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APPLICATION OF ELECTRIC WELL LOGGING AND OTHER WELL LOGGING METHODS IN HAWAII

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November 1969

Water Resources Research Center

University of Hawaii, Honolulu, Hawaii

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APPLICATION OF ELECTRIC WELL LOGGING AND OTHER WELL LOGGING METHODS IN HAWAII

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ABSTRACT

In 1966, the Water Resources Research Center initiated a comprehensive study of electric well logging and other geophysical well-logging techniques in Hawaii. The primary objectives of this study were to determine what results could be obtained by the use of conventional electric and geophysical well-logging methods under Hawaiian conditions and to collect as much basic geologic, hydrologic, and geometric information as possible from wells in Hawaiian aquifers. The functions logged include spontaneous potential, point resistivity, short and normal resistivity, lateral resistivity, water temperature, water conductivity, and caliper.

Resistivity logging in Hawaii produced much important qualitative information and some quantitative information. Resistivity logs from wells in basaltic aquifers indicate the location, number, thickness, and total thicknesses of permeable and less permeable formations and are extremely useful as indicators of water-yielding zones. High resistivities generally are indicative of dense impermeable basalts and low resistivities are indicative of porous permeable zones most likely to contribute water to the borehole. The logs also provide a direct measurement of depth to water, depth of casing, and depth of hole.

Spontaneous potential logs sometimes are inconsistent and unreliable and are used primarily for correlation with other logs.

Conductivity and temperature logs provide a direct quantitative measure of water conductivity and water temperature and provide considerable insight into the depth, thickness, quality, and temperature of waters contained in the wells of Hawaii. Borehole conductivity and temperature data also aid in the interpretation of the complex dynamic Ghyben-Herzberg lens relationships.

The caliper module, which provides a measure of the well diameter, has been subject to frequent mechanical breakdown, however, recent alterations of the caliper module's design should allow the device to perform to its expected capability.

Borehole photography employed recently by the Board of Water Supply provides positive identification of most Hawaiian rock types. Correlation between the photologs and electric logs is very good.

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INTRODUCTION

Background of Study

In spite of their almost universal application to oil-well development and analysis and their extensive application elsewhere to water development and analysis, the application in Hawaii of geophysical well-logging techniques, prior to 1966 has been limited to crude temperature, water conductivity, and flow logging. Electric logging techniques had not been tried at all because of the high costs of the equipment and the uncertainty of the results that might be obtained. Owing to the peculiarities of Hawaiian geology and hydrology, it was anticipated that techniques found useful in Hawaii might differ materially from those useful in continental areas. Although general expectations could be stated as to parameters of interest from the known characteristics of Hawaiian aquifers, most of the techniques of geophysical well logging are so highly empirical that only experience could indicate with certainty which would be of use.

Objectives

The geophysical well logging study had the following basic objectives:

1) Determine what results could be obtained by the use of conventional electric well-logging methods under Hawaiian conditions.
2) Determine which of the conventional methods have possible practical utility in Hawaii.
3) Investigate, if time and funds permit, some of the well-logging methods that are less conventional, but for theoretical reasons seem to have possible special applicability.
4) Provide resistivity data for correlation with the U. S. Geological Survey's surface resistivity program at Moluleia, Oahu.
5) Complete the conversion of the Ewa Beach Test Well for hydrologic monitoring as well as for obtaining electric well logs for correlation with its complete cores.
6) Train personnel from agencies concerned with ground-water

development and well problems in the field and in analytic techniques of electric well logging.

Conduct of Study

The investigation, on which this report is based, was begun in the fall of 1965 with a review of electric well-logging parameters and equipment of probable utility in Hawaii (Cox, 1965). Plans for the project itself were formulated in December 1965.

The Board of Water Supply of the City and County of Honolulu provided a grant to begin work in April 1966, the basic logger, which included spontaneous potential and resistivity probes, was purchased.

Late in 1966, a conductivity-temperature probe was received. However, owing to persistent circuit problems this instrument did not perform satisfactorily until overhauled by the manufacturer a procedure which took several months.

By the end of 1966, when a progress report was prepared (Lao, 1967), facility with logging techniques were developed, 34 wells and test holes on Oahu were logged, and useful initial correlations were established between electric logs and driller's and geologic logs.

In 1967-68, the Honolulu Board of Water Supply provided additional support to continue the Oahu work and, in addition, purchased a caliper tool. The support was supplemented by a smaller grant from the Division of Land and Natural Resources, by means of which some work was done on Kauai.

In total, 65 wells were logged in the study, including 53 on Oahu and 12 on Kauai, and since the project was formally ended in June 1968, the Honolulu Board of Water Supply has logged approximately 25 more new wells. Several wells were logged more than once to obtain all the logging data possible, and 4 deep monitor wells on Oahu have been logged periodically for salinity and temperature.

When active work on the project was terminated in June 1968, the logging equipment was transferred to the Honolūlu Board of Water Supply for operation and maintenance. It will remain available for use by all interested parties, however, and the Water Resources Research

Center has retained title to the basic equipment so as to be free to use it for future research.

Accomplishments and Scope of Report

The emphasis of this report is on methodology in geophysical well logging and well-log interpretation developed by the project for use in Hawaii. Illustrative logs are presented with interpretation but no attempt is made to present interpretations of all of the logs obtained during the course of the investigation. However, Appendix I shows the location of all of the wells logged in this study, and Appendix II includes a list of all the surveys conducted and comments on all the wells for which there are electric logs. All of the master logs from this study are on file at the Water Resources Research Center and copies are on file at the Honolulu Board of Water Supply. Copies of logs of wells not owned by the Board of Water Supply are being provided to the owners. All of the logs are available to interested parties upon request.

Several wells were logged in the vicinity of Mokuleia, Oahu to provide correlation with the U. S. Geological Survey's surface resistivity program in this area. The results from these logs are included in the summary of resistivities from well logging in Table 2 in the section entitled, "Electric Well Logging Procedures and Results in Hawaii." In general, good correlation was achieved.

Results of the conversion of the Ewa Beach Test Well to hydrologic monitoring, including electric logs of that well, have been reported elsewhere (Cox and Lao, 1967). The electric logging results are, however, discussed further in this report.

Training personnel of other governmental agencies to operate the logger thus far has been limited to the Honolulu Board of Water Supply. Because of project committments of the other agencies, neither time nor personnel could be committed to the well logging project for the required time. Nevertheless, other agencies concerned with the development of ground water in Hawaii will, it is hoped, avail themselves of training opportunities in the future.

GEOLOGY AND GROUND WATER OF OAHU AND KAUAI

Because the geophysical well-logging program has been restricted, to date, to the islands of Oahu and Kauai, only the geology and ground-water or these islands will be discussed here. Hydrogeologic conditions on the other Hawaiian islands are similar. Furthermore, the discussion of the geology and occurrence of ground water presented here is quite brief, and is intended to provide only the general background necessary for the interpretation of geophysical well logs. If more detailed information on the subjects is desired, the following references should be consulted: Stearns and Vaksvik (1935, 1938), Stearns (1939, 1940), Wentworth (1938, 1940, 1941, 1942, 1945, and 1951), Stearns and Macdonald (1942, 1946, 1947), Macdonald, Davis and Cox (1960), and Visher and Mink (1964).

Geology of Oahu

The island of Oahu, Hawaii consists essentially of two eroded shield volcanoes, the Waianae volcano to the west and the Koolau volcano to the east. Each volcano is composed primarily of thin basaltic lava flows, dipping away from axial rift zones. The Schofield plateau, between the two volcanoes, was formed by the ponding of late lavas from the Koolau volcano against the eroded lower slopes of the Waianae volcano. The margins of the volcanic mountains are overlapped by prisms of coastal plain composed of sediments of terrestrial and marine origin which were deposited during the long period of quiescence following the active Waianae and Koolau volcanic periods. Sea-level changes caused by isostatic adjustment of the earth's crust in response to the island mass during Pleistocene time greatly influenced the construction of these coastal plain deposits. A restricted renewal of volcanism resulted in small areas of the southeastern portion of the Koolaus being covered by the Honolulu volcanic series. These rocks, formed during the later period of shifting sea levels and continued down to recent time, comprise Diamond Head, Punchbowl, Koko Head, Tantalus, Kaimuki, etc.

The principal water-bearing rocks of Oahu are the lava flows of the Koolau and Waianae volanic series. Lavas and pyroclastics of the Honolulu series are so limited in extent that they are relatively unimportant as aquifers. The Koolau and Waianae series include both pahoehoe and aa flows, which are generally less than 20 feet thick and normally have dips less than 10 degrees. These lavas are remarkably uniform in composition and all, except the latest Waianae flows and a 400-foot thick Waianae trachyte flow at intermediate depth, are classified as tholeiitic basalts. The Honolulu series and the youngest Waianae lavas are alkalic basalts which form relatively thin caps over the tholeiitic basalt shields.

The permeability of unweathered Hawaiian lavas is generally high, but it is also quite variable on a coarse scale owing to the effects of major flow structures such as clinker zones in aa, lava tubes and gas cavities in pahoehoe, vertical contraction joints formed by cooling of the lavas, and irregular openings associated with the surfaces between flows.

The rift zones of the Koolau and Waianae volcanoes contain many vertical or steeply dipping dikes which cut through the lava flows. In the central portions of the rifts, the dikes are closely spaced and almost completely replace the lava flows. Toward the outer edges of the rift zones the dikes are more widely spaced and form large compartments which enclose permeable lavas. Because the dikes are dense and have low permeabilities, ground water may be impounded within these compartments.

The principle pyroclastic materials on Oahu consist of cinders, ash, and tuff. These materials generally have little importance as aquifers owing to their limited extent and volume although an area in the Makiki district underlain by permeable cinders is an important intake area for a small perched supply for Honolulu. However, weathered ash and tuff, because of their extremely low permeabilities, act as perching members over small areas, especially in the Honolulu volcanic series.

The wedges of coastal plain sediments are composed of both terrestrial and marine sediments, including boulder conglomerate, mud, reef rock, calcareous sands, beach rock, and eolianite. Overlying or interbedded with the sediments in places are pyroclastic rocks and flows of the Honolulu series. Alluvium and marine sediments comprise the greatest volume of the wedges, which at the coastal margins of southern Oahu have thicknesses of over 1,000 feet. Although the permeability of the components of the coastal wedge varies widely, the overall effect is one of low permeability compared to the basalt. The coastal sediments contain large quantities of water, varying from fresh to sea water. Compared to the basalt aquifers, however, the capacity of the wedges to store and transmit water is small. Consequently, the wedges act as a caprock retarding the seaward movement of fresh ground water from the more permeable underlying basaltic aquifer.

Ground Water on Oahu

Replenishment of the Oahu aquifer system comes primarily from precipitation incident on upland watersheds. The Koolau and Waianae Ranges force the moisture-laden trade winds to rise, cool, and precipitate. The windward flanks of the mountain are substantially wetter than the leeward flanks and the higher elevations wetter than low-lying areas. Infiltration capacities of the soils and rock are very high.

Two modes of occurrence of ground water may be distinguished on Oahu: high-level ground water and basal ground water. Dikes in and near the rift zones of the Koolau and Waianae volcanoes impound large volumes of fresh water. The compartments formed by the dikes are commonly saturated to levels several hundred feet above sea level and natural discharge often occurs in the form of high-level springs. Other high-level water is perched on beds of weathered ash, tuff, soil, and thick sills or flows. Perched water makes up only a very small part of all high-level water.

The principal source of fresh ground water on Oahu is the lens-shaped basal water body, commonly called the Ghyben-Herzberg lens, floating on denser salt water. The basal water body is largely unconfined in the interior portions of the island. Where the basaltic aquifer is directly overlain by the sedimentary caprock along the coastal margins, artesian heads of a few feet to over 20 feet above sea level commonly occur.

When steady-state conditions exist, the location of the bottom of the fresh-water lens floating on sea water is dependent on the relative densities of the two liquids, and a sharp interface may exist. However, in most natural situations steady-state conditions are not achieved. Because of constant movement of the interface between fresh and salt water owing to tidal fluctuations, seasonal fluctuations in recharge and discharge, and discharge caused by pumping, mixing of the salt and fresh water takes place and the salt-water grades upward into fresh water forming a zone of transition. On Oahu, the depth to the bottom of fresh water is normally a few tens to many hundreds of feet. The thickness of the transition zone varies from 200 feet in the Punaluu area in northern Oahu to as great as 1,000 feet in the Kaimuki (Lau, 1967) and the Pearl Harbor areas (Visher and Mink, 1964). Furthermore, the center of the transition zone may be displaced from its equilibrium position for considerable lengths of time (Wentworth, 1951; Cox, 1954).

Geology of Kauai

Kauai is a single volcanic shield, considered to be one of the oldest and structurally the most complicated in Hawaii. One of its most notable features is the broad caldera, largest in the Islands, formed near the end of the shield growth when the summit collapsed. The principal depression is 10 to 12 miles across and is underlain by depressed fault blocks. A smaller caldera occurs on the southeastern side of the dome, a few miles south of Nawiliwili Bay. In both calderas lavas ponded into thicker, more massive flows than the flank-forming basalts. Talus eroded from the fault scarps bounding the caldera are buried by the caldera-filling flows. Further collapse on the southwest side of the main caldera formed a fault-bounded depression into which poured flows from the main caldera. The shield-forming rocks are known as the Waimea Canyon series, which consists primarily of tholeiitic basalt and small amounts of alkalic basalts and basaltic andesites. The series includes the flank-forming thin-bedded flows of the Napali formation, the thick main caldera flows of the Olokele formation, the Haupu formation of the small caldera, the graben-filling flows of the Makaweli formation, and sediments associated with the Olokele and Makaweli formations. A late collapse is considered to be the cause of a large depression on the eastern flank of the volcano.

Renewed volcanism following a long period of erosion resulted in the eruption of lava, cinders, and ash over the eastern two-thirds of Kauai. The resulting rocks are known as the Koloa volcanic series and include cinder cones, one tuff cone, and lava cones. The lavas are alkalic basalts contrasting with the predominantly tholeiitic basalts of the Waimea Canyon zones. The period of volcanism was long but not continuous over the entire area, allowing areas to become eroded and re-covered again by new flows. The latest flow appears to be very recent.

During the erosion period preceding, during, and following the Koloa series eruptions, coastal plain sediments similar to those on Oahu accumulated around the most of the margins of Kauai. Much of the coastal plain has been deeply buried by the Koloa series volcanics. Inland, the Koloa series flows and pyroclastics are interbedded with extensive alluvial deposits.

Ground Water on Kauai

The Napali formation is highly permeable and contains fresh basal water almost everywhere toward the margins of the island and dike-compartmented water inland in some areas. The basal water is impounded in most areas, contained by coastal plain sediments or by the less permeable rocks of the Makaweli formation and the Koloa volcanic series. The caldera-filling lavas of the Olokele and Haupu formations are generally poorly permeable and yield little water. The Makaweli formation is poorly to moderately permeable. Locally, small bodies of fresh water are perched on interbedded conglomerates and breccias and basal water may be recovered in some areas.

The Koloa lavas are poorly permeable. As on Oahu, some members such as coral reefs are permeable, but most contain only brackish water and are of only local importance.

WELLS AND PREVIOUS WELL-LOGGING IN HAWAII

Wells in Hawaii

Most wells in Hawaii fall into one of the following categories:

1) Tunnels developing water confined by dikes or perched ash or soil beds.
2) Maui wells, consisting of shafts to the water table and skimming tunnels, developing basal ground water especially where the Herzberg lenses are thin.
3) Simple pits, mostly developing water in sediments.
4) Drilled wells mainly developing basal ground water, especially artesian water, mostly in basalts (Stearns, 1939; Cox, 1954).

The techniques of well logging discussed in this report pertain only to the latter category.

