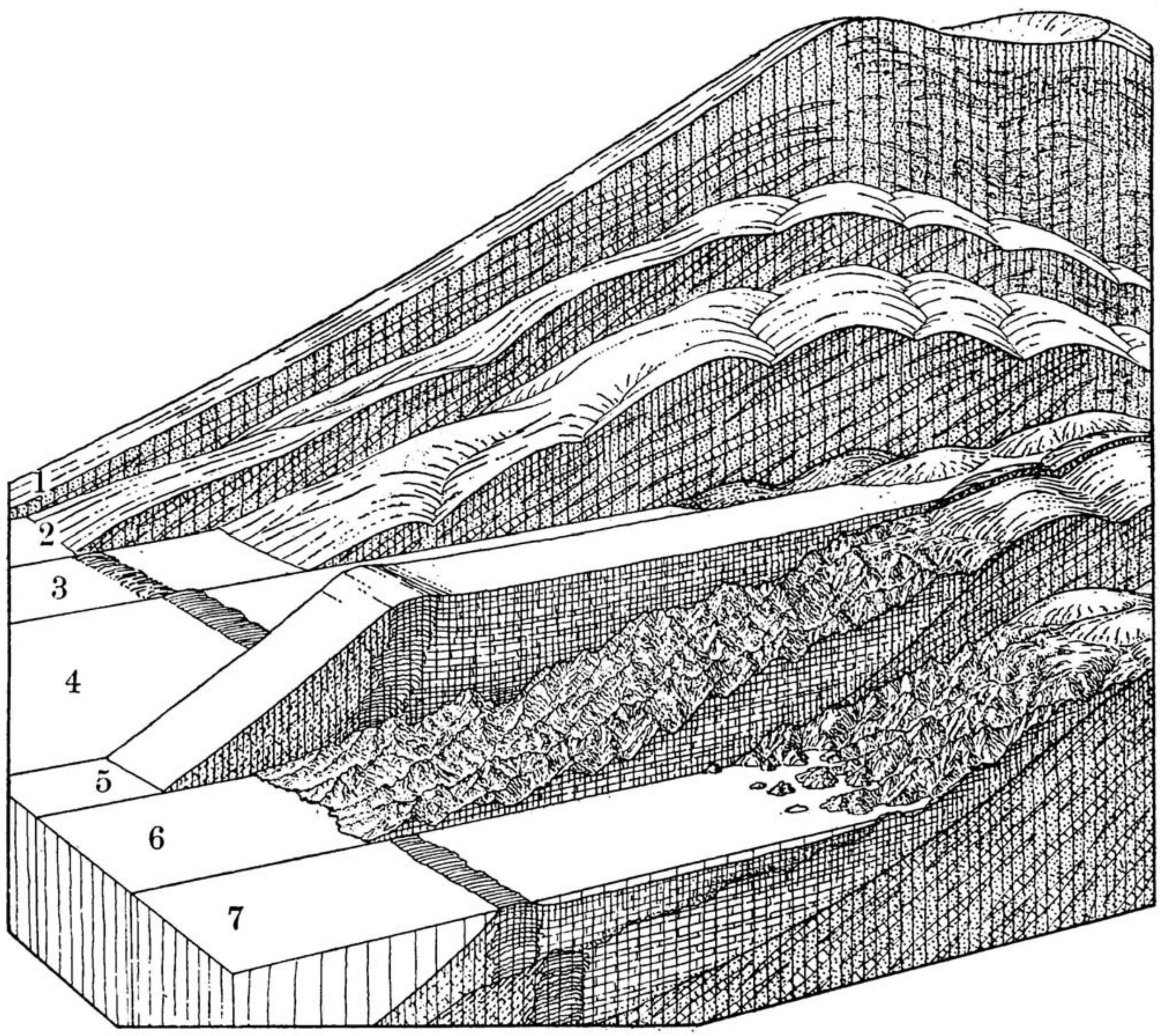


Figure 6: A diagram showing the successive stages in the development of an uplifted and dissected reef, enclosed by a new barrier reef (Source: Davis, 1915). This figure can be used today to generally describe what has happened on Oʻahu. There are seven stages:

1. A young volcano is formed.
2. Erosion of the young volcano occurs.
3. The volcano subsides and a coral reef forms
4. The volcano continues to subsides.
5. The coral reef is uplifted.
6. Limestone erosion occurs.
7. A barrier reef forms.

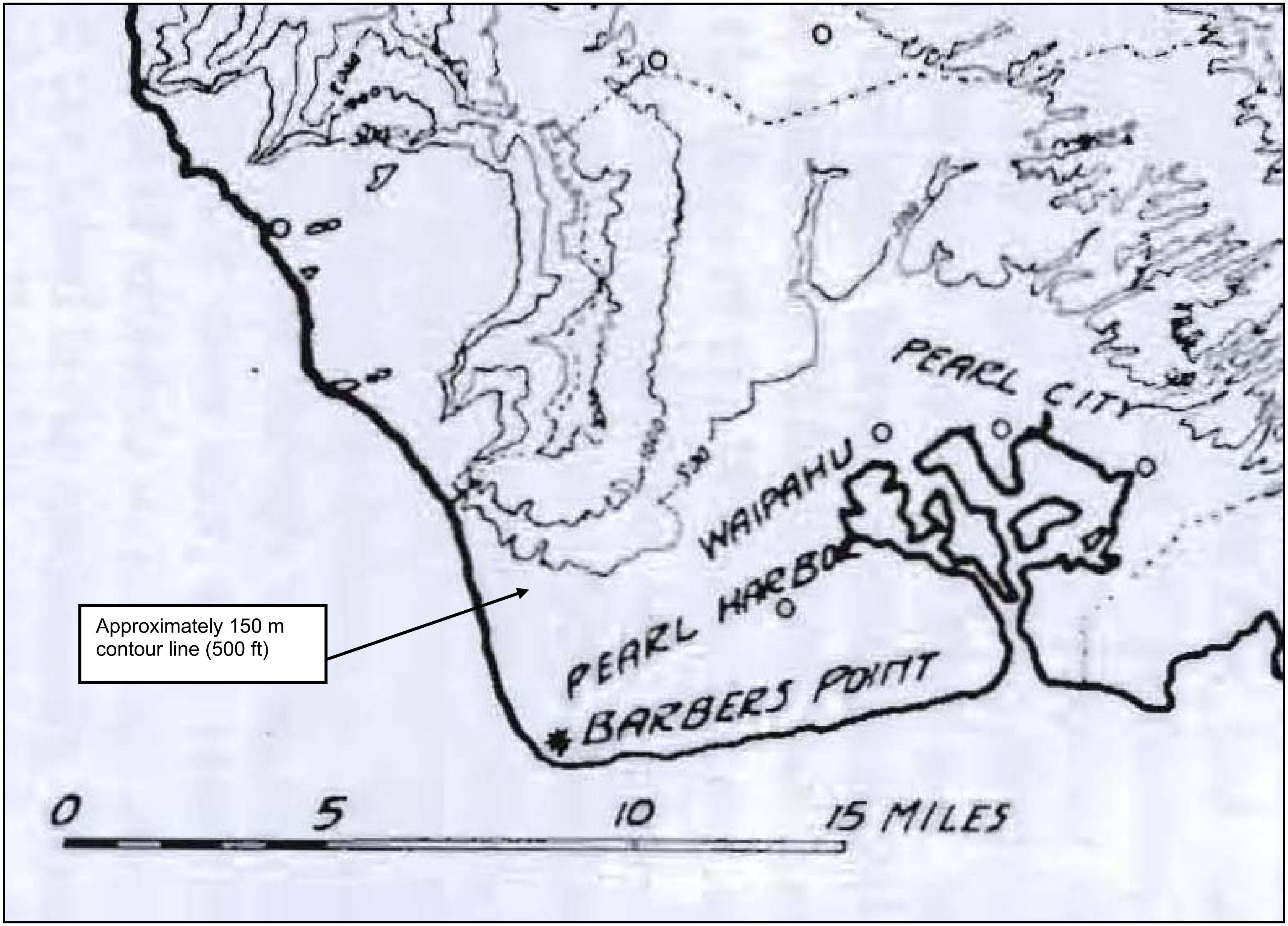


Figure 7: An excerpt from Pollock (1929) showing the “original shape” of the Pearl Harbor bay. According to Pollock (1929), the 150 m contour line represents the original shape of the Pearl Harbor bay and therefore the landforms presently in Pearl Harbor are a result of marine deposits being shaped by wave and tidal erosion and sea level changes (Source: Pollock, 1929).