There are about 750 drilled wells on the island of Oahu (Stearns and Vaksvik, 1938) and about 150 on Kauai (Macdonald, Davis, and Cox, 1960). The number of drilled wells on Hawaii, Maui, Molokai, Lanai, and Niihau is considerably smaller. Well depths range from a few tens of feet to over 1,000 feet but most of the wells in use are less than 700 feet deep and were drilled in the period from 1880 to the 1930's. All wells drilled prior to 1946 were drilled by the cable tool method. Since then about half have been drilled by the rotary method. Drilling mud has been used, in general, only in rotary drilling. Mud recovery has frequently been a problem where it has been used. Artesian wells, flowing and non-flowing, generally are cased through the sedimentary caprock and the weathered top sections of the basalt aquifer, and the fresh section of the basalt aquifer is left uncased. Non-artesian wells generally are cased to a depth of 10 to 30 feet below the water table. Drillers logs exist for only a few of the wells drilled prior to 1930 but they are fairly common for wells after that time and are required for new wells.

In addition to the production wells there are many diamond drill test holes ranging from a few tens to over 1,000 feet in depth. Most of those drilled prior to 1950 were E or EX size. AX holes have predominated since, but there are a few NX holes.

Many of the wells and test holes are lost, caved, sealed, or cased in such a way that they cannot now be probed. On many more, delivery pipes, valves, or pumps are installed in ways that make probing infeasible except in combination with major overhauls.

New wells and large diameter test holes are being drilled at a rate of 10 or 15 a year.

Types of Well-Log Information in Hawaii

Well logging, whether driller's logging, geologic logging, electric logging, or other types of logging, may be considered as having the objective of supplying the following types of information:

1) *GEOLOGIC INFORMATION*, useful in developing an understanding of the performance of a well and in planning further well development near the logged well or in other areas of similar geology.
2) *HYDROLOGIC INFORMATION*, useful in the same ways as the geologic information and in evaluating the probable performance of an incomplete or untested well.
3) *GEOMETRIC INFORMATION*, useful in designing casings, pumps, and seals or other remedial treatments.

These types of information were more or less inadequately supplied by the earlier logging techniques used in Hawaii.

GEOLOGIC INFORMATION. Geologic information desired from logging consists primarily of identifying rock characteristics which aid in the construction of geologic well logs, which are intended to identify in geologic terms the rocks penetrated by a well. Of greatest importance under Hawaiian conditions is the distinction between sedimentary rocks and impermeable lavas that most commonly act as aquicludes and the lava flows that most commonly act as aquifers. For stratigraphic analysis and for the identification of caprock aquifers, either as potential sources of water supply or as potential zones to which leakage might occur, identification of the sedimentary rocks as well as the impermeable lavas is frequently desirable. Discrimination among gravel or conglomerate, fine-grained alluvium, coral reef and rubble, calcareous sands, beach rock, aeolianite, lagoon marls and clays, and the pyroclastics, cinders, ash, and tuff is particularly useful. For distinguishing between shield-forming and post-erosional lava flows and, less commonly, for distinguishing late, differentiated, shield-forming flows (usually less permeable) from the primitive tholeiitic basaltic shield-forming lavas (usually more permeable), and for determining the stratigraphy and structure of post-erosional flows, petrographic logging of the lavas may be required. In addition, the degree of weathering of the lavas is of considerable importance, both geological and from the standpoint of interpreting the geophysical well logs.

Generally, driller's logs of churn-drilled (cable-tool) wells provide a good deal of geologic information, although some translation of drilling terms is necessary (see Table 1).

TABLE 1. DRILLER'S LOG TERMS AND EQUIVALENT GEOLOGIC TERMS.

DRILLER'S LOG TERMS	GEOLOGIC TERMS
MUD-ROCK	TUFF, WEATHERED LAVA, WELL CONSOLIDATED ARGILLACEOUS SEDIMENT
CINDERS	AA CLINKER
AA	AA CLINKER OR SCORIACEOUS OR CAVERNOUS PAHOEHOE
PAHOEHOE	DENSE PAHOEHOE OR DENSE AA
CORAL	CORAL REEF, CORAL RUBBLE, BEACH ROCK, OR AEOLIANITE
SOFT ROCK	PARTLY WEATHERED LAVA, CLINKER, OR CAVERNOUS PAHOEHOE
HARD ROCK	DENSE AA OR PAHOEHOE
BLUE ROCK	FRESHEST DENSEST LAVA

By megascopic and hand-lens study of cable-tool cuttings, in addition to the driller's log, a geologist may generally prepare a good log which may be further improved by selective petrographic analysis.

Good geologic logs rarely can be prepared for rotary-drilled wells because the origin of the cuttings cannot ordinarily be closely determined.

Most of the well logs reproduced in the bulletins of the Hawaii Division of Hydrography (*e.g.*, Stearns and Vaksvik, 1938; Macdonald, Davis, and Cox, 1960) are cable-tool driller's logs annotated by a geologist. A few were prepared on the basis of geologic examination of cuttings. Examples of other published geologic logs may be found in the reports on test wells drilled for the Hawaii Division of Water and Land Development.

The best geologic logs are those based on core drilling where direct examination of the cores or cuttings is possible. Core-drilling, mostly diamond drilling, has been used principally for small-diameter test holes. Good examples of diamond drill test hole logs are those of the 100 holes drilled by East Maui Irrigation Co. in exploration for perched water and perched artesian water (the complete logs are available only in manuscript form but Macdonald (1942) shows graphic logs based on them) and the 84 holes drilled by the Board of Water Supply in the 1930's and 1940's (the logs appear in the detailed Board of Water Supply manuscript reports by C. K. Wentworth on the geology and ground-water resources in individual districts on Honolulu).

HYDROLOGIC INFORMATION. Hydrologic information desired from logging consists of measurements or estimates of rock porosity and permeability, head, flow velocity, water salinity or conductivity, and water temperature.

Rock Porosity. There are very few significant quantitative measures of porosities of either aquifer or aquiclude material in Hawaii. Undisturbed samples of the poorly consolidated or unconsolidated sediments and of the clinkery or badly fractured lava flows are not obtainable by any of the conventional methods used in the islands for either well drilling or test-hole drilling.

Test-hole cores of the more massive parts of coral reefs, aeolianites, and beach rocks are available, but their porosities rarely have been measured because, by themselves, the measurements would be of little significance. Tens of thousands of feet of lavas have been core-drilled, but the average core recovery is probably only on the order of 30 percent. Although a few continuous cores have been limited in length only by the 10-foot length of the core barrels conventionally used, the cores recovered generally represent only the less porous and less permeable parts of the lavas. It must be recognized that, over lengths on the order of a few tens of feet, the porosity of even a single lava flow may range from a small percentage in massive sections to perhaps 50 percent in clinker beds and to 100 percent in lava tubes. Useful estimates of average permeability, therefore, are not available.

When diamond drill test hole cores are available from the well site, with experience, a hydrogeologist may be able to estimate the qualitative specific capacity of a well in lavas from the porosity of the cores and the amount of core recovery. In general, however, owing to difficulties similar to those encountered in determining porosity, significant quantitative permeability measurements are unavailable from Hawaiian wells and test-hole logs.

Bailing tests conducted during the course of drilling a cable-tool well may provide useful information on yield, but only on yields inadequate for most practical purposes. For a few wells, pump tests repeated after well deepening provide a simple sort of specific capacity log. It should be noted that the inapplicability of most well-yield formulae to Hawaiian conditions limits the exactitude with which permeabilities may be calculated from specific capacities.

Head. Driller's logs commonly provide a record of the depth to water. However, in spite of the fact that occasional notices of water level changes during drilling appear in the early well logs, drillers have customarily overlooked the possibility that the head may vary with depth and time even in what are still considered essentially isopiestic areas. Hence, there is usually only a single head measurement given, and not uncommonly based on some temporary point of reference, such as the top of the drilling platform. In cable tool wells, a record of the depth to water at the beginning of each day of drilling may be very useful if it is based on a permanent datum and if there is a negligible tidal effect or if the time is recorded so that tidal effects may be computed. Stearns and Vaksvik (1935, p. 257) give one example of a water-level log for a well at Moanalua, Oahu.

In rotary-drilled wells where mud is used, water levels are rarely of any value. The mud is intended to seal the walls of the well. Even if the seal is only partly effective, it is generally uncertain at what depth the fluid level in the well is in balance with the head outside the well, and the density of the mud results in an uncertainty in calculating the head from the fluid level. Water-level measurements integrate the effects of head throughout the depth of a well, and true head measurements as a function of depth are possible in a large-diameter well only by the use of packers, a technique that is quite uncommon in Hawaii. In small-diameter test holes, however, approximations to head measurements in the lower parts of the holes may be obtained by measuring water levels in the drill rods with the core barrel at the bottom acting as a packer.

Examples of thorough head logging of test holes may be found in the East Maui Irrigation Co. logs of the 100 diamond-drill holes at Nakiku previously referred to in the section entitled "Geologic Information," and especially for the last of the holes in which the complications of perched artesian water were encountered.

Vertical Flow in Well. Because wells usually have been considered isopiestic under static conditions, tests of flow in wells rarely are made under natural conditions. An exception is vertical flow logging in old artesian wells to detect and locate leakage out of the cased portions of the wells into coral or other permeable aquifers in the sedimentary caprocks with heads lower than those in the major bedrock aquifers. The technique has been described by McCombs (1928) and by Vaksvik (Stearns and Vaksvik, 1935). The Au propeller-type deep-well current meter described by Fiedler (see McCombs, 1928) is used. The 4-inch meter is usually mounted in a closed section of a 6-inch pipe which is run down the well on a cable to produce essentially a velocity log. The meter in its housing may be calibrated by observations while it is being raised and lowered at constant known rates. With additional baffles essentially sealing the current-meter housing to the casing on the sides of the well it may be used to approximate a flow log. Irregularities in well diameter invalidate flow measurements, however. Examples of well sealing operations in which velocity logging was used may be found in the biennial reports of the Honolulu Board of Water Supply prior to about 1950.

In the Kuhiwa well, drilled by East Maui Irrigation Co. in 1948 to test the yield of a perched artesian ground-water body, thorough use was made of the Au meter to measure both upward and downward flows. In other East Maui Irrigation Co. diamond-drill holes in the Nakiku area of East Maui, which were drilled to explore normal perched and perched artesian ground-water bodies, many flow logs were made using improvised propeller-type current meters built into core barrels. To distinguish between upward and downward flows, ball-check valves were installed in the current meters. Such valves were used in many of the East Maui Irrigation Co. Nakiku test holes.

Similar flow logs were made in the drilling exploration program for Lihue Plantation Co. on Kauai using an improvised propeller-type current meter in a housing lowered by cable. In these holes, high rates of revolution of the meter were measured by matching the tone produced in earphones connected in series with a battery and a contact closed by the propeller to a tone produced by rotating a many-toothed pinion against a reed which measured the rate of rotation of the pinion. The rate of rotation was then multiplied by the number of teeth. (Manuscript logs of these holes were prepared by the Experiment Station of the Hawaiian Sugar Plantation Association).

The location of zones of inflow and outflow in wells and their respective flow rates generally have been unattainable in Hawaiian wells except for estimates based only on the divergence or convergences indicated by vertical flow measurements.

Water Salinity or Conductivity. In spite of the critical importance of salinity, prior to 1950 there was only one salinity log run under static conditions in a Hawaiian well or test hole. There have been studies of salinity in relation to depth in groups of wells in various areas, especially in Honolulu, and logs of the salinity of water discharged from individual wells as they were deepened or plugged back (Palmer, 1927), as well as extensive records of long-term salinity monitoring on individual wells. The first log of salinity as a function of depth in an already drilled test hole was made by R. E. Hughes in a diamond-drill hole on the fair ground in Kahului, Maui (Stearns and Macdonald, 1942). This log was made by pumping water at a low rate from a small-diameter pipe as it ran into the well.

In the 1950's a number of conductivity logs were run by the Hawaiian Sugar Planters' Association in wells using a conventional bridge and a weighted cell lowered on a long neoprene-jacketed cable. The bridge used a balancing variable capacitance to balance the cable capacitance. The impedence effects required that the cable and cell be specially calibrated. The results were at least consistent, although in an absolute sense the conductivities may not have been quite accurate.

Water Temperature. The well-water temperature data available for Hawaiian wells are similar to but much sparser than the well-water salinity and conductivity data. A few temperature logs were run by using ordinary mercury thermometers, which were jacketed to slow their response, and left at various depths for extended lengths of time and raised quickly to the surface for reading. The bulk of the temperature data is for water discharging from wells.

GEOMETRIC INFORMATION. Geometric information desired from logging consists primarily of measurement of well diameter, and incidentally of measurement of depth to the water, depth of the casing, and depth of the hole.

Very little information is available on the dimensions of most Hawaiian wells except nominal casing diameters, nominal well diameters (diameter of bit), and corresponding depths. The depths reported in driller's logs have sometimes referred to temporary datums such as drill rig platforms whose elevation from the ground level were not recorded.

Well depths may easily be checked by sounding. Many wells have been found to be materially shallower than recorded, presumably as a result of backfill by cuttings and other material settling from the walls of the wells.

Steel casing depths have been checked, especially in wells to be sealed, by raising a heavy permanent magnet on a cable and noting the depth at which drag against the casing begins (McCombs, 1928, Stearns and Vaksvik, 1935).

Casing diameters have in a few cases been checked by running templates or swages on drilling tools.

FUNDAMENTALS OF GEOPHYSICAL WELL LOGGING

Geophysical well logging is the recording of various geophysical parameters associated with earth formations penetrated by a borehole. These properties are measured *in situ* by means of appropriate down-hole sondes or probes and are continuously recorded at the surface. Probably the most widely used geophysical logging technique in water wells is electric logging.

Electric resistivity well logging was first introduced by Conrad and Marcel Schlumberger in the Pechelbronn oil field in France in 1927. In 1928 the Schlumberger brothers discovered the existence of naturally generated potentials in wells (Pirson, 1963). In the years immediately following, the resistivity logging method was used in oil wells in Venezeula, Russia, Romania, and Oklahoma. In 1932, it was introduced in California and in 1933 in the Gulf Coast (Lynch, 1962). In the past 40 years, since the Schulumberger brothers first introduced the method, electric well logging has been developed primarily to meet the needs of the petroleum industry. It has been only in the past 20 years that electric logging techniques have been used in water wells.

Some types of electric logs presently in use are: single point resistivity, short and long normal resistivity, lateral resistivity, lateralog, spontaneous potential, conductivity, micro-resistivity, and induction logs.

Some other types of geophysical logs, which utilize much of the same equipment, and are made in conjunction with electric well logs, include temperature, fluid flow, magnetic, seismic, acoustic, gamma, and neutron logs. Still other types of logs, using the same equipment, are frequently included, although they are not really geophysical in nature, for example, caliper logs.

The logging program conducted by the Water Resources Research Center has included spontaneous potential, point resistivity, short and long normal resistivity, lateral resistivity, fluid conductivity, temperature, and caliper logging.

The logger used by WRRC and some of the auxiliary equipment are shown in Figure 1A and 1B.

This report is not intended to be a comprehensive study of the theoretical aspects of electrical well logging. However, short dis-

FIGURE 1A. JEEP MOUNTED LOGGING EQUIPMENT.

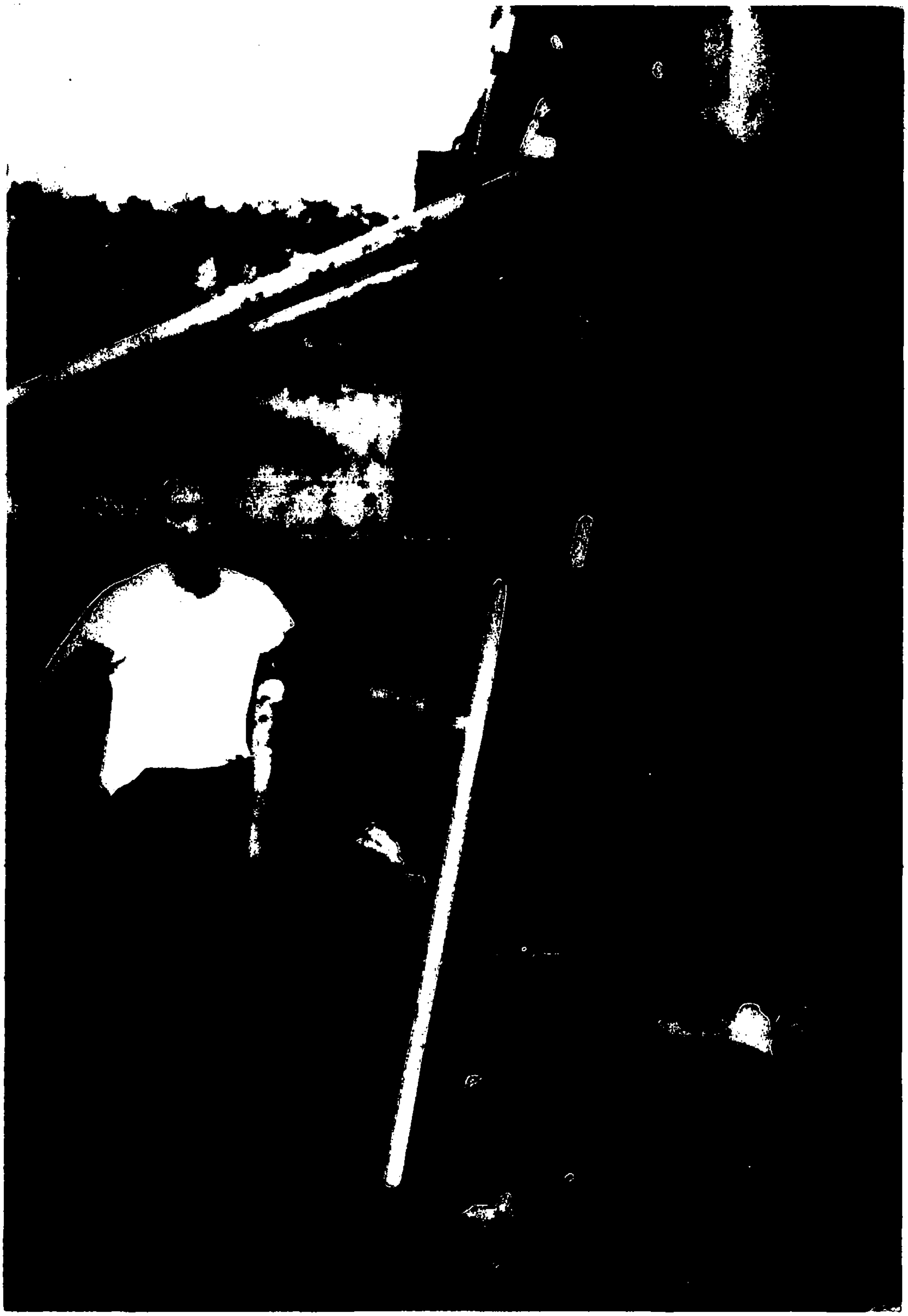


FIGURE 1B. LOGGING SONDES.

cussions of the general theory of spontaneous potential logging and resistivity logging are included in the following sections to facil-iate electric well-log interpretation. The theory presented in these sections generally follows that given by Guyod (1952, 1954, 1957, and 1965), Lynch (1962), Pirson (1957, 1963), and Patten and Bennett (1963). In addition, numerous charts and tables from publications of the Schlumberger Corporation and Mandrel Industries (Anonymous,undated, 1958, 1961, 1962, 1963) have been consulted throughout this study.

Spontaneous Potential Logs

Spontaneous electrical potential logs, also known as self-potential, or simply SP logs, indicate natural electrical potentials found within the earth. The potential can be caused by an electro-chemical behavior, similar to that in a battery, which results at the junction between the fluid-filled borehole and the boundary be-tween formations of dissimilar composition, usually such as sand-stones and shales, or between permeable beds and impermeable beds, or by the electrokinetic effect of fluids moving through permeable formations.

An electrochemical potential is created when solutions with different concentrations of the same salts are placed in contact and ions diffuse toward the solution of lower activity. In general, positive and negative ions will not diffuse at the same rate across a given boundary and a potential is established. If the circuit is com-pleted, a current will be produced.

In water wells, potentials are produced at contacts of chemically different borehole and formation fluids across direct liquid junctions opposite sandstones and other permeable zones and across charged mem-branes opposite shale. Usually several ionic species, which do not have the same valence, are present.

Electrical potential also may be produced at the phase boundary when a solid and a flowing liquid are in contact. Although little quantitative information is available, on the basis of theory, flowing, or so-called streaming potentials should be proportional to the pres-sure differential causing flow and the resistivity of the electrolyte and inversely proportional to the viscosity of the electrolyte (Lynch, 1962).

The spontaneous potential in a well is determined by measuring the potential difference between a single electrode lowered into the uncased well and a reference electrode immersed in a small hole at the surface, filled with drilling mud or water, to insure good electrical contact. The potential at the reference electrode remains relatively constant. The measured potential difference results from natural spontaneous potentials produced in the earth, and are measured by the electrode lowered into the well. Figure 2 shows a diagram of the electrical circuit. Potential values generally range from zero to several hundred millivolts.

By convention, electrical well-logging apparatus is constructed so that deflections on logs to the left of zero represent negative potentials and deflections to the right of zero represent positive potentials. When spontaneous potentials result from electrochemical effects, impermeable formations usually produce zero or very low SP's and permeable formations produce high SP's which may be either positive or negative in sign. Generally, if the formation water is more saline than the borehole fluid, negative potentials are produced and if the formation water is less saline than the borehole fluid, positive potentials are produced. When spontaneous potentials result from electrokinetic effects, usually positive SP's are produced in formations where the direction of flow is from the formation into the borehole and negative SP's are produced in formations where the direction of flow is from the borehole into the formation.

In sedimentary formations, where electrochemical effects predominate, the spontaneous electrical potential is an extremely useful tool to identify permeable beds, to locate the tops and bottoms of beds, and to estimate water quality. Permeable beds usually are indicated by either positive or negative deflections and formation boundaries are marked by points of inflection. Quality of water in the formations can be estimated from the potential logs by means of various approximate equations, departure curves or nomograms. In particular, the equation,

$$SP = K \log \frac{R_{mf}}{R_w} , \qquad (1)$$

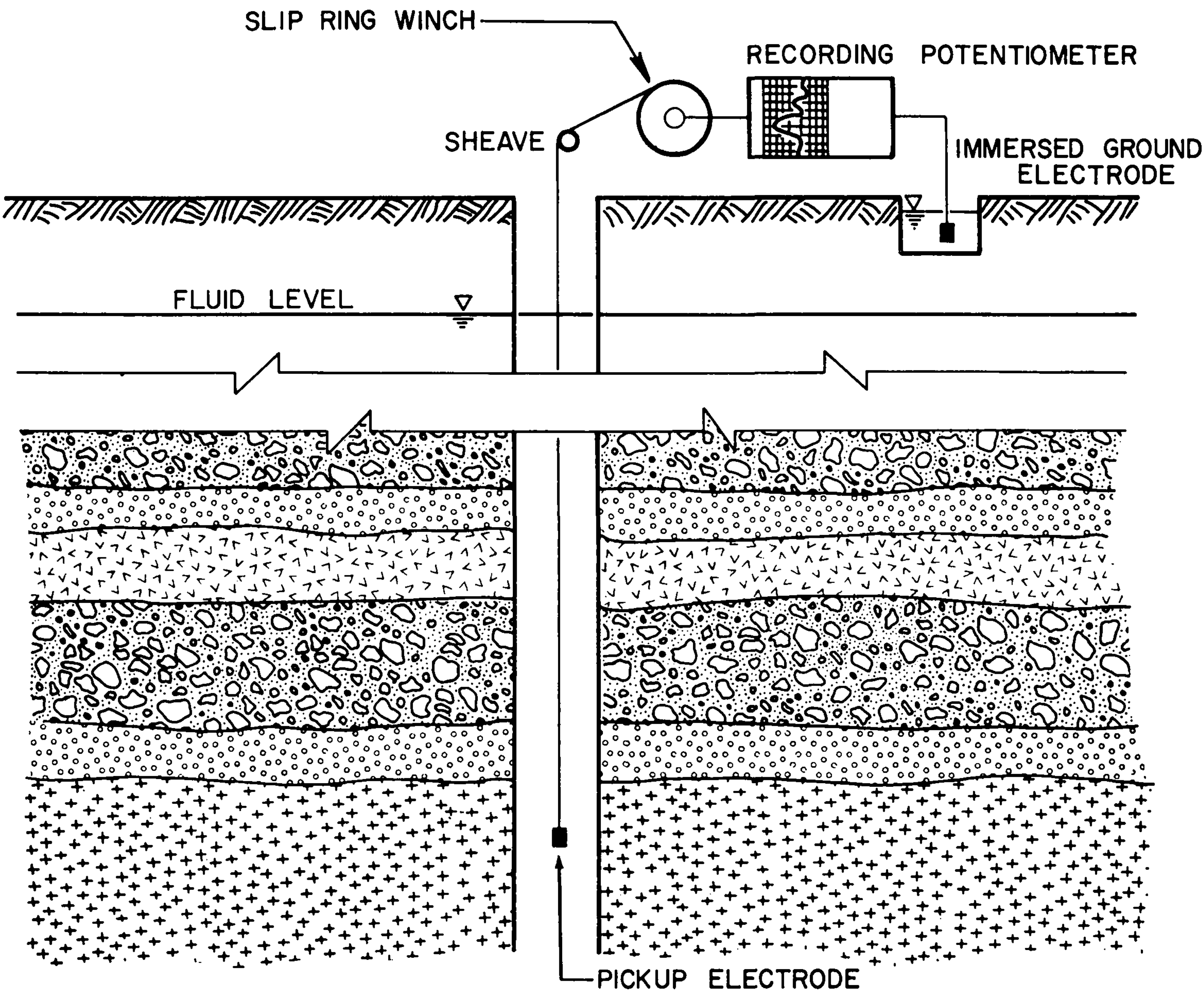


FIGURE 2. CIRCUIT FOR RECORDING SPONTANEOUS POTENTIAL.

which was developed for use in oil wells, where SP is the measured spontaneous potential, K is a factor depending mainly on temperature (at 25°C, K = 70.7), R_{mf} is the resistivity of the mud filtrate, and R_w is the resistivity of the formation water, often is used to estimate quality of formation water.

The use of equation (1) for quantitative spontaneous potential interpretation involves several assumptions which generally are not applicable in water wells, especially in water wells that do not contain drilling mud (Patten and Bennett, 1963). The equation is only valid if there is an extremely large difference in salinity between formation water and drilling mud. Consequently, water quality estimates obtained with this equation are open to considerable doubt.

Because Hawaiian aquifers consist almost entirely of basalt lavas of remarkably uniform composition, the spontaneous potential may be produced primarily be electrokinetic rather than electrochemical effects, *per se*. Consequently, in Hawaiian volcanic rocks spontaneous potential logs probably indicate, for the most part, zones of flow in a well and are used primarily as a supplement to resistivity logs. Spontaneous potentials in sedimentary caprocks in Hawaii, which are probably produced primarily by electrochemical effects, can be treated much like SP logs from other sedimentary formations.

Resistivity Logs

Resistivity logs measure the effect of an applied electric current which is produced at the surface and transmitted to the formation through electrodes lowered into an uncased well.

The basic law describing movement of electric current through any conductor is Ohm's law, which states that the rate of flow of electric current is proportional to the electrical potential difference causing flow. The constant of proportionality is the resistance. Expressed in equation form,

$$V = IR \,, \qquad (2)$$

where V is the electrical potential difference in volts, I is the electic current in amperes, and R is the resistance in ohms.

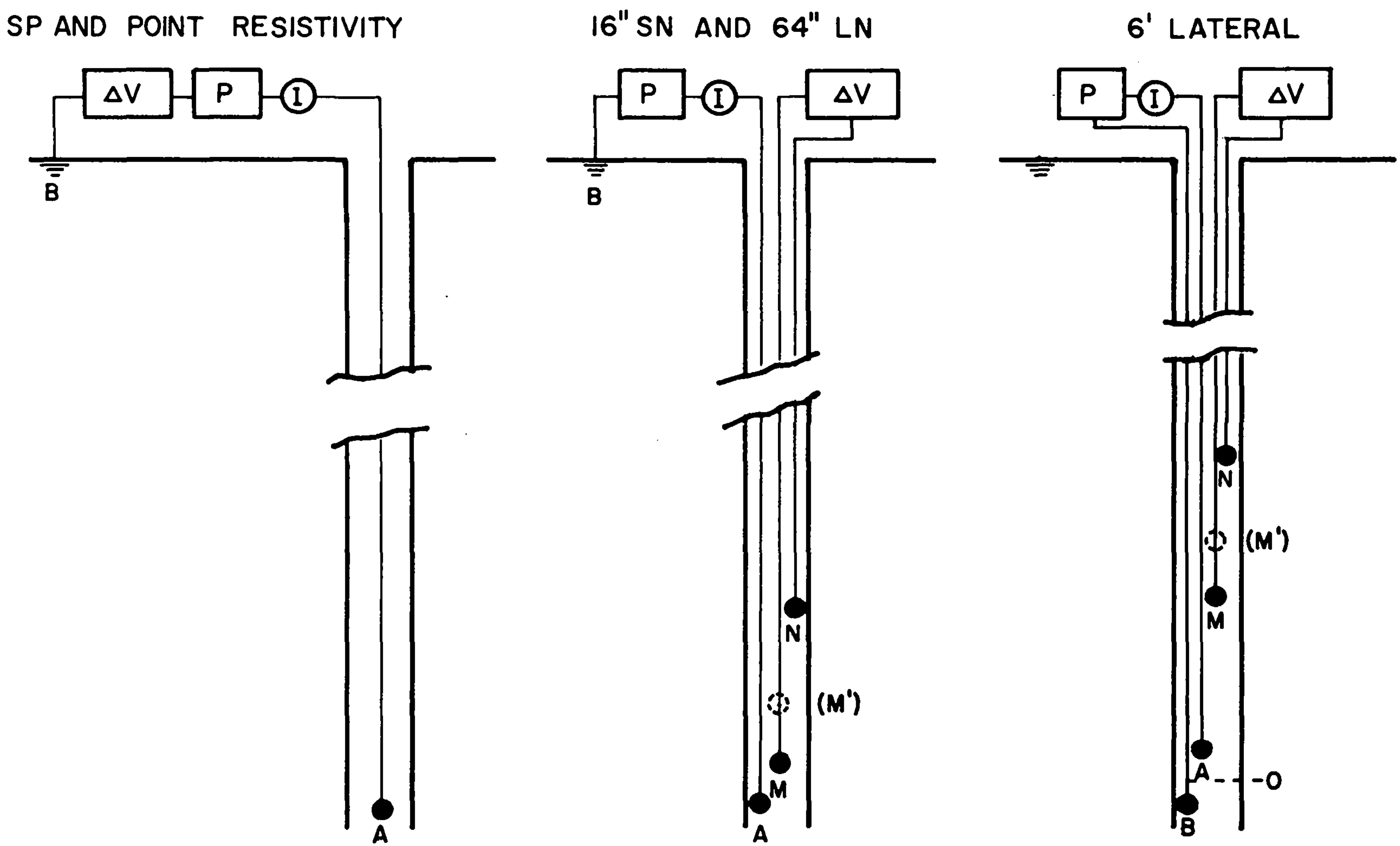
The resistance depends not only on the material which is conducting the current, but also on its physical dimensions. The resistance of a conductor is doubled by doubling its length or by halving its cross-sectional area normal to the current flow. By incorporating the length and area terms with the resistance, it is possible to obtain a parameter which is a function only of the material of which the conductor is composed. This parameter, called the resistivity, e, is defined as

$$e = R(A/L) \quad , \tag{3}$$

where A is the cross-sectional area of the conductor and L is its length. In electric logging practice, the units of ohm-meters^2/meter or simply ohmmeters are most commonly used for resistivity. Resistivity in these units, then, may be defined as the resistance between opposite faces of a cubical element of material, the edges of which are 1 meter in length. It is often convenient to refer to the reciprocal of the resistivity, which is the conductivity, or the reciprocal of the resistance which is the conductance.