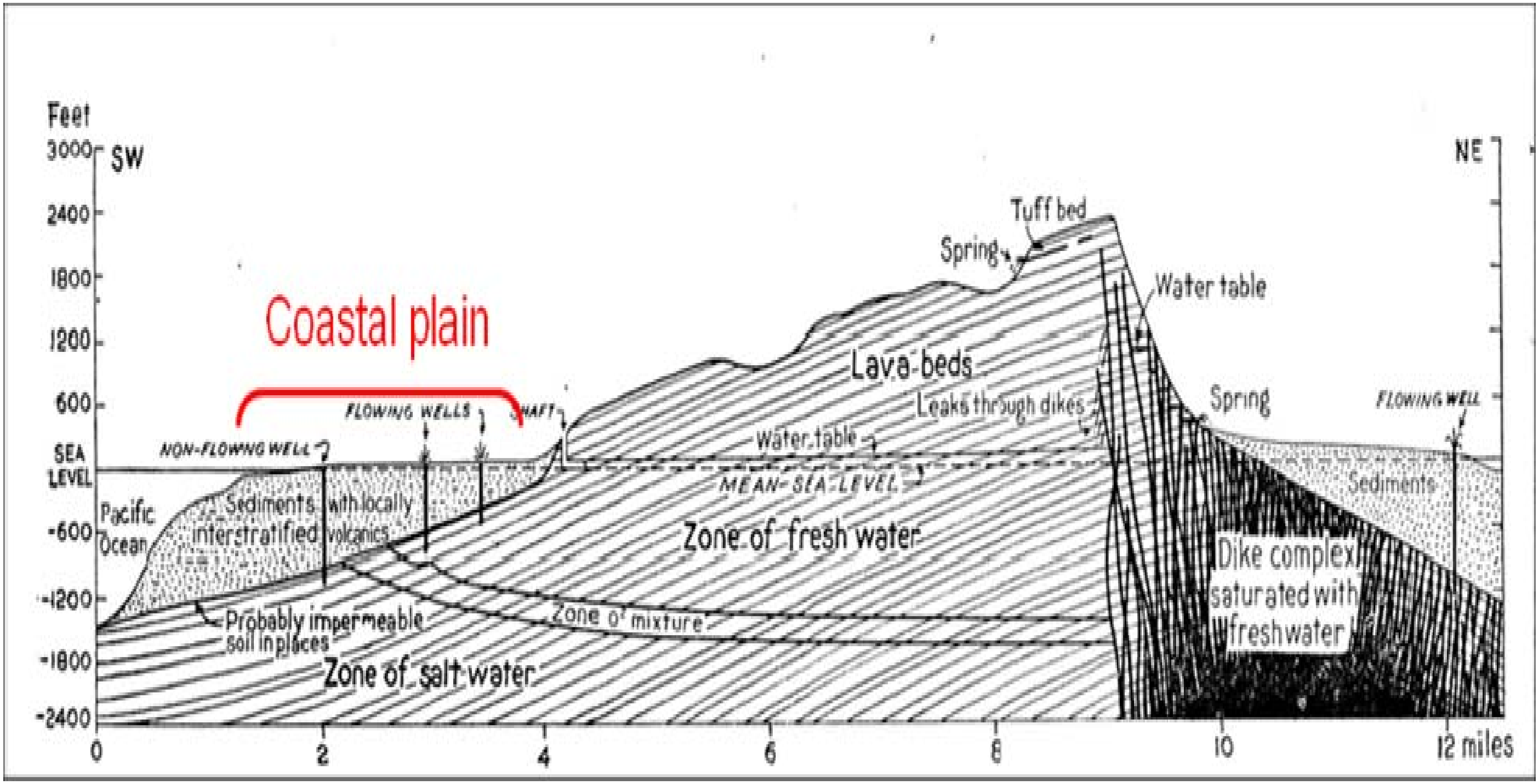


Figure 8: A cross-section of the Ko'olaus. The coastal plain is shown on the southwest and northeast sides. Stearns and Vaksvik (1935) indicated the coastal plain reached a thickness of at least 365 m, part of which is above sea level (Source: Stearns and Vaksvik, 1935).

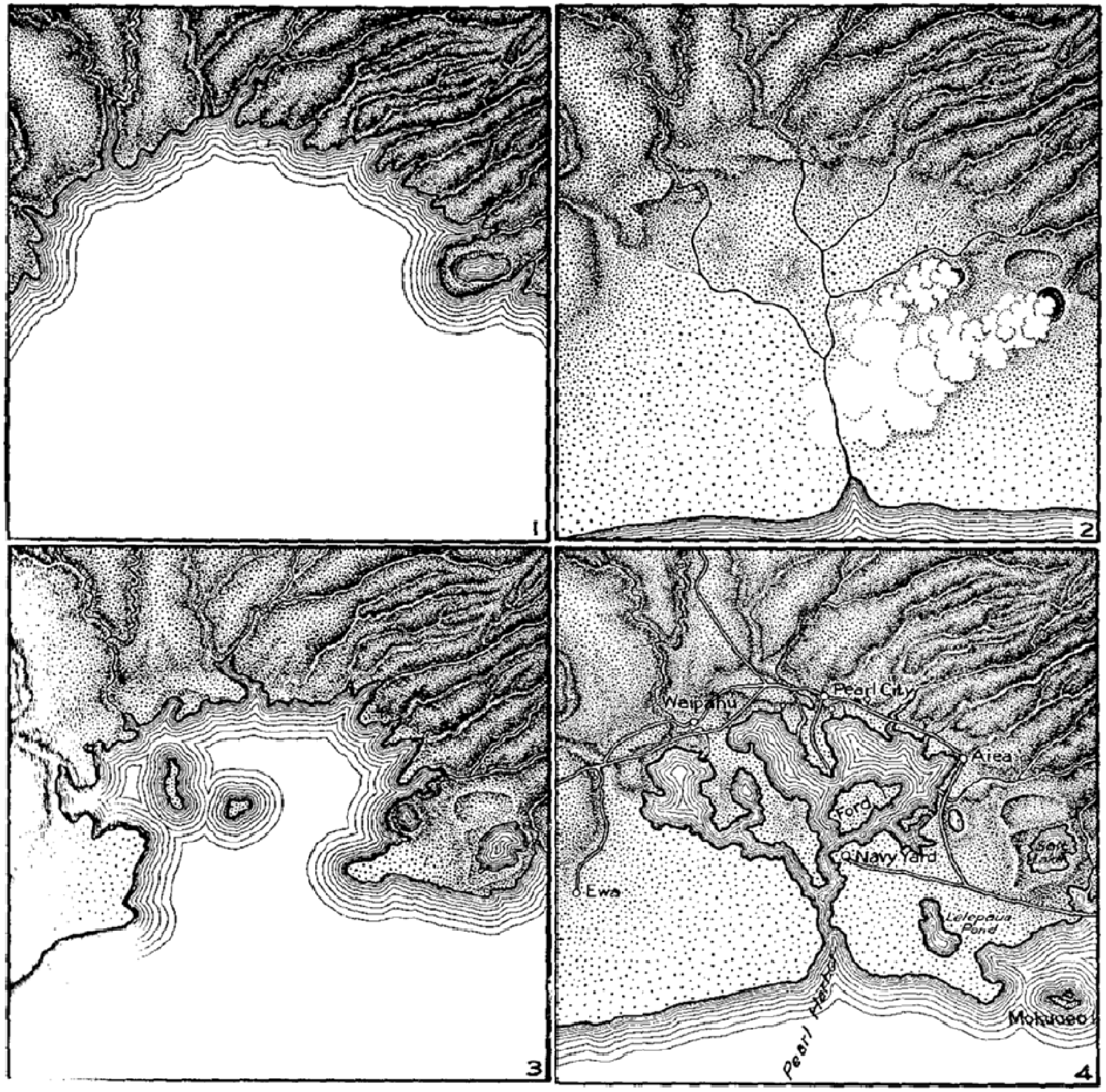


Figure 9: 1939 diagram showing geologic history of Pearl Harbor. Each frame is described below as interpreted in 1935 (Source: Stearns, 1939):

1. Deposition of calcareous and noncalcareous sediments during a period of high sea level preceding the Waipiʻo stand. The Waipiʻo stand was thought to have occurred approximately 350,000 years ago (Gavenda, 1992).
2. Sea receded to about 18 m below present sea level. Valleys are cut by streams in the approximate position of the present lochs. Tuff is deposited by eruptions at Salt Lake craters.
3. Submergence to about 7.6 m above present sea level and drowning of valleys to form an ancestral Pearl Harbor. Irregular reef patches on former stream divides grow and noncalcareous sediments are deposited near shore.
4. Recession of ocean to present level, causing the exposure of irregular patches of reef where former divides existed. Widening of lochs by wave action, especially near their heads, where soft silts occurred instead of hard limestone, and formation of deltas at the mouth of each valley.