Resistivities of natural earth formations vary widely, depending upon the material, its density, porosity, pore size and shape, water content and quality, and temperature. Dense crystalline rocks such as granite or limestone may have resistivities of 10^5 to 10^{12} ohmmeters, whereas clays and shales may have resistivities as low as 1.0 ohmmeter. In porous formations, the resistivity is controlled primarily by pore geometry and content and quality of water in the rock formations, rather than by the resistivity of the rock itself. Consequently, in saturated formations, the resistivity becomes a function of water quality, porosity, and temperature. For example, saturated dense non-porous non-conductive rocks, such as limestone or dense lava flows, normally have high resistivities, porous materials saturated with fresh water have intermediate resistivities, and porous materials saturated with saline water have low resistivities.

Resistivity logging in a well, like SP logging, involves lowering resistivity sondes into the uncased well and immersing a reference electrode into a wetted hole at the surface. A combination of several electrode arrangements and current settings is used to achieve varying radii of effective formation penetration. Figure 3 shows the configurations used in Hawaii. A constant logging current is maintained between



A AND B = CURRENT ELECTRODE
M, M', N = POTENTIAL ELECTRODE
P = POWER SUPPLY
I = CURRENT REGULATOR
ΔV = RECORDER
O = MID-POINT BETWEEN A AND B

FIGURE 3. RESISTIVITY SONDE LOGGING CONFIGURATIONS.

electrodes A and B, and a recording galvanometer measures the potential between N and A for single-point resistivity, N and M for 16-inch short-normal resistivity, N and M' for 64-inch long-normal resistivity, and N and M for 6-foot lateral resistivity. The radius of the A electrode, r_a, is considered to be a point, $\overline{AM}$ is 16 inches, $\overline{AM'}$ is 64 inches, and $\overline{MO}$ is 6 feet. The distances between the pickup electrode, N, and A, M, and M', respectively, are large relative to the above-given distances, and electrically they have the effect of being infinite. The utility and capabilities of the different resistivity configurations used in Hawaii are explained in the following sections.

The resistance, R, of a spherical shell in an infinite, homogeneous, and isotropic electrical medium to a 3-dimensional radial current is given by the expression,

$$R = \sum_{r_1}^{r_2} \frac{e\Delta r}{4\pi r^2} = \frac{e}{4\pi} \left(\frac{1}{r_1} - \frac{1}{r_2} \right) , \tag{4}$$

where r_1 and r_2 are the radii of the inner and outer bounding surfaces of the shell, Δr is the radial thickness of the shell, r is the mean radius of the shell from the center of the current pattern, and e is the previously defined resistivity of the medium. Equation (4) is a special case of the more general formula for resistance given by equation (3). From Ohm's law, the potential difference developed between the bounding surfaces of such spherical shells is given by

$$V_1 - V_2 = IR_{1-2} = \frac{Ie}{4\pi} \left(\frac{1}{r_1} - \frac{1}{r_2} \right) . \tag{5}$$

From equation (5), the potential difference between a point at a distance, r, from the current source and a point an infinite distance away is given by

$$V_1 - V_2 = \frac{Ie}{4\pi} \left(\frac{1}{r} \right) . \tag{6}$$

If homogeneous and isotropic conditions are assumed, if the effects of the borehole are ignored, and if the distances $\overline{AN}$, $\overline{MN}$, and $\overline{M'N}$ are assumed to have the effect electrically of being infinite, the following equation can be used to approximate resistivity measured by the various configurations,

$$e = \frac{V}{I} 4\pi r \quad . \qquad (7)$$

When $r = r_a$, e is the resistivity measured by the point resistivity sonde, when $r = \overline{AM}$, e is the resistivity measured by the 16-inch SN sonde, when $r = \overline{AM'}$, e is the resistivity measured by the 64-inch LN sonde, and when $r = \overline{MO}$, e is the resistivity measured the 6-foot lateral sonde.

As discussed earlier, as r increases and the cross-sectional area perpendicular to flow expands rapidly, the resistance decreases rapidly for a given logging current. Calculations using equation (5) show that nine-tenths of the voltage drop recorded between r and infinity occurs between r and 10r owing to the concentration of resistance primarily in a zone near the source of current (Patten and Bennett, 1963). In practice, the zones of investigation probably are restricted even further so that the point resistivity measures effectively the resistivity of a spherical zone of the borehole and earth material extending to a radius of 2 r_A, the short normal measures effectively the resistivity of a spherical shell with a radius extending from $\overline{AM}$ to $\overline{2AM}$, the long normal measures effectively the resistivity between $\overline{AM'}$ and $\overline{2AM'}$, and the lateral between M and O.

All the concepts and equations developed in the previous sections assume that the medium surrounding the sondes is perfectly homogeneous. In practice, the resistivities measured by borehole devices are only apparent resistivities and often are not true formation resistivities owing to the heterogeneity within the earth formations investigated. When electrical heterogeneity prevails, the resistivity measured is a composite value of all the resistivities of the component parts. Heterogeneity created by the borehole especially affects the point resistivity and short normal devices. The resistivity readings of the point resistivity, and the short normal device to a lesser extent, are greatly affected by the borehole, while the resistivity readings of the long normal and lateral devices are relatively unaffected by the borehole and are closer to the true formation resistivity.

Resistivity logs are used primarily as aids in correlating the lithology of the formations penetrated and in estimating the character of the pore fluid. Detailed formation resistivity and formation boundaries are located most readily with the point resistivity and short normal devices, whereas true formation resistivities uninfluenced by borehole fluids can be obtained best with the long normal device. The lateral device is also useful for measuring true resistivity.

Formation porosity sometimes is estimated by using the equation,

$$\phi^M = \frac{1}{F} = \frac{R_w}{R_o} , \tag{8}$$

where ϕ is porosity, F is the formation factor, R_w is the resistivity of the water in the formation, R_o is the bulk resistivity of the saturated formation, and M is an exponent which depends on the mineralogy and pore characteristics of the rock. However, as discussed in a later section on the interpretation of the resistivity logs, equation (8) does not appear applicable to the determination of porosities in Hawaiian basalts.

Equation (8) can be used in some regions such as Louisiana (Turcan, 1966; Whitman, 1965) and Florida (Jones, 1951) to estimate water quality if a reasonable value for porosity is assumed. True formation resistivity can be determined from resistivity curves. Often a wide electrode spacing combined with a thick homogeneous aquifer will give, by direct inspection, resistivities which are close to the true resistivity. For most work, however, elaborate corrections must be made for factors like borehole diameter, electrode spacing and arrangement, aquifer thickness, temperature, and mud resistivity and depth of invasion of mud filtrate if drilling mud is present when the hole is logged (Guyod, 1954). The logging program in Hawaii makes use of a continuous water-conductivity sonde which yields accurate detailed data so far as the water in the well is concerned. Hence, water-quality estimates are not attempted from resistivity logs.

By convention, the resistivity logs are recorded on the right side of the chart and spontaneous potential on the left.

Fluid-Conductivity Logs

Conductivity logs of a water-filled borehole indicate the electrical conductive properties of the water, which, in turn, can be used to estimate the chemical quality of the water.

Specific electrical conductance or electrical conductivity is the reciprocal of resistivity and is measured in mhos. When working with fresh water, the mho usually is too large a unit to be convenient so micromhos, or millionths of mhos, generally are used. The specific conductance of water is directly dependent on the concentration and the types of ions present and on the temperature (see Fig. 4). The specific conductance readings made with the equipment used in Hawaii are instrumentally adjusted to 25°C, so that variations in conductance are a function only of the concentration and type of dissolved constituents present.

Water conductivity is measured by lowering a conductivity sonde into the well, which may be either cased or uncased, and the water may be flowing or static. If the well is not flowing, and the water has not been recently disturbed, the measured values may represent formation water changes with depth.

Temperature Logs

Temperature logs of a well directly measure the temperature of the water in the borehole. In Hawaii borehole temperature is measured with the same sonde used to measure fluid conductivity. The conductivity log is prepared first as the sonde is inserted into the well, and the temperature log is prepared as the sonde is being withdrawn from the well. A thermal lag, which depends on the withdrawal rate of the sonde, occurs owing to time required for the sonde to reach equilibrium.

Temperature logs u ually are used to determine the water temperature variation with depth and to locate zones contributing water of different temperatures, however, other uses sometimes are made of temperature logs, such as locating freshly cemented zones.

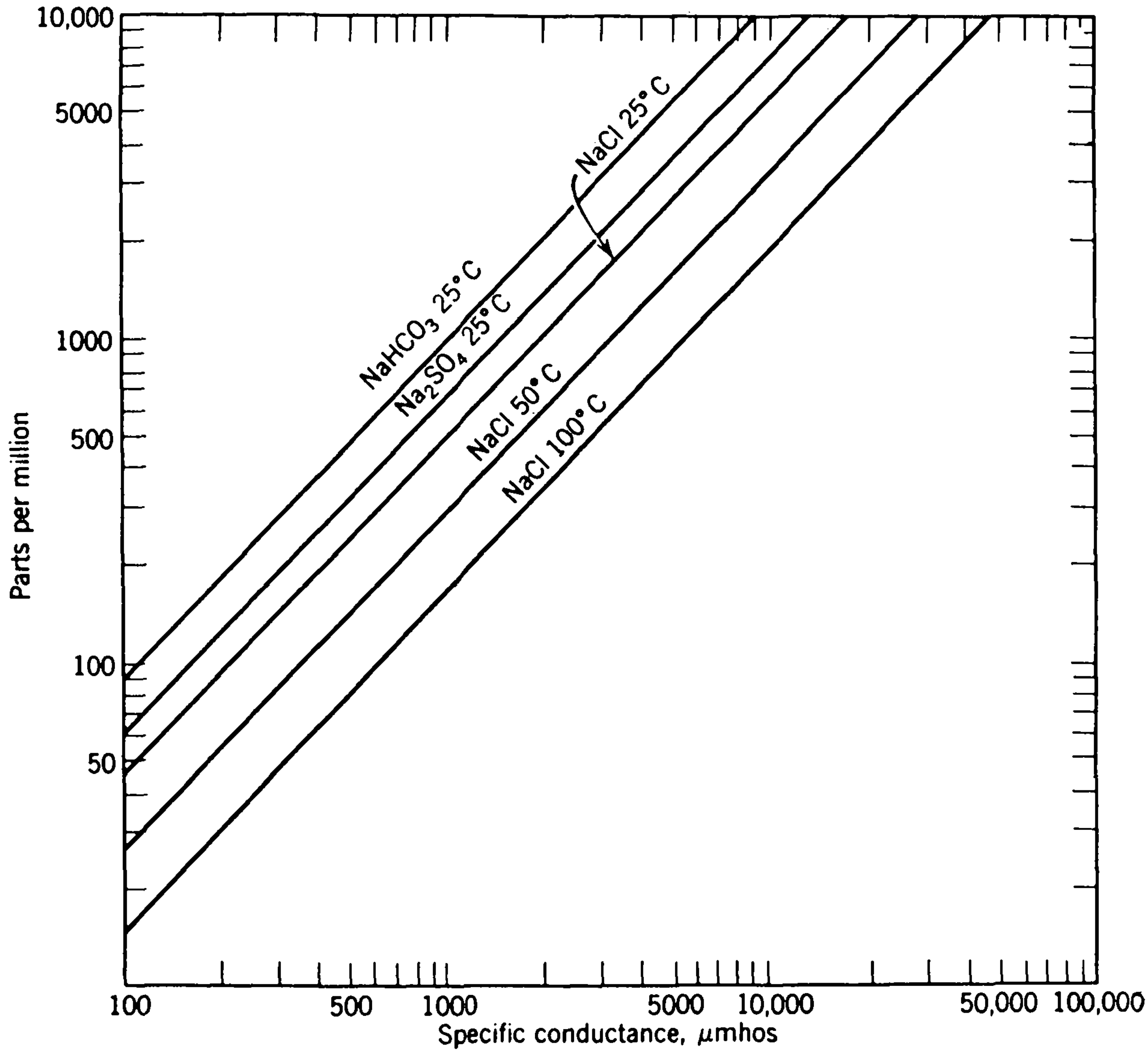


FIGURE 4. SALINITY, TEMPERATURE, AND CHEMICAL EFFECTS ON CONDUCTIVITY. (AFTER DAVIS AND DEWIEST, 1966).

Borehole Caliper Logs

Caliper logs of a well measure directly the diameter of the borehole and are used for determining borehole correction factors for electric logging. The logs are also used for locating zones suitable for packers. In Hawaii, the caliper device has been used for locating casing breaks. Correlation has been made with the resistivity logs where zones of caving are indicative of loose permeable clinker zones.

ELECTRIC WELL LOGGING PROCEDURES AND RESULTS IN HAWAII

Wells Logged

Most of the wells which were electric logged in the Hawaiian project had been drilled many years or even decades prior to the logging. Most were wells from which pumping equipment had been removed temporarily or permanently. Some were flowing agricultural artesian wells or wells in batteries connected to a common pump suction header, which required only the removal of fittings for access. A very few wells were logged immediately after drilling. Besides the wells, a number of test holes and observation wells were logged. These generally had been pump-tested and the drilling mud, if any had been used, had been removed before the logging.

In all of the water wells logged, the productive aquifer was the basalt lavas. Other than a few wells producing salt water for air conditioning or industrial cooling there is, in fact, only one drilled well at Punaluu, Oahu known to be producing brackish water from sediments. Many of the producing wells were drilled through sedimentary sections prior to entering the basalts, but in all of these, the sedimentary sections were cased off.

Most of the wells logged on Oahu were basal water wells. Dike-zone wells were logged at Makaha and at several places between the Pali Highway and Waihee on Oahu. On Kauai, wells drilled in dike zones included the well near Polihale and those on the north side of the island.

Well-Logging Procedure

The procedures used in the geophysical well logging on Oahu and Kauai were essentially standard procedures.

The well logger was mounted in a jeep which also carried a generator or an alternator as a power source, the selsyn sheave that measures and transmits to the logger the length of cable paid out, down-hole logging tools, and other miscellaneous parts and tools.

Preparatory to logging a well the jeep was maneuvered conveniently close to the well. The selsyn sheave was suspended centrally above the well, ordinarily by mounting it on a light-weight aluminum tripod. Where there was a well drilling rig over the well, the sheave was suspended from the travelling block of the rig or from a pipe lashed to the tower. On some wells the sheave was lashed to standpipes and over one well the sheave was suspended from a convenient tree limb.

A conductivity survey on non-flowing wells was always the first to be logged and it was made with the sonde going down the well to disturb the water standing in the well as little as possible. The sequence of logging all the other functions is of no importance, however, the temperature log was always run next after the conductivity log as this function is also provided by the conductivity sonde. On flowing wells, the logging sequence, including conductivity logging, is of little importance, however, the conductivity log as a matter of standard operating procedure was always run first.

More detailed information on logging procedures is available in the Operational Procedures and Trouble-Shooting Procedures sections in the appendix of this report, and in the manufacturer's instruction manual for the logger which was kept with the logging equipment at all times (Appendices D and E).

Log Interpretation

The interpretation of electric logs from the few wells in Hawaiian sedimentary rocks is not substantially different from the interpretation of logs from continental sedimentary aquifers. However, the interpretation of certain of the electric logs from wells in the volcanic rocks, which constitute by far the most important aquifers in Hawaii, differs significantly from the interpretation of such logs from sedimentary aquifers. In particular, the extremely uniform chemical composition of Hawaiian basalts complicates the interpretation of SP logs and the high resistivity and the extremely heterogeneous nature of the basalts complicates interpretation of the resistivity logs. The closest resemblance to the basaltic rock as far as logging conditions are concerned would be stratified limestones which have an entirely different physical structure but are fairly similar in chemistry and mineralogy. Limestone formations are usually logged with induction and neutron devices which were not available for this study.

In general, the interpretation of the other geophysical parameters logged in Hawaii, fluid conductivity, fluid temperature, and borehole diameter, follow conventional water-well techniques.