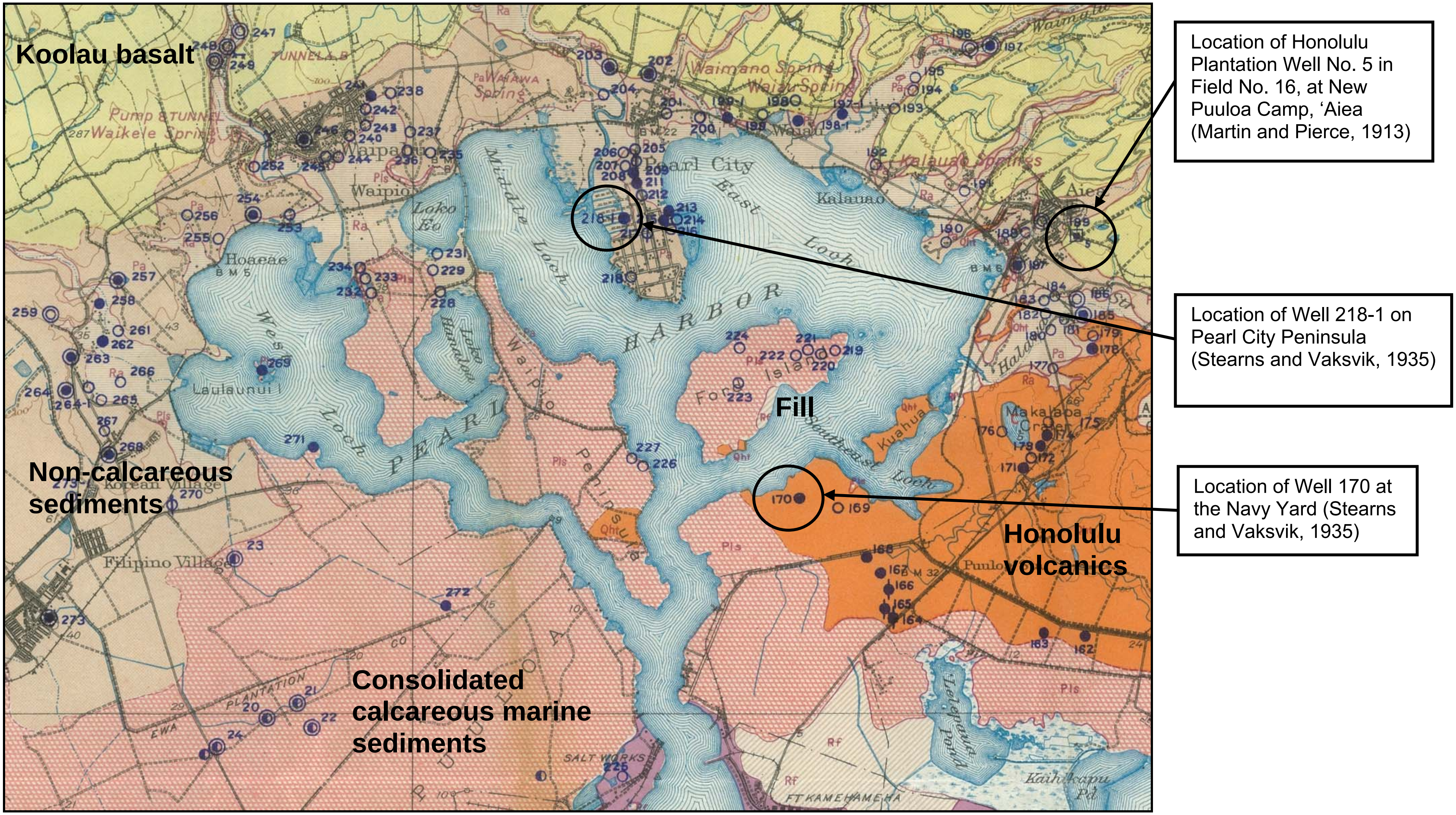


Figure 10: Geologic map of Pearl Harbor and Ford Island. Three geologic units occur on Ford Island, Consolidated calcareous marine sediments (Pls), Honolulu volcanic series (Qht), and Artificial fill composed of marine deposits (Rf). These units also compose the majority of the geology for the surrounding lands at Pearl Harbor. Also shown are the nearest well locations with available borelog information (Source: Stearns, 1939).

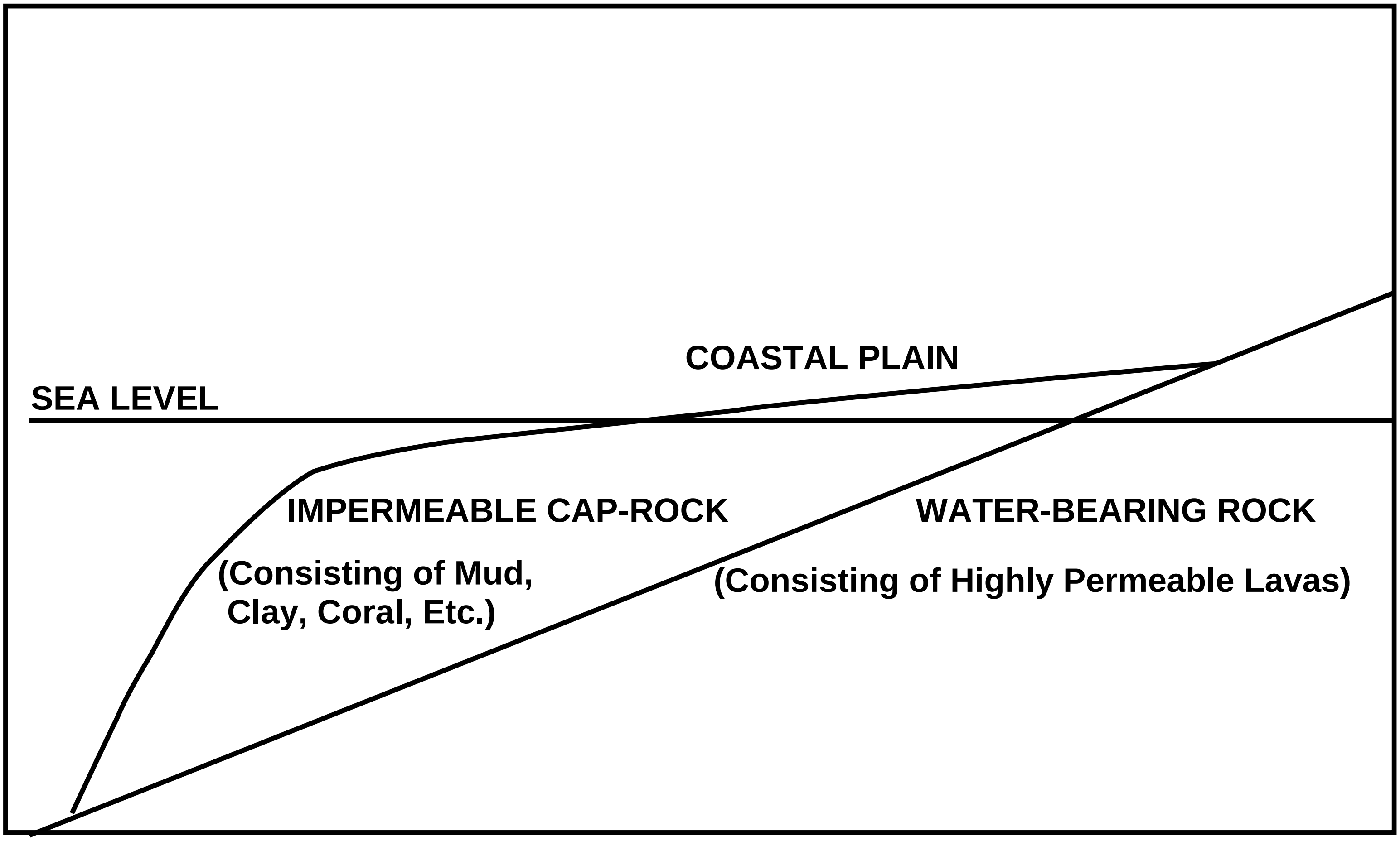


Figure 11: Diagram showing cross-section of the coastal plain and caprock at Honolulu (not to scale) (Source: Palmer, 1946).