In addition to the unique hydrogeologic conditions in Hawaii, differences in the use of drilling mud in well construction in Hawaii necessitate differences in well-log interpretation. Cable-tool drilling, a method which uses little or no drilling mud, is still actively used for well drilling in Hawaii, even to depths as great as 1000 feet. Rotary drilling where air is used to lift cuttings is also practiced in Hawaii where the artesian head is sufficient. Furthermore, except for the few wells which were constructed during the duration of this study and then logged immediately after construction, the well logging in this study was done months or more commonly years after the wells were drilled so that even if mud was used in drilling most of it was pumped out of the borehole and formation prior to logging. In contrast, many mainland wells are drilled by rotary methods which require the use of drilling mud and are logged soon after drilling is completed while the drilling mud is still present in the borehole and the formation. Consequently, great emphasis has been placed on mud cake, mud filtrate, the extent of the mud-invaded zone, and other parameters usually not pertinent for logs in Hawaii.

For the few mud-filled wells that have been logged, the depth of mud invasion in basalts has not been studied. Penetration is likely to be deep in zones where the flow channels are large and continuous, shallow where the pore spaces are small, and nil in dense layers. The extent of invasion also is dependent upon the degree of hydrodynamic unbalance between the mud column and the formation water. High specific-gravity muds and high mud-pump pressures used for bringing up the cuttings will maximize penetration of mud into the formations. The presence of mud affects the apparent resistivity to a degree, depending on the contrast of the resistivity between the mud and the formation.

CALIPER LOGS. Caliper log interpretation is straightforward in that the log provides a direct measure of the variation of borehole diameter with depth. Unfortunately, for the instrument used in Hawaii, diameter readout is non-linear despite the circuit adjustments that supposedly can be made to accomplish this result. An accuracy of approximately an inch can be achieved with confidence. The greatest accuracy can be achieved by calibrating the caliper logger in a casing of known diameter, such as is always available in new wells. Because the reference length of the caliper sonde changes as the extension of sonde arms changes in response to hole diameter variations, the reference lengths of this sonde must be calibrated in relation to hole diameter (Fig. 5). For general work, 4.5 feet, 5.0 feet, and 5.5 feet may be used as the reference lengths for the 12-inch, 24-inch, and 36-inch arms, respectively. If accuracy of depth is required, a further correction should be made (from Correction Chart Number 1, "Caliper Log Operational Manual"). Typical caliper surveys of wells in Hawaii are shown in Figures 6a to 6c.

In the Hawaiian project, caliper logs have been used effectively to locate trouble spots in casings such as was done in well 88-B, to guide in the selection of suitable sections of the borehole with uniform diameters for packer positions as proposed for the Punaluu and Puuanani Board of Water Supply research wells, to calculate the volume of material needed to backfill a well as in 88-B, and to locate caved zones which probably are permeable, high-water producing formations as in 7a. In addition, the logs can be used to provide corrections to calculate formation resistivity from apparent resistivity.

TEMPERATURE LOGS. Temperature logs provide a direct measure of the variation of temperature of borehole fluids with depth and, for the most part, interpretation is straightforward. The range of temperatures found in ground water on Oahu and Kauai is relatively small, between 19°C and 23°C, and is only a few degrees centigrade in any given well, including the deep wells penetrating to salt water. The wells logged on Oahu and Kauai normally show quite uniform temperatures throughout their depth except for a thin layer which is confined to the top where thermal flux is added by conduction from the casing or the air and

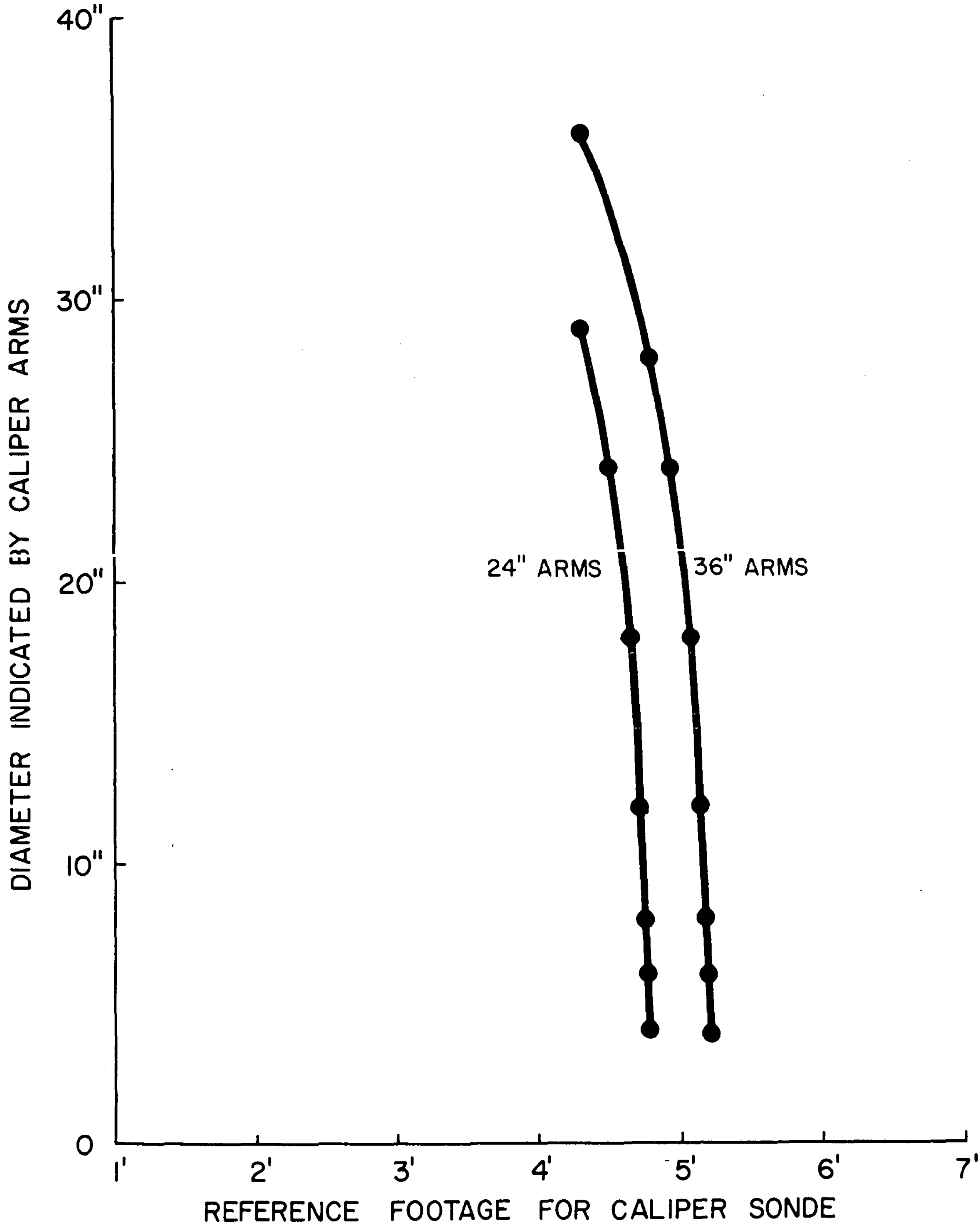
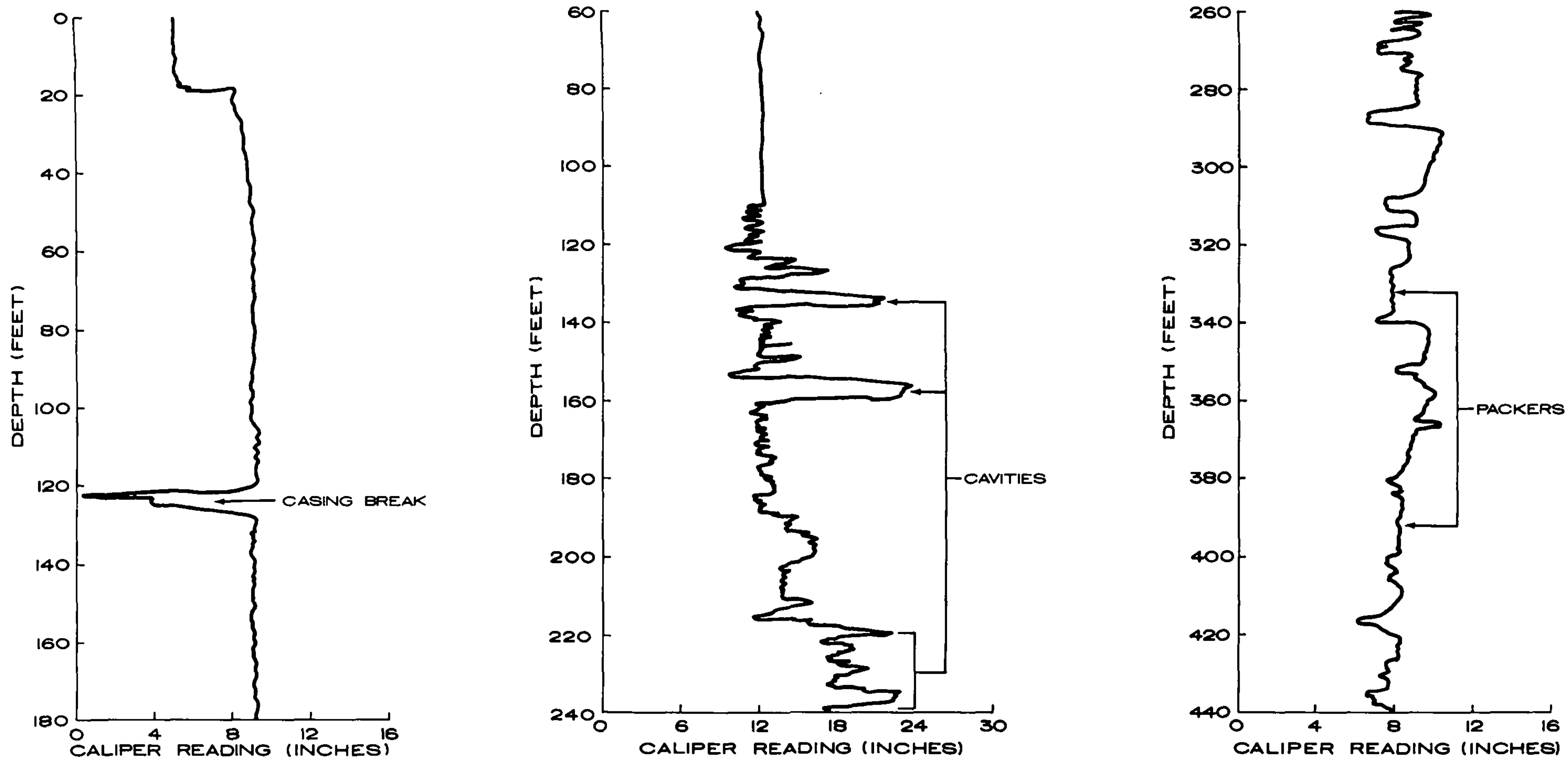


FIGURE 5. CORRECTION CURVE FOR CALIPER REFERENCE FOOTAGE.



A. CALIPER LOG SHOWING CASING BREAK IN BERETANIA WELL 88-B.

B. CALIPER LOG SHOWING CAVITIES IN KAIMUKI WELL 7A.

C. CALIPER LOG SHOWING PACKER LOCATION IN PUNANANI WELL 196-2.

FIGURE 6. EXAMPLES OF CALIPER LOGS.

where return irrigation water is warmer than basal water. The wells of over 1000-foot depth on Oahu exhibit thermal characteristics suggestive of geothermal heat.

A typical temperature log with calibration marks made during logging is presented in Figure 7. Note that no attempt has been made to provide a calibration such as one inch of chart equals one degree centigrade. Calibration of this sort can be made, but it is almost as convenient to read the numbers.

In addition to providing a direct measure of water temperature for general water quality purposes, temperature logs from Hawaiian wells have been used to determine thermal gradients and to help locate, together with resistivity and conductivity logs, water-contributing zones. Borehole temperatures are normally used for correction of apparent formation resistivity and formation conductivity but the range is so slight in Hawaii that it can be neglected. In addition, information from temperature logs has been used to aid in the interpretation of regional ground-water flow patterns and velocities and to aid in the interpretation of the complex, dynamic, Herzberg lens relationships.

FLUID CONDUCTIVITY LOGS. Fluid conductivity logs provided by the logging module used in Hawaii, which has automatic temperature compensation, indicate the conductivity of the fluid in the well corrected to a standard reference temperature of 25°C. The range of fluid conductivity logged in wells on Oahu and Kauai is very wide. Values have varied from a few hundred micromhos near the top of some wells to more than 40,000 micromhos at the bottom of several deep test holes which completely pass through the fresh-water lens and into salt water.

In wells from which there has been no discharge during or for some time prior to logging, it may be assumed that the conductivity of the water in the well is the same as the conductivity of the water in the formation outside the well at the same depth. In discharging wells, the conductivity of the water at any depth is a composite dependent on the conductivities of water entering the well and the relative rates of inflow below that depth.

As indicated in a previous section, specific conductance is a function of the type and concentration of ions in the water and

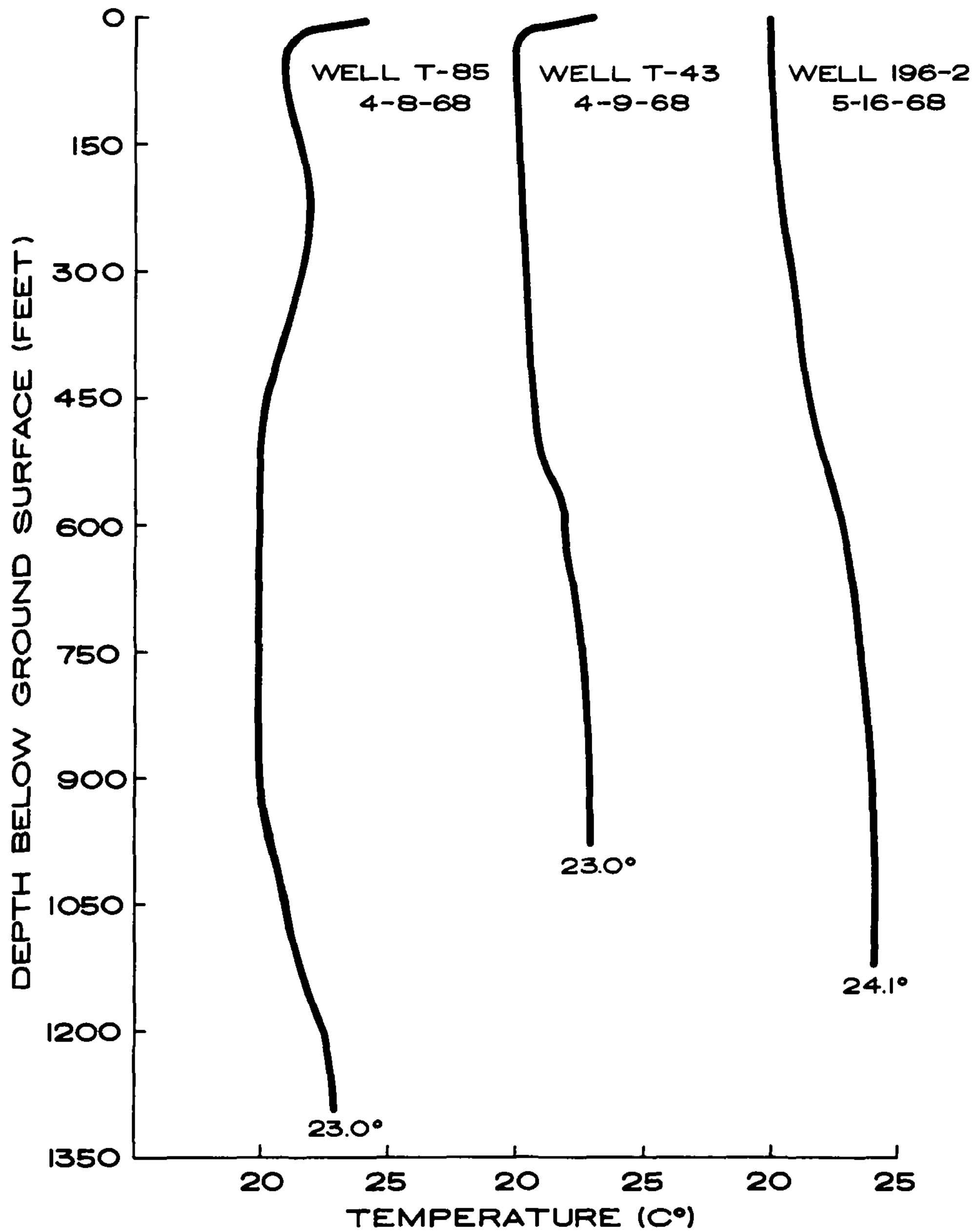


FIGURE 7. TEMPERATURE LOGS FOR WELLS T-85 (BERETANIA), T-143 (PUNALUU), AND 196-2 (PUNANANI).

and the water temperature. If the geochemical character of water is relatively uniform over an area, detailed laboratory analyses may show consistent relationships between conductivity and chemical constituents. With the aid of these relationships, accurate estimates can be made from conductivity data for the various chemical constituents, including total dissolved solids. Unfortunately, there are not enough data on compositions of dissolved solids to determine the relationships for waters in all areas of Hawaii. However, because salinity in most wells in Hawaii results from admixture of sea water with water of very low content of dissolved solids, it may be assumed for most general purposes that there is a unique relationship between conductivity and either total salinity or the concentrations of any of the major ions. A useful approximation which often is applied to relatively low conductivity water in Hawaii is that the concentration of Cl^- in parts per million is about 1/4 of the specific conductivity in micromhos. A more accurate estimate of chlorinity as a function of conductivity can be obtained by using the relation pertaining to diluted sea water graphed for various temperatures in Figure 8.