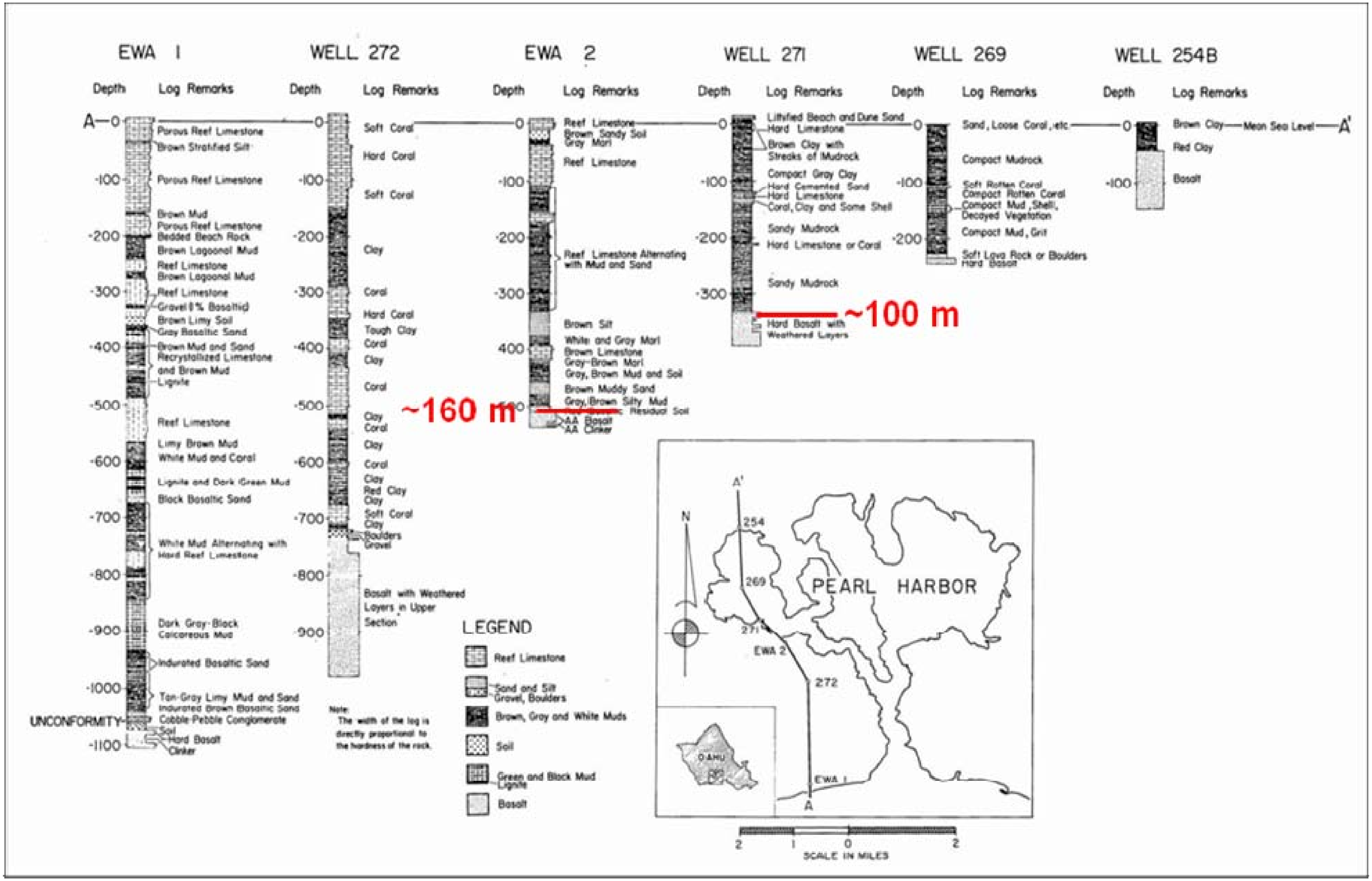


Figure 12: From Stearns and Chamberlain's 1967 publication, this figure shows the location of the North to South geologic cross-section across the Ewa Coastal Plain, O'ahu, which include borings Ewa 1 and Ewa2 (Source: Stearns and Chamberlain, 1967).

Figure 13: Location of the landfill on Ford Island. In 1993, Ogden Environmental and Energy Services Co., Inc. completed a site inspection for the landfill and described its geology as consisting of lithified to semi-lithified limestone overlain with fill.

.

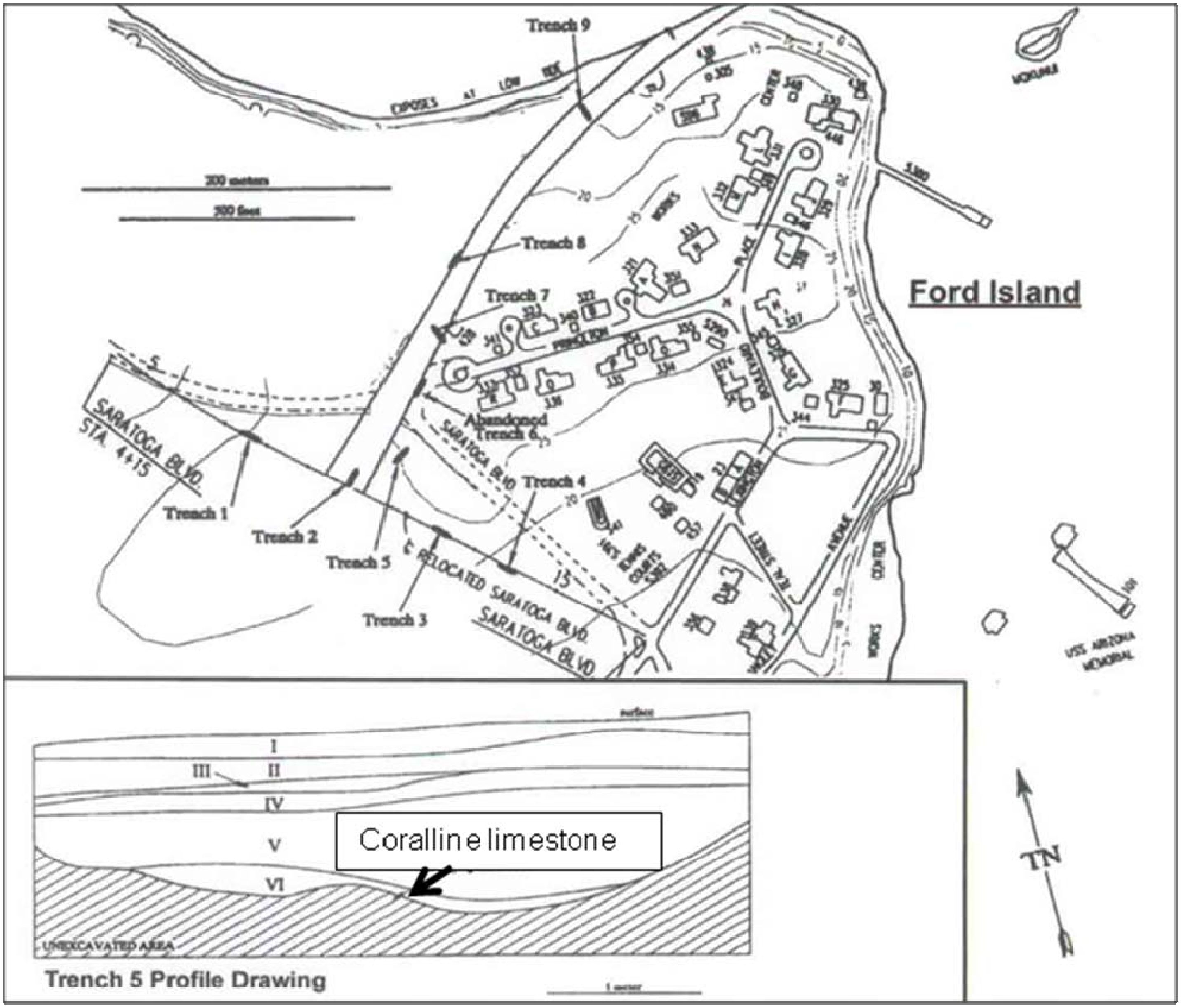


Figure 14: Trench locations at the northeast end of Ford Island in support of an archaeological study for re-development of the island. The northeast end of Ford Island has the highest elevation on the island (~8.5 m above present sea level). Trench depths averaged 0.8 m and encountered limestone bedrock overlain with clay, sand, and loam (Source: Erkelens, 1995)