Another important use of conductivity logs in Hawaii, in conjunction with resistivity logs, is to help locate zones contributing water of anomalous or objectionable quality. For example, the conductivity log and the resistivity log for a well at Pearl City, Oahu (see Fig. 9) indicate that if the casing of this well had not been perforated and if it had been seated in the dense basalt at 320 feet depth, then the poorer quality upper water probably would have been shut off or at least reduced in quantity and an overall improvement of the water quality would have resulted.

One of the most important uses of conductivity logs, together with temperature logs, in Hawaii is to provide data for the interpretation of the complex Ghyben-Herzberg lens relationships. The heads indicated in wells in Hawaii are the result of complex dynamic relationships of time, tides, recharge, discharge, and the changes of density with depth. The problem of imperfect balance of the Ghyben-Herzberg ratio in Hawaii was recognized by Wentworth (1939). Cox (1954) and Lau (1960, 1962 and 1967) have discussed the shape of the salinity and temperature curves with depth. With the data

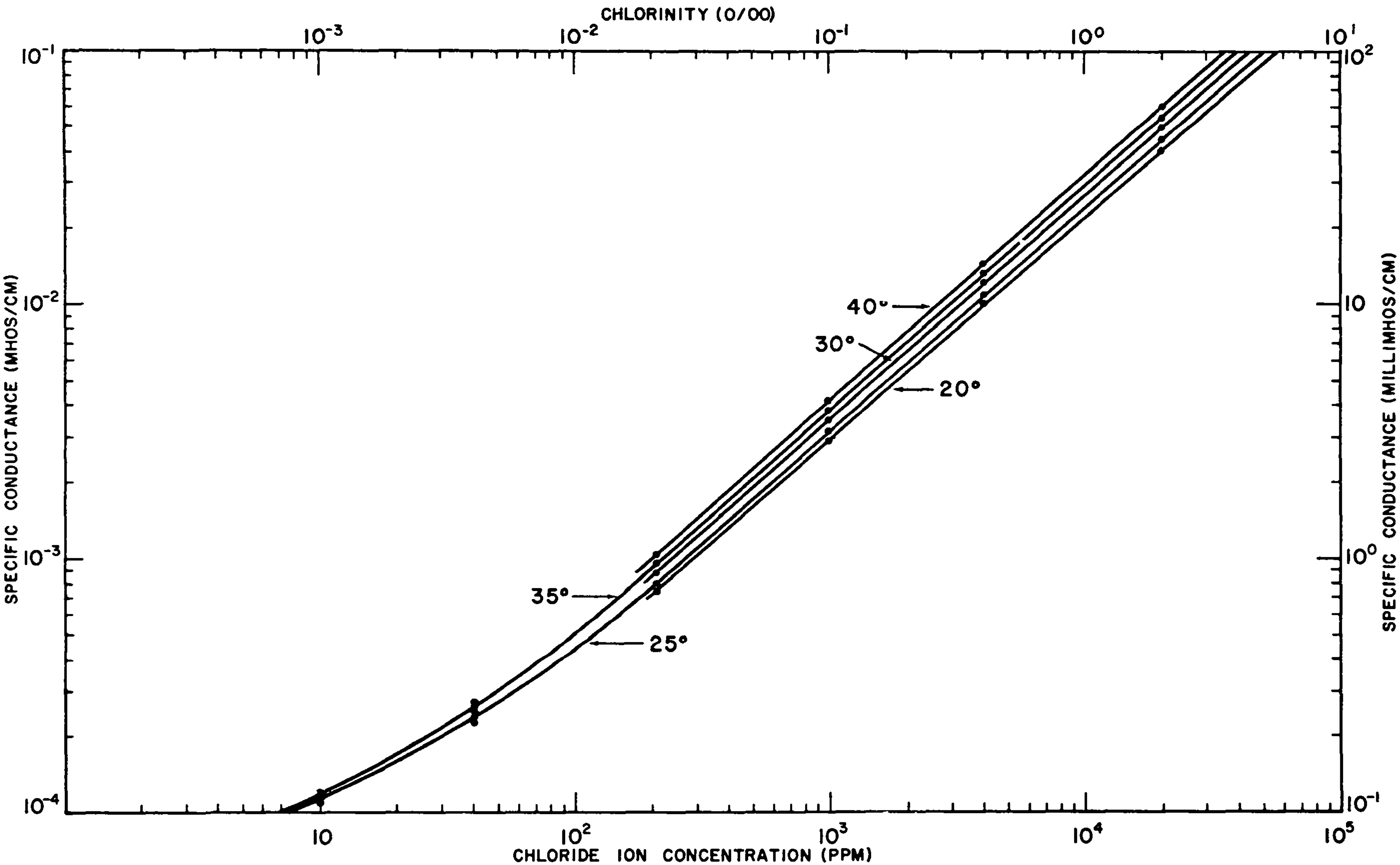


FIGURE 8. SALINITY VERSUS CONDUCTIVITY (AFTER COX, ET AL., 1969).

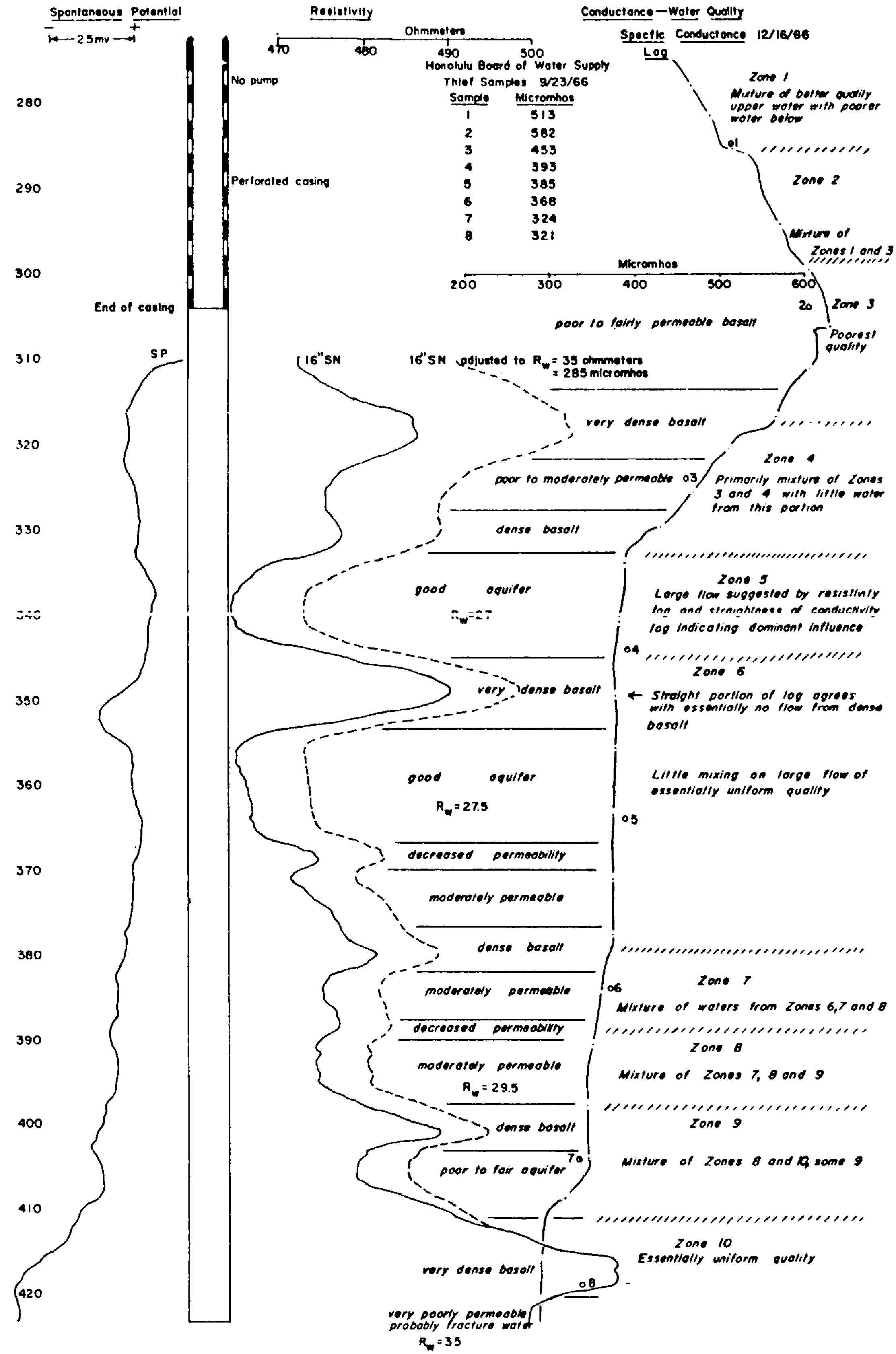


FIGURE 9. ELECTRIC WELL LOGS FOR WELL NO. 202-C, PEARL CITY, OAHU.

currently available on temperature and salinity profiles, corrections of density with depth are possible. By study of head changes in the well and monitoring of the salinity and temperature, more reliable estimates can be made of ground-water storage. At present, the Honolulu Board of Water Supply has a continuing program of logging deep wells penetrating to salt water for borehole conductivity and temperature at periodic intervals. Re-runs have revealed changes in the depth and thickness of the fresh water and the transition zones and show that the lens is dynamic (Fig. 10).

Finally, to avoid possible erroneous interpretation of resistivity logs, conductivity data has been used to adjust resistivity logs when a substantial salinity gradient occurs in a well.

SPONTANEOUS POTENTIAL LOGS. The interpretation of SP logs, unlike conductivity, temperature, and caliper logs, is generally not straightforward because the parameters of interest, the depths of formation boundaries, formation permeability, and formation water quality are not directly measured. Instead, the naturally occurring electrical potentials measured with SP logs provide only a very indirect determination of these parameters which is subject to considerable differences in interpretation.

Electropotentials from wells in sedimentary rocks arise primarily from electrochemical sources and electrokinetic potentials generally are negligible. Consequently, conventional interpretative techniques used for SP logs from continental wells, which are generally in sedimentary rocks, are based on potentials from electrochemical sources and ignore electrokinetic potentials. Interpretation of SP logs from the few wells in sedimentary rocks in Hawaii (three wells logged in this study) follows conventional SP interpretative practices. Figure 11 shows SP and resistivity logs of a sequence of reef deposits and interbedded muds of probable terrestrial origin. Opposite the reef deposits, the SP log shows negative deflections, indicating these formations were more permeable than the muds and that the formation water was more saline than the drilling mud in the borehole. The general increase of negative SP with depth in this well was caused by increasing salinity in the formation water with depth.

Most wells in Hawaii, however, are in basalts with remarkably uniform chemical composition, so that conventional interpretative techniques for SP logs are not applicable. The contributing proportions of potential from electrochemical and electrokinetic sources are not known at present, but the electrokinetic potential from fluid flow is suspected to be dominant.

Generally, in basalts, positive SP deflections occur opposite zones with flow from the aquifer into the well and negative SP deflections occur opposite zones with flow from the well into the aquifer on the no-flow base (see Fig. 12). However, this is not always true. In some instances SP deflections are not observed or are in reversed position opposite zones which are shown by resistivity and conductivity logs to be permeable, water-contributing formations. Because of these uncertainties, SP logs from wells in Hawaiian basalts have been used primarily to supplement and, where possible, to confirm the findings of resistivity and other geophysical well logs. Furthermore, owing to the uncertain nature of the SP logs, no attempt was made to apply quantitative interpretations to SP logs in Hawaiian rocks.

RESISTIVITY LOGS. The interpretation of resistivity logs is not always straightforward because, like SP logs, resistivity logs do not provide a direct measure of the parameters of greatest interest, namely, formation lithology and porosity. Instead, resistivity logs measure the composite resistivity of the borehole, the invaded zone if drilling mud was used, and the formation and formation fluid. From this information, formation lithology and porosity must be ascertained. Nonetheless, resitivity logs have proved to be most useful for obtaining geologic and hydrologic information from water wells in Hawaii.

Basalt is normally among the most resistive rocks and the values of resistivity range to 100,000 ohmmeters (see Table 2). Surface resistivity surveys in Hawaii indicate values ranging from about .5 to 300 ohmmeters (Hussong and Cox, 1967) and 800 to 1,000 ohmmeters (Keller, 1967). Zohdy (1966) found resistivity values of fresh basalt saturated with fresh water in the Waianae Range and in the Pohakuloa area on the island of Hawaii to be 300 to 700 ohmmeters. The values of down-hole resistivity found in the WRRC study agree

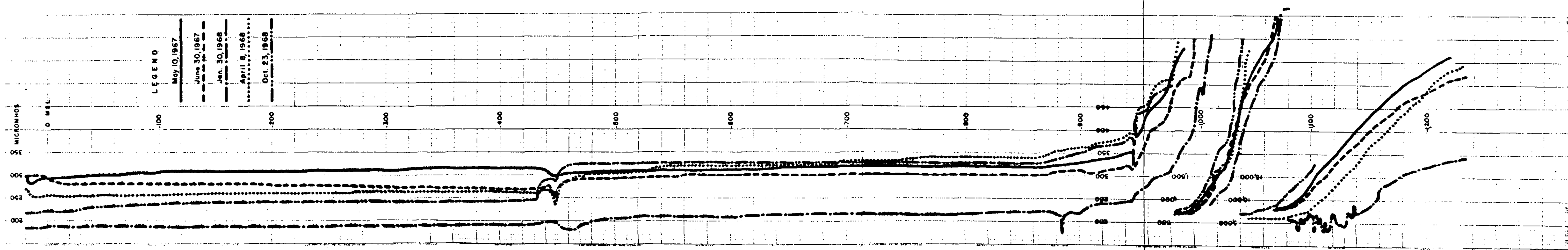


FIGURE 10. PERIODIC CONDUCTIVITY PROFILES FROM WELL NO. T-85, BERETANIA, OAHU.