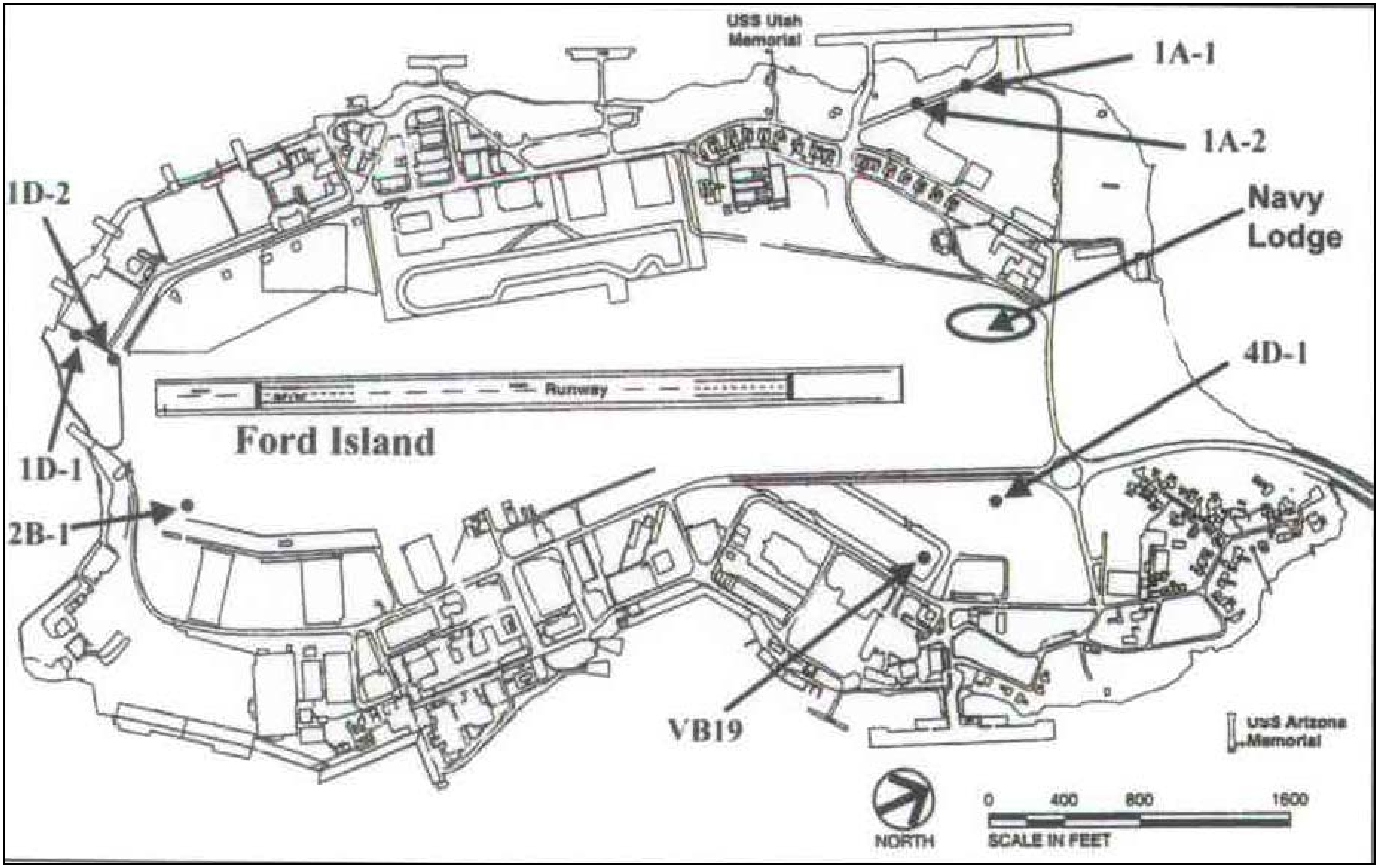


Figure 15: Trench locations at the Navy Lodge and various aviation gasoline pipeline sections for the Archaeological Monitoring Plan. Trenches averaged a depth of 2 m and encountered limestone bedrock overlain with clay and fill (Source: Department of the Navy, 2003).

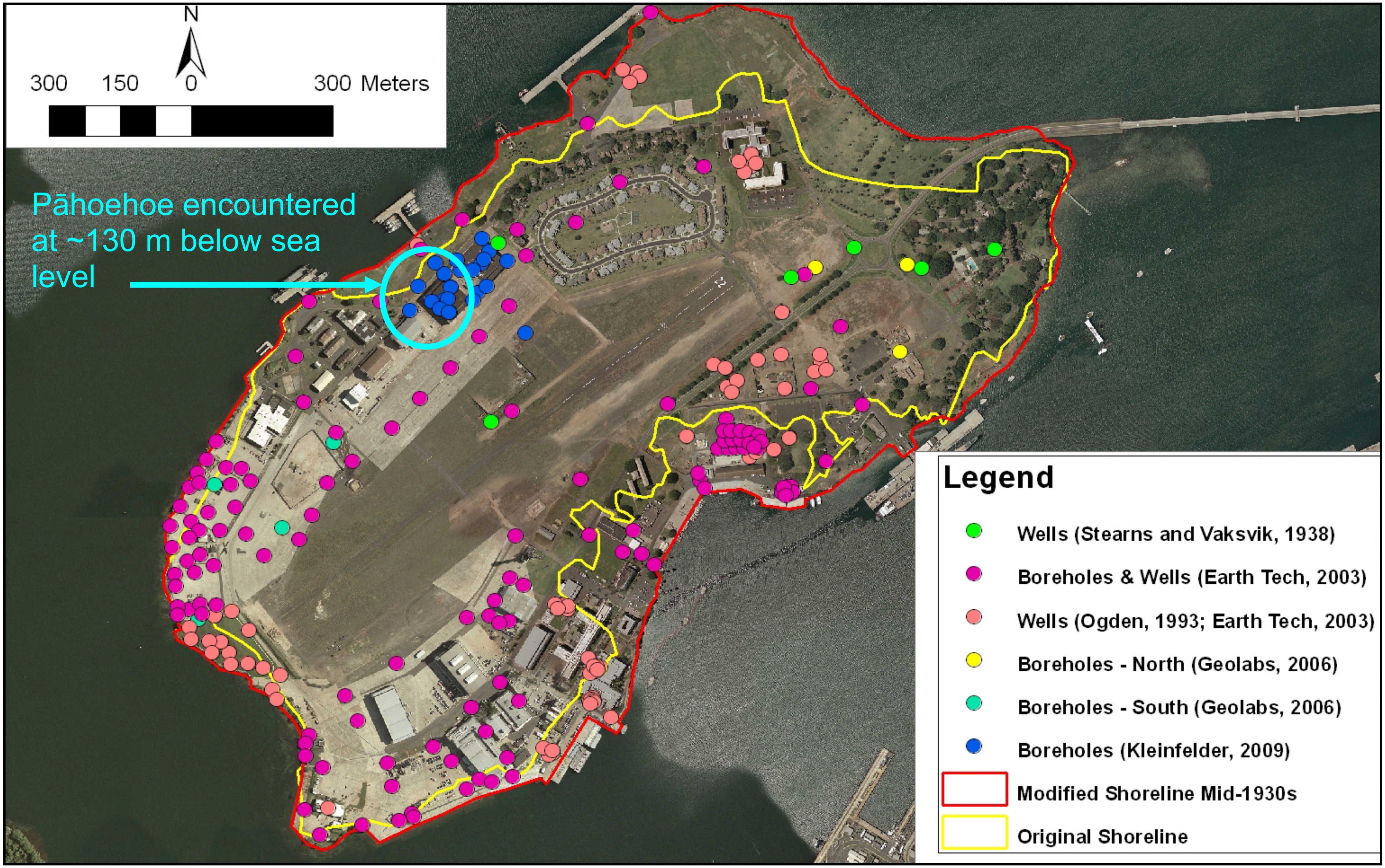


Figure 16: Present day (2004) Ford Island with borehole locations and historic shorelines.