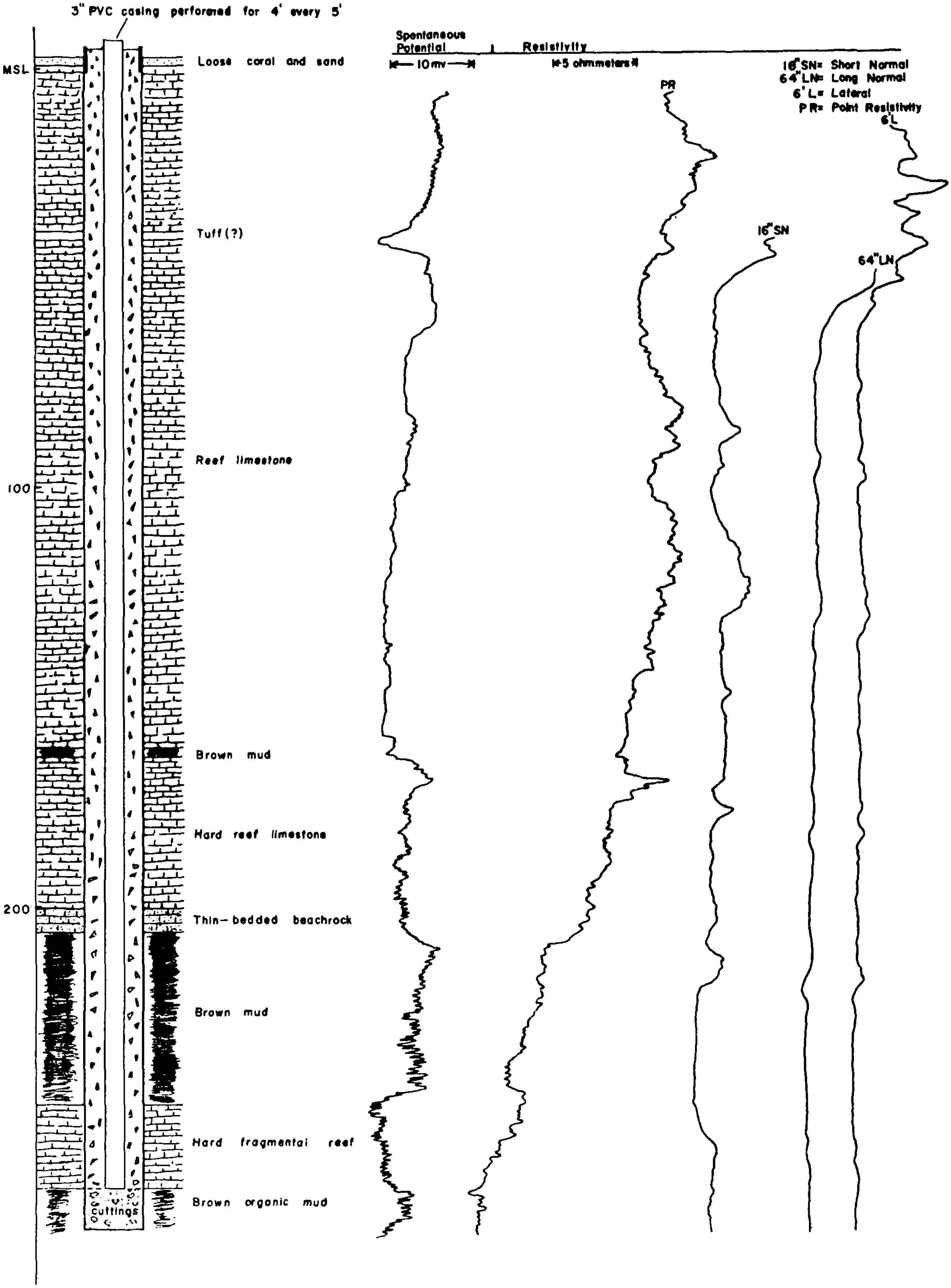


FIGURE 11. ELECTRIC LOGS AND GEOLOGIC LOG FROM WELL NO. T-133-1, EWA BEACH, OAHU.

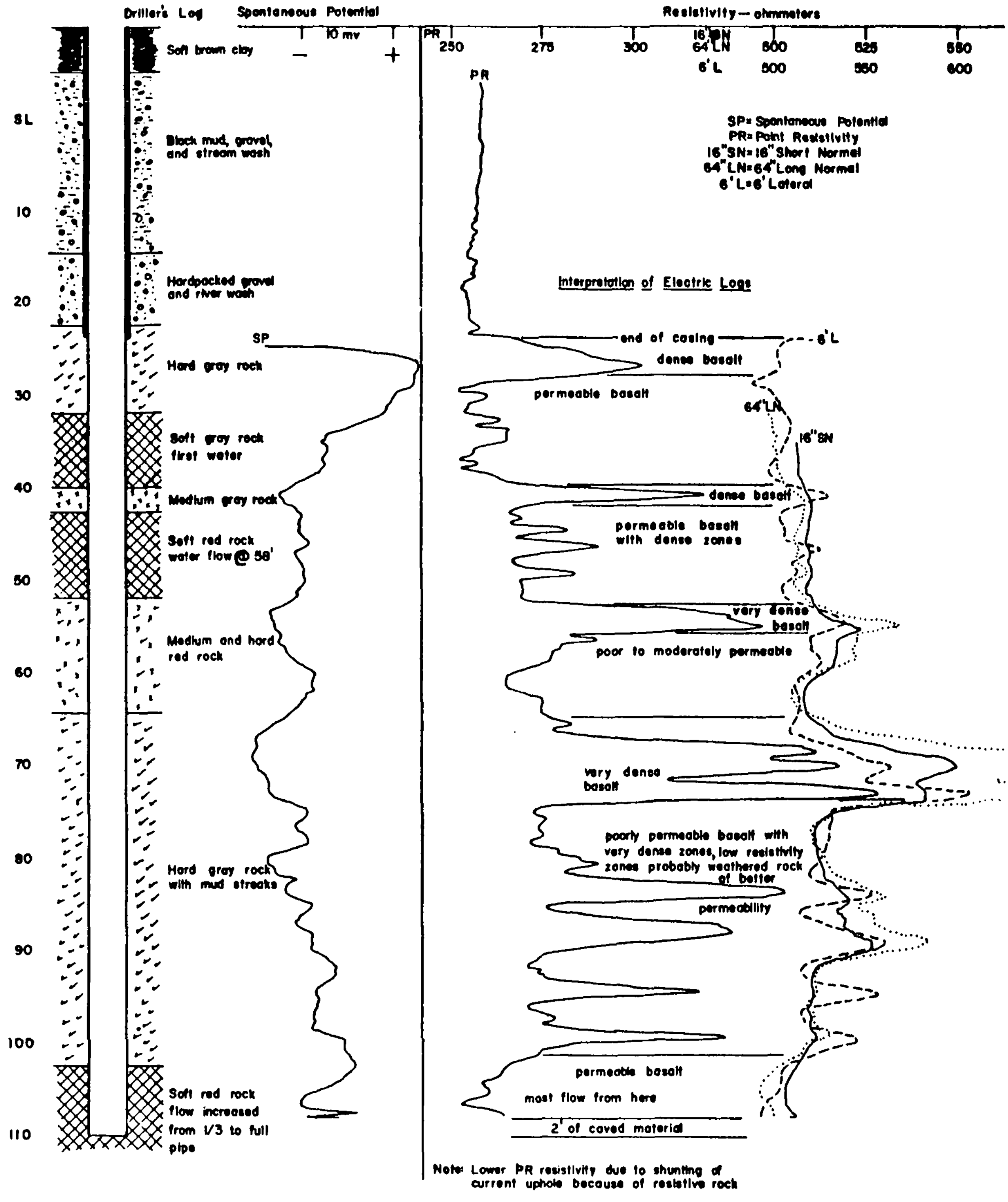


FIGURE 12. ELECTRIC LOGS AND GEOLOGIC LOG FROM WELL NO. 200-4, PEARL CITY, OAHU.

TABLE 2. RESISTIVITIES OF ROCK IN HAWAII AND COMPARATIVE RESISTIVITIES ELSEWHERE (VALUES IN OHMMETERS).

RESISTIVITY VALUES FROM ELECTRIC WELL LOGGING	
WRRC (1966, 1967, 1968 OAHU AND KAUAI)	
BASALT SATURATED WITH FRESH WATER, EXTREMES	300-700
BASALT SATURATED WITH FRESH WATER, NORMAL VALUES	450-550
BASALT SATURATED WITH FRESH WATER, CHANGE IN RESISTIVITIES IN ANY ONE WELL	5-100
CORALS SATURATED WITH FRESH WATER, EWA BEACH	503*
CLAYS SATURATED WITH FRESH WATER, EWA BEACH	500*
BASALT SATURATED WITH SALT WATER	UNRELIABLE
ELECTRO-TECHNICAL LABORATORIES (BULLETIN EL-215, 1961)	
GROUND WATER	0.1-30
SEA WATER (30,000 PPM)	0.3
SOFT ROCKS (25% POROSITY, SATURATED)	1-300
FIRM ROCKS (25% POROSITY, SATURATED)	4-1,000
HARD ROCKS (6% POROSITY, SATURATED)	40-5,000
LOG MASTER SERVICES MANUAL (SELECTED FORMATIONS BASED ON SINGLE POINT)	
LIMESTONE (POROUS AND DENSE)	$20\text{-}10^6$
SHELL OR CLAY	1-100
SAND OR SANDSTONE	1-1,000
RESISTIVITY VALUES FROM SURFACE SURVEYS	
HUSSONG & COX (1967, PAHALA, HAWAII)	
UNWEATHERED AA	10,000-200,000
UNWEATHERED PAHOEHOE	5,000-20,000
WEATHERED LAVAS	1,000-8,000
DRY SOIL	500-5,000
WET SOIL	50-500
FRESH WATER SATURATED LAVAS, GENERALLY	.5-300
FRESH WATER SATURATED LAVAS, MAXIMUM	485
ZOHDY (1965, 1966, MOKULEIA, OAHU AND POHAKULOA, HAWAII)	
CLAY SATURATED WITH BRACKISH TO SALINE WATER	1-3
CLAY SATURATED WITH BRACKISH TO FRESH WATER	5-8
CLAY AND SILTY SAND WITH FRESH WATER	11-25
SAND AND CORAL	80-400
WEATHERED BASALT WITH FRESH WATER	30-60
FRESH BASALT WITH FRESH WATER	300-700
FRESH BASALT WITH SALINE WATER	30-40
KELLER (1962, KILAUEA VOLCANO)	
SHALLOW, VERY RECENT FLOWS	50,000-100,000
UNDERLYING BASALT ABOVE SEA LEVEL	800-1,000
OLDER ROCKS BELOW SEA LEVEL	LESS THAN 10

*DEPENDING ON ELECTRODE USED, RESISTIVITY VARIED SLIGHTLY BUT THE 3-OHMMETER GREATER VALUE PERSISTED FOR CORAL. THE BASALT WAS 3-9 OHMMETERS GREATER THAN CORALS.

with Zohdy's values and range from 300 to approximately 700 ohmmeters. The highest values were found in wells of the Makaha area which penetrate a dike compartment in Waianae basalts saturated with water having a conductivity of 350 to 370 micromhos. The lowest values of 290 to 340 ohmmeters were found in Koolau flows in the Kaimuki area of Honolulu. Comparison of surface resistivity with down-hole resistivity values should be made only with great care as surface resistivities are the averages of large volumes of rocks, including low resistive soils, whereas borehole values indicate the resistivity of only a small volume of material near the bore.

Interpretation of resistivity logs from the wells in sedimentary rocks in Hawaii generally is similar to interpretation of resistivity logs from wells in continental sedimentary rocks. From Figure 11 it can be seen that low resistivities occur opposite the muddy zones which consist predominately of ionized clays, intermediate resistivities occur opposite the more porous but un-ionized reef and beach-rock deposits, and high resistivities occur opposite dense reef limestone and aa basalt. Interpretation of resistivity logs from wells in Hawaiian basalts, however, is considerably different from that of logs in sedimentary rocks. In basalts, intermediate to high resistivities generally occur opposite dense impermeable zones such as the cores of aa and thick pahoehoe flows, and low resistivities occur opposite porous water-bearing zones such as permeable pahoehoe and aa clinker (Fig. 12). Care must be taken not to confuse low-resistivity, porous, water-saturated basalts, which generally have high permeabilities, with highly weathered basalts and buried soils, which also have low resistivities but in general, low permeabilities. In Hawaiian water wells this is not a common problem, however, as weathered layers and soils are not common in the flanks of the volcanic shields formed by lava flows laid down in rapid succession, which constitutes the major aquifers. Even on Kauai, the oldest and the most geologically complex of the Hawaiian islands, no logs were obtained which were thought to indicate soils or weathered layers. SP logs often may be used to aid in the interpretation of suspected buried soils or weathered zones because these zones generally have very low SP's.

When used in conjunction with other available geophysical logs, the interpretative methods described are usually adequate for quick qualitative appraisals and yield useful information concerning the location and general characteristics of water-yielding formations. However, if, true formation resistivity or other quantitative information is desired, the following factors must be considered: (1) borehole diameter effects and bed thickness in relation to electrode spacing, which cause measured apparent resistivities to differ from true formation resistivities, and (2) temperature and water quality variations which cause measured formation resistivities to vary from resistivities at standardized temperatures and salinities.

The well diameter affects apparent resistivity because the zone where resistivity is indicated by the sonde includes the well, filled only with water or drilling fluid, as well as the water-saturated rock. Furthermore, in wells containing brackish or saline water the ease of electrical flow often is greater in the borehole fluid than through the rocks. Consequently, the well-logging current may be shunted up the borehole and may bypass the rock formations, thus suppressing values of measured apparent resistivity. This shunting phenomenon also is often encountered in logging wells in dense limestone formations (Patten and Bennett, 1963). In order to overcome this problem and make logs from wells in limestone more quantitative, special limestone logging devices are used. Hummel and Kulke (1937) suggest a quantitative correction for logs from wells in which shunting is a problem, however, their method applies only to a few restricted cases and is based on mud-filled bores.

As discussed in the preceding section on fundamentals, the well-diameter effects are most pronounced for resistivities indicated by the point resistivity sonde, whose logs are in any case used only in a qualitative way except in the location of tops and bottoms of beds. For the multi-electrode sondes, the well diameter effects are not critical in qualitative evaluation in wells of less than about 24 inches in diameter in fresh water. Most of the water wells in Hawaii have nominal diameters of 12 inches or less and none that have been logged have nominal diameters exceeding 24 inches.

However, in the clinker beds which constitute some of the most permeable portions of basalt lava aquifers, it is not uncommon that caving has resulted in the enlargement of a well far beyond its nominal diameter. The effect of such caving on apparent resistivity is to exaggerate the already low apparent resistivity, thus making clinker zones even more easily distinguishable from dense zones. Lava tubes also produce similar low resistivity zones. The logging results indicate, however, that even in 12-inch diameter wells containing brackish water (conductivities exceeding about 5,000 micromhos or borehole fluid resistivities less than about 2 ohmmeters) the contrast in apparent formation resistivities is materially reduced.

When accurate true formation resistivity is desired, it is necessary to account for well diameter. Schlumberger departure curves (Anonymous, 1962, p. B-2) can be used to compute the effects of borehole diameter on formation resistivity. Based on the ratio of R_{16}/R_m, where R_{16} is the apparent resistivity measured by the 16-inch normal sonde and R_m is the resistivity of the drilling fluid, these curves are primarily useful only for logs from mud-filled holes in sedimentary formations. If the resistivity of the borehole water, R_w, can be substituted for R_m, a sample correction can be applied to resistivities measured in Hawaiian wells. For example, the measured R_{16} in Well #277-102 at Makaha, Oahu ranged from 380 to 560 ohmmeters and the resistivity of the borehole water is 21 ohmmeters. The corrected resistivities using the Schlumberger curves for a 12-inch diameter hole are 440 and 690 ohmmeters, respectively.

The validity of substituting R_w for R_m, or even using the Schlumberger curves in Hawaii at all, is questionable because the curves are based on a three-layer case consisting of a mud-filled borehole, an invaded zone, and the uninvaded formation. Further, the Schlumberger corrections are available only for 16-inch normal and 18-foot lateral configurations. In Hawaiian wells only two different resistivity layers exist, a water-filled borehole and a formation which is saturated with borehole fluid. It is anticipated that curves similar to those given by Schlumberger can be computed for the two-layer case pertinent to Hawaiian wells which will provide corrections for borehole diameter effects for each of the logging sondes in use in the Hawaiian program.