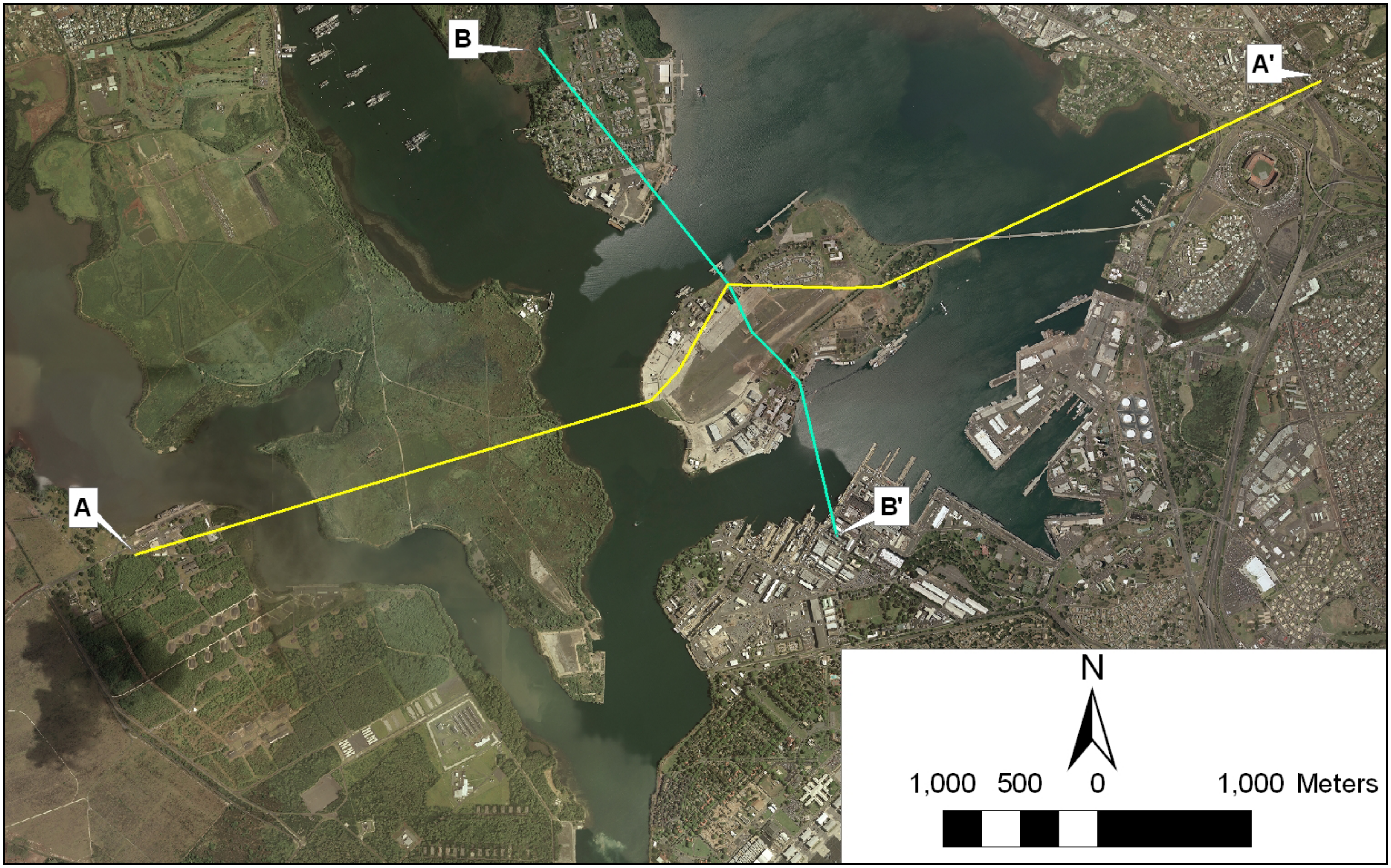


Figure 17: Cross-section locations. Cross-section A-A' goes from the Ewa 2 boring to Ford Island and ends at the Honolulu Plantation Well in 'Aiea. Cross-section B-B' goes from Well 218-1 on Pearl City Peninsula to Ford Island and ends at Well 170 in the Navy Yard.

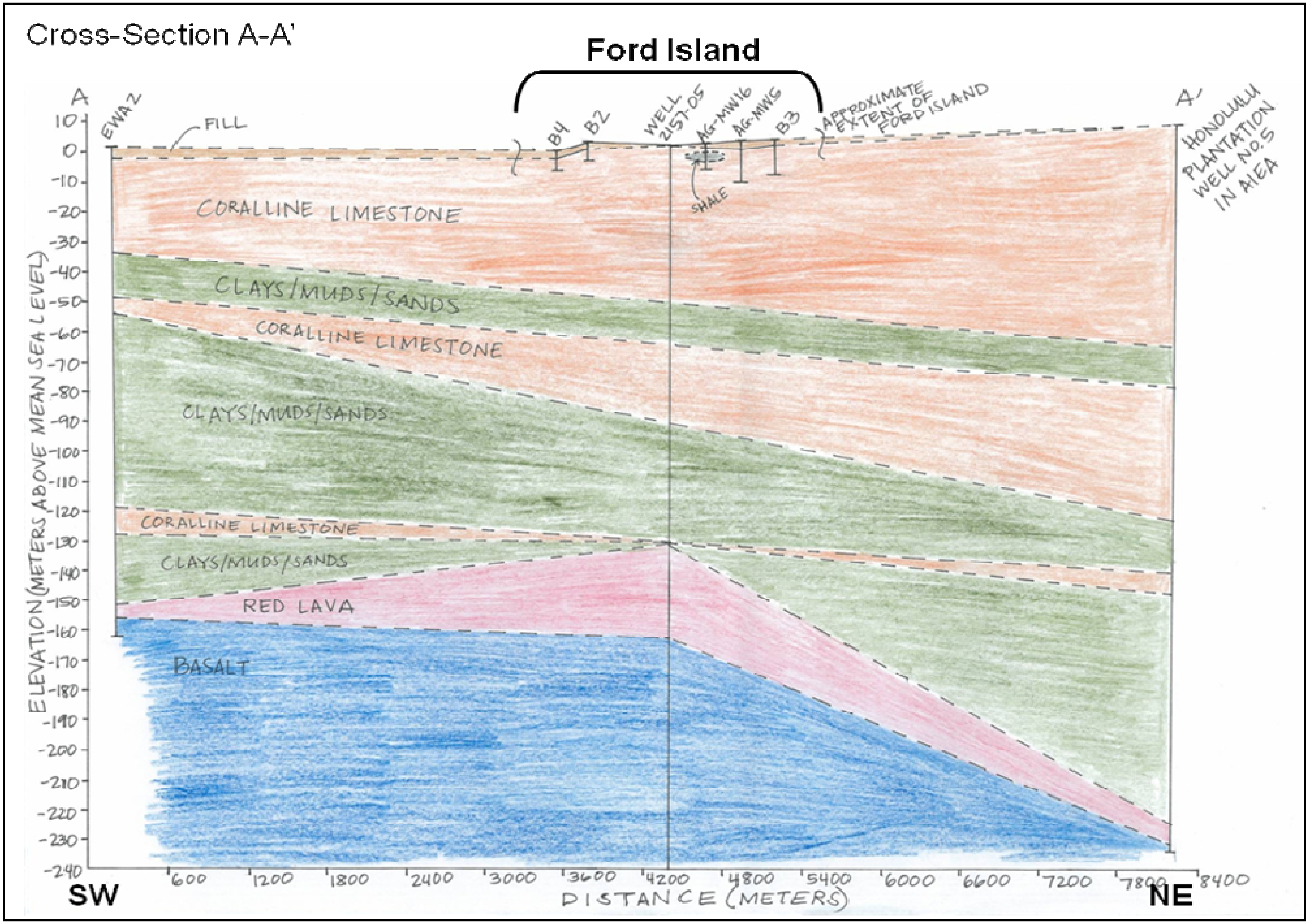


Figure 18: Cross-section A-A' showing borings on Ford Island and borings from Martin and Pierce (1913) and Stearns and Chamberlain (1967).

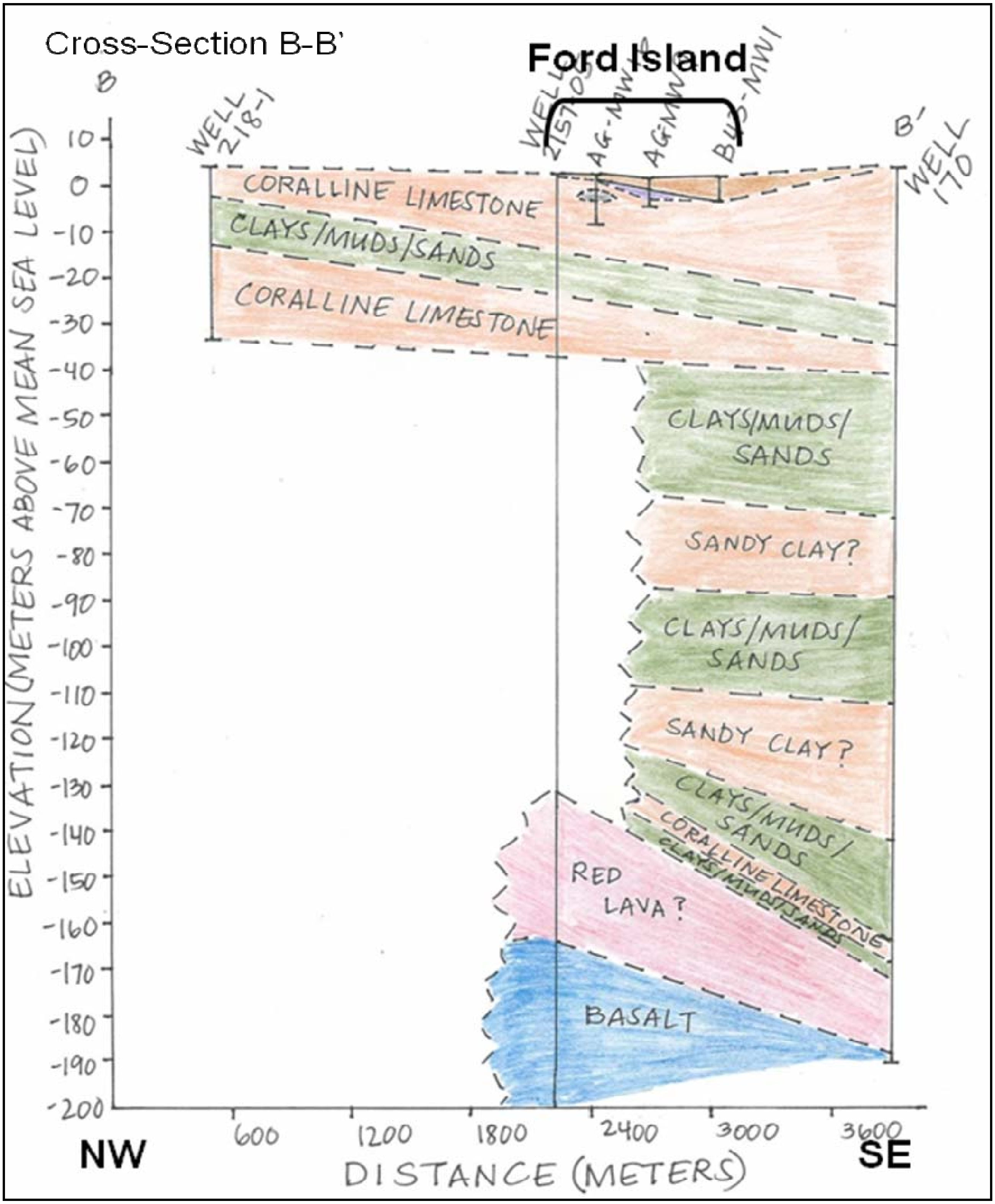


Figure 19: Cross-section B-B': Goes from Well 218-1 on Pearl City Peninsula to borings on Ford Island and ends at Well 170 at the Navy Yard

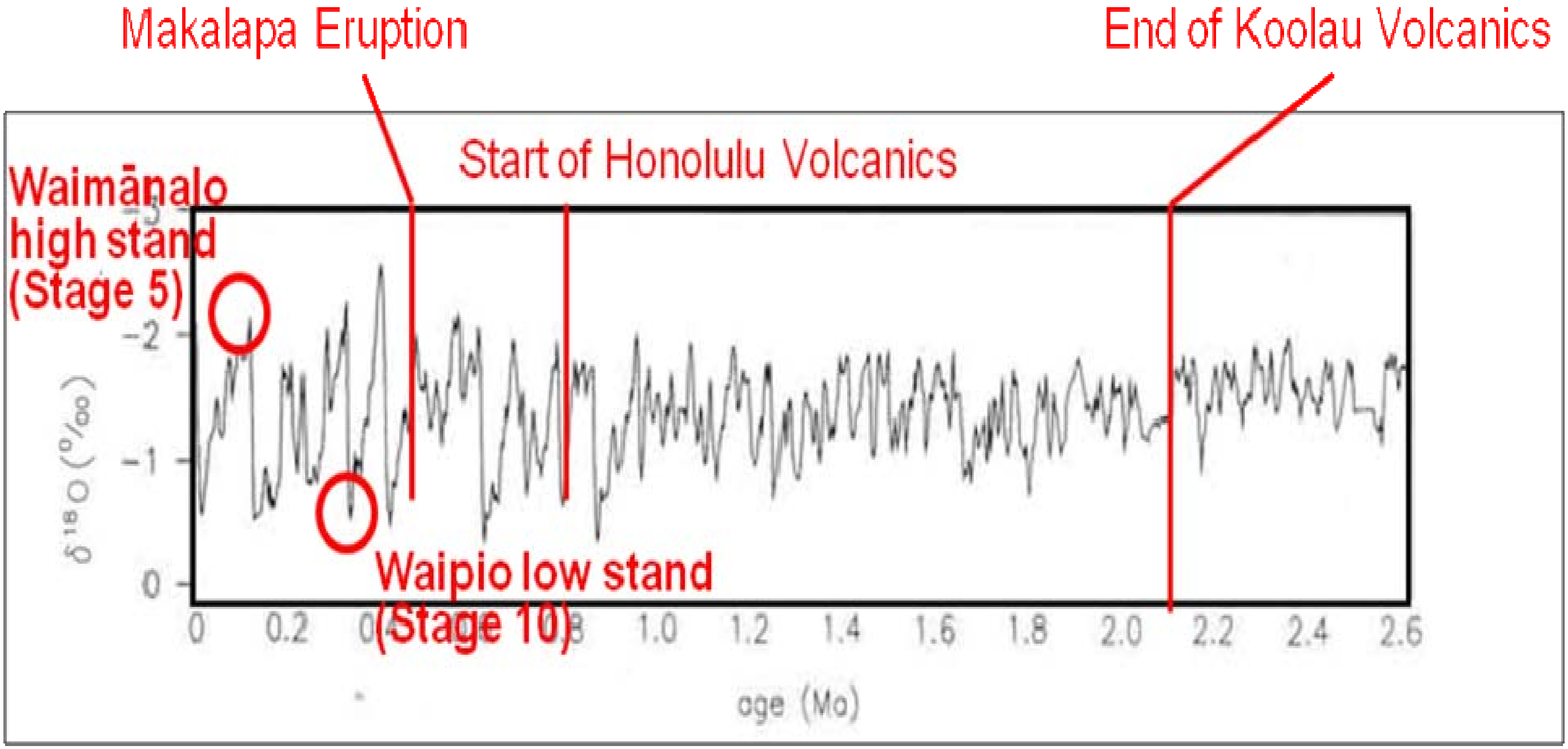


Figure 20: Planktonic oxygen isotope data for the past 2.6 million years for ODP 677 (Source: Shackleton *et al.*, 1990). Marine isotope stages (MIS) are alternating warm and cool periods in the Earth's paleoclimate; and are deduced from oxygen isotope data such as the planktonic oxygen isotope data shown above. The isotope data reflect temperature curves and corresponding sea levels.

.

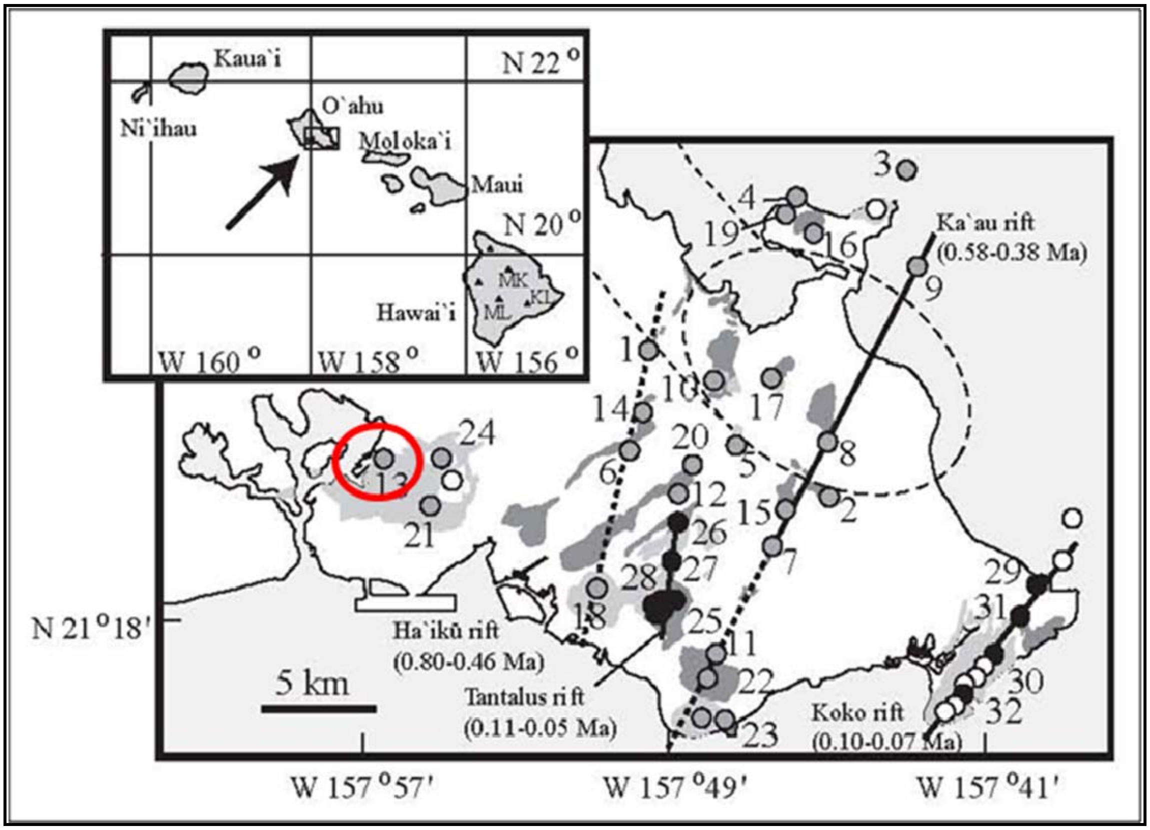


Figure 21: Locations of vents, flows, and tephra from Honolulu eruptions (Source: Ozawa *etal.*, 2005). The red circle indicates the Makalapa eruption which occurred 470,000 ± 60,000 years ago.

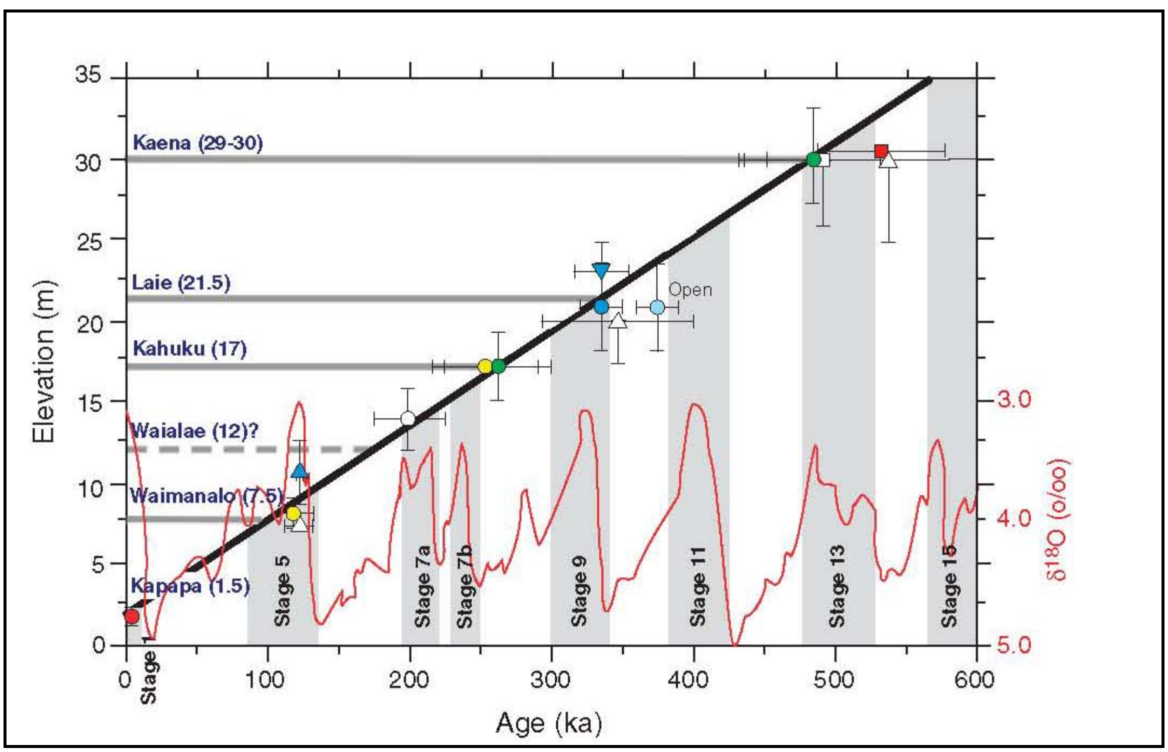
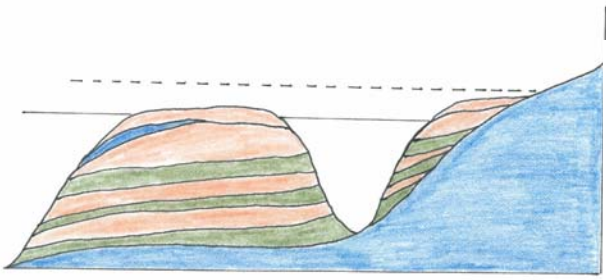
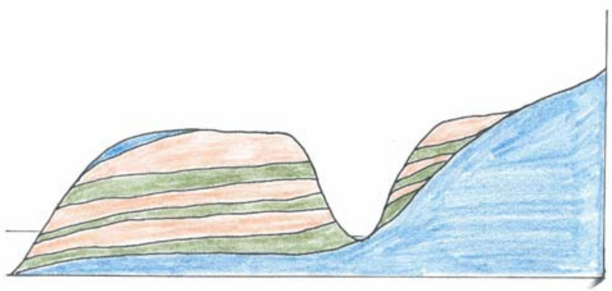


Figure 22: Mean or best ages versus maximum measured terrace elevation for known elevated reefs on O'ahu, Hawai'i. Age ranges for late Pleistocene interglacial periods (shaded bars) and benthic δ^{18} O curve (red line) are also shown derived from proxy compilations as well asHawaiian sea stand names and maximum elevations (Source: McMurtry *et al.*, 2010)

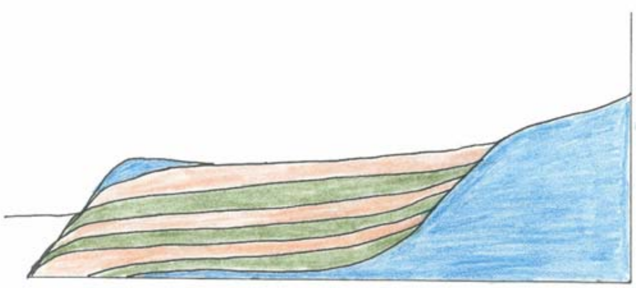


(d) 125,000 years ago - Waimanalo reef deposited when sea level is 7 m higher than present.

Sea level rises to present sea level, flooding the valleys and isolating Ford Island. Fill is later added to the perimeter of the island.

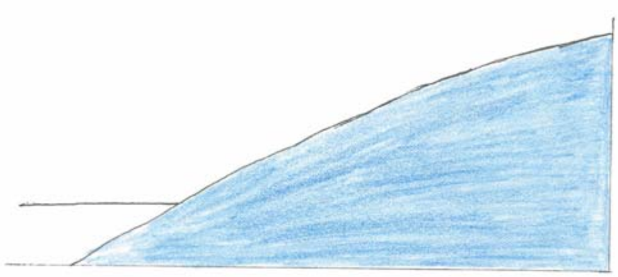


(c) Valleys cut and widened during sea level low stands (one or more of Marine Isotope Stages 12, 10, 8, 6)



(b) Continued (but slowing) subsidence, sea level fluctuates, producing interbedded coral and sediment.

470,000 ± 60,000 years ago - Makalapa crater erupts (Ozawa, 2005), depositing ash and lapilli. Sea level was approximatey 80 m below present. Uplift occurs at a rate of 0.020± 0.003 m/kyr (Hearty, 2002).



(a) 2.1 million years ago - Koʻolau volcanics ended (Ozawa, 2005), eustatic sea level approximately 25 – 50 m higher that today and volcano subsiding.

Figure 23: Diagrams illustrating the geologic history of Ford Island (in reversed chronological order and not to scale).