A correction for bed thickness must be made in the determination of true formation resistivity if the thickness of the bed is less than approximately twice the electrode spacing. The average resistivities indicated by the long normal and lateral logs are thought to represent true average formation resistivities for sections on the order of ten feet or more. The short normal logs commonly indicate true formation resistivities for sections with thicknesses greater than three feet except where the well diameter is considerably enlarged by caving. The true formation resistivity is rarely of concern in Hawaiian lava flows or lava flow sequences for thicknesses less than three feet.

Resistivity varies with changes in temperature (see Fig. 13). A change of 5°C in the water temperature amounts to about a 20 percent change in resistivity, decreasing for colder and increasing for warmer waters. It is often desirable to correct resistivity values to a single standardized temperature. In water quality studies the usual standard reference temperature for comparisons of resistivity or conductivity is 25°C (77°F). In oil-well logging, Schlumberger uses 75°F (24°C). As indicated earlier, the range of temperatures found in ground waters on Oahu is relatively small and is only a few degrees centigrade or less in any given well. Furthermore, wells on Oahu normally show quite uniform temperatures throughout their depth, varying from well to well from about 19° to 24°C. Hence apparent formation resistivities on Oahu should be increased by about 8 to 24 percent to conform to standard reference temperatures. However, for the purposes of local interpretation this is not considered necessary if the range of temperature is restricted to a few degrees because usefulness of a log is not changed by a uniform small change of resistivity.

The conductivity of water in Hawaiian wells, as indicated in the previous section on interpretation of fluid conductivity logs, often changes during logging, especially in deep wells. Because water in the borehole generally is identical to formation water in Hawaiian wells, increases in borehole fluid conductivity cause apparent formation resistivities to decrease and decreases cause resistivities to increase. Often it is desirable to apply a correction to resistivity values so

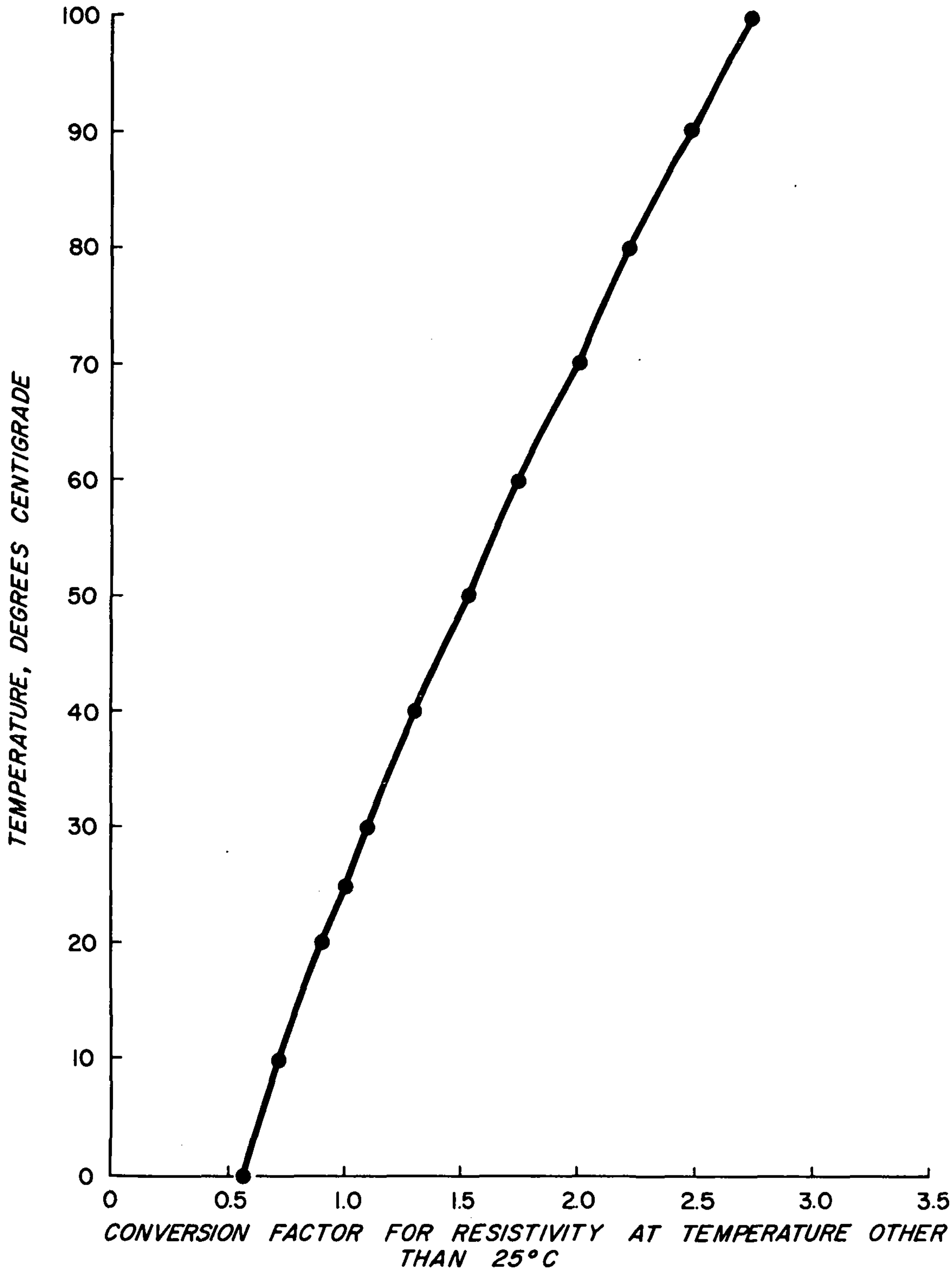


FIGURE 13. CURVE FOR ADJUSTING RESISTIVITY TO 25°C.

that they are standardized to a constant borehole water conductivity. If the resistivity log is not corrected, in some cases erroneous interpretation may result. For example, low resistivity resulting from high formation water conductivity may be confused with low resistivity resulting from highly porous rock layers such as clinkers. A simple empirical method of correcting the measured formation resistivities to a constant fluid resistivity using the conductivity log is outlined below:

1) Pick appropriate points on the fluid conductivity log and convert the conductivities to resistivities by using Figure 14 or equation 9:

$$\text{Resistance (ohmmeter}^2\text{/meter)} = \frac{10{,}000}{\text{Specific Conductance (micromhos)}}. \quad (9)$$

2) Select a convenient point on the conductivity curve, preferably a low value, to serve as a reference value.
3) Subtract or add the reciprocal values of conductance to the resistivity curve according to whether the particular point exceeds (add) or is less (subtract) than the reference conductivity.

Figure 9 shows a 16-inch short normal resistivity log corrected to a constant fluid conductivity of 285 micromhos (fluid resistivity of 35 ohmmeters). This value was used for reference because it is the lowest value of conductivity measured in the hole.

OBTAINING WELL YIELD FROM ELECTRIC WELL LOGS. Probably the most important information, which well logs might contribute, is an estimate of the yield or potential yield of the well or the permeability of the aquifers. The logging techniques used in this study cannot directly indicate yield or permeability, but it was hoped that an estimation of aquifer porosity in the basalt flows might be correlative with permeability.

Data from logs of wells drilled in Hawaiian basalts, however, do not appear to yield reliable quantitative porosity values. This primarily is because (i) the apparent resistivities measured in this study do not always provide accurate indications of true formation resistivity, especially in brackish water-filled holes, and as discussed in the

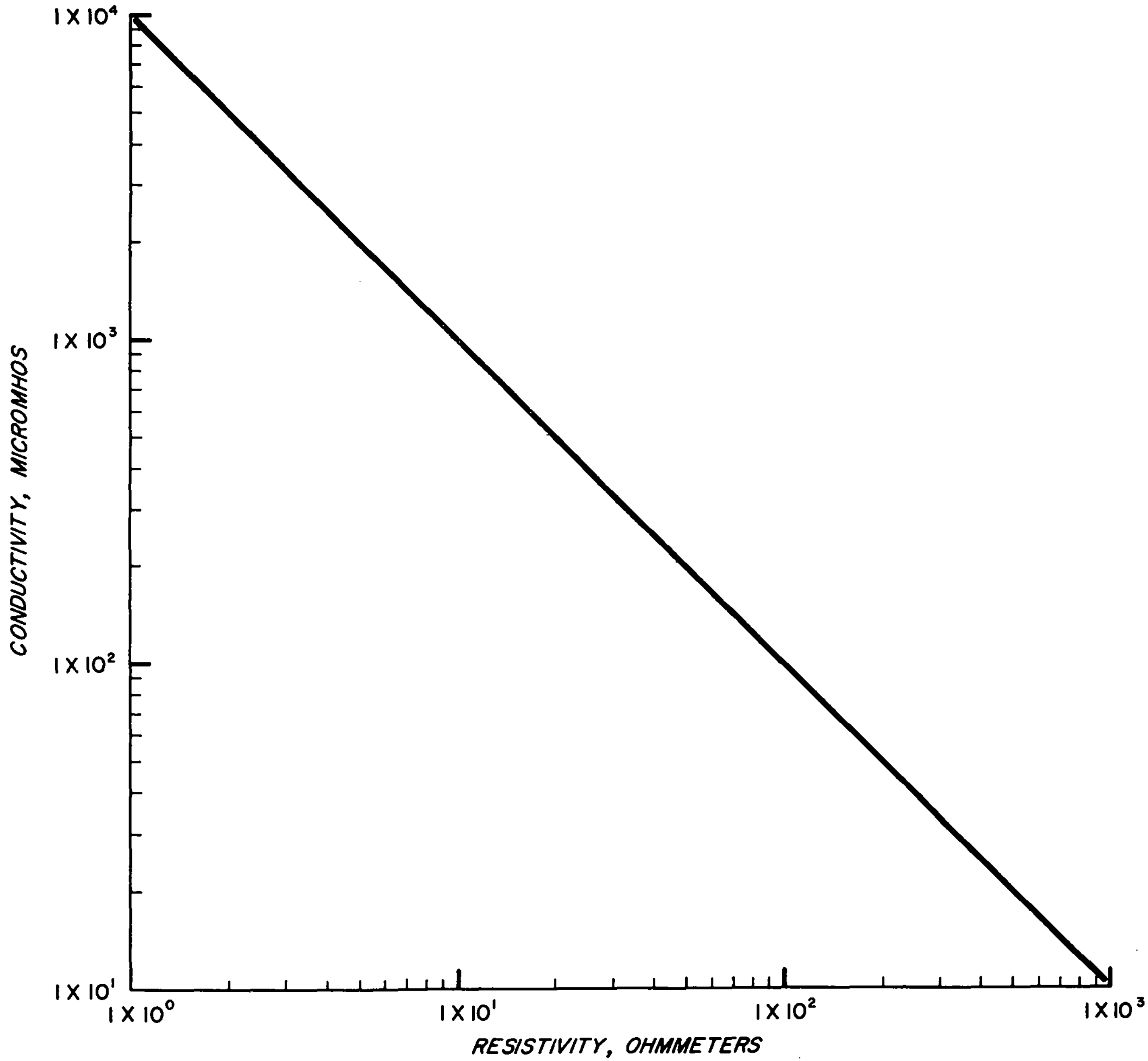


FIGURE 14. CONVERSION OF CONDUCTIVITY TO RESISTIVITY.

previous section, good corrections for the various well diameters, bed thicknesses, and water quality effects are not yet available, and (ii) the currently available formulas, such as equation (8) and tables from standard logging references were developed for obtaining porosity information primarily in sedimentary formations and are not applicable to Hawaiian rocks without great modification. In particular, the constant M in equation (8) is difficult to evaluate in Hawaiian basalts because it probably is extremely variable. Furthermore, equation (8) is basically empirical in nature, even in sedimentary formations, and should not be applied to an aquifer until experimental control has established the validity of the equation in the aquifer and the value of the constant M for the aquifer.

An attempt was made to calculate representative porosities for Hawaiian aquifers using several different borehole fluid conductivities and arbitrary values of M. Values of porosity given for the maximum and minimum resistivities measured in Hawaiian wells, 300 to 700 ohmmeters, respectively, should indicate the range of possible porosities in Hawaiian aquifers. These results are summarized in Table 3. In general, no single set of maximum

TABLE 3. SAMPLE POROSITY CALCULATIONS

CONDUCTIVITY (MICROMHOS)	R_W (OHMMETERS)	R_{01} (OHMMETERS)	R_{02} (OHMMETERS)	m	POROSITY IN PERCENTAGE		F_1	F_2
					ϕ_1	ϕ_2		
				1	33	14		
100	100	300	700	2	57	38	3	7
				3	69	52		
				1	17	7.1		
200	50	300	700	2	41	27	6	14
				3	55	41		
				1	6.7	2.9		
500	20	300	700	2	26	17	15	35
				3	40	32		
				1	3.3	1.4		
1000	10	300	700	2	19	12	30	70
				3	35	24		

and minimum values are very close to what is generally thought to be the true range of porosities in Hawaiian basaltic aquifers. Probably the most reasonable values are obtained by using M = 2 and a fluid conductivity of either 200 or 500 micromhos. However, in both of these cases, the range between minimum and maximum porosities appears to be too small and the minimum porosities calculated from the maximum resistivity of 700 ohmmeters appear to be much too high. A sample porosity calculation, using equation (8), is given below:

Assume: R_w = 20 ohmmeters (conductivity = 500 michomhos)

R_{o1} = 300 ohmmeters

R_{o2} = 700 ohmmeters

$M = 2$

Then: $F = R_o/R_w$

$F_1 = 300/20 = 15$

$F_2 = 700/20 = 35$

$\phi^M = 1/F$

$\phi_1 = \sqrt{1/15} \times 100 = 26\%$

$\phi_2 = \sqrt{1/35} \times 100 = 17\%$

In general, a distinct lack of data exists for porosity determinations from electric logs of water wells in consolidated rock, especially in bores filled with fresh water. At one point in the investigation, some thought was given to making laboratory measurements of resistivity on core samples. However, a core sample would be unlikely to possess the quantity or the wide range of void types responsible for conducting electric current on the scale measured in the field, nor would resistivity from this method provide a representative aquifer sample. Also, the difficulty of coring increases with increased porosity, so that a representative formation ratio of voids to solids in the core would be difficult if not impossible to obtain.

Actually, permeability or effective porosity rather than the intrinsic porosity measured in the field or laboratory is the desired quantitative factor relating to yield of water. In sands and sandstone, porosity is reasonably related to potential yield because porosity generally results from micro-structure in granular material; except for cinders, this is perhaps not completely correct for basalt aquifers. From fresh basalt exposures, one can easily observe the wide variation of structures varying from pure micro to very large macro sizes that govern porosity. The structures include cracks and joints of all sizes, vesicles of varying size and number, cavities and lava tubes, irregular contacts between flows and most important, the clinker zones. Water flow in these structures ranges from very low in dense unjointed rock or rock with poorly connected vesicles to conduit flow of large magnitude (Table 4). For example, porosity in a vesicular flow

TABLE 4. TOTAL POROSITY IN CORES OF KOOLAU BASALTS FROM OAHU (AFTER WENTWORTH, 1938).

LOCATION		PERCENTAGE POROSITY
HOLE	22-43'	42.6
	22-77'	58.3
	24-75'	51.4
	24-154'	44.3
	27-333'	5.2
	27'374"	6.5

might be high, but because the vesicles are poorly interconnected both effective yield and permeability are low, whereas, some large cracks of clinkers would have much higher yield and permeability.

From correlation of good driller's logs with electric logs and well performance, clinker zones seem to be the best water producers, and, especially if unweathered, have porosities up to perhaps 50 percent. At the other end of the porosity scale dense flows may have porosities of less than 5 percent, cracks included.

Borehole Photographic and Television Logging

In addition to the conventional well-logging techniques reviewed in the third chapter of this report and the geophysical logging techniques which were introduced through the project and the results of which are the principal topic of this report, two optical logging techniques have been used in Hawaiian wells. One involves television with incidental photography of the television screen and the other involves down-hole photography.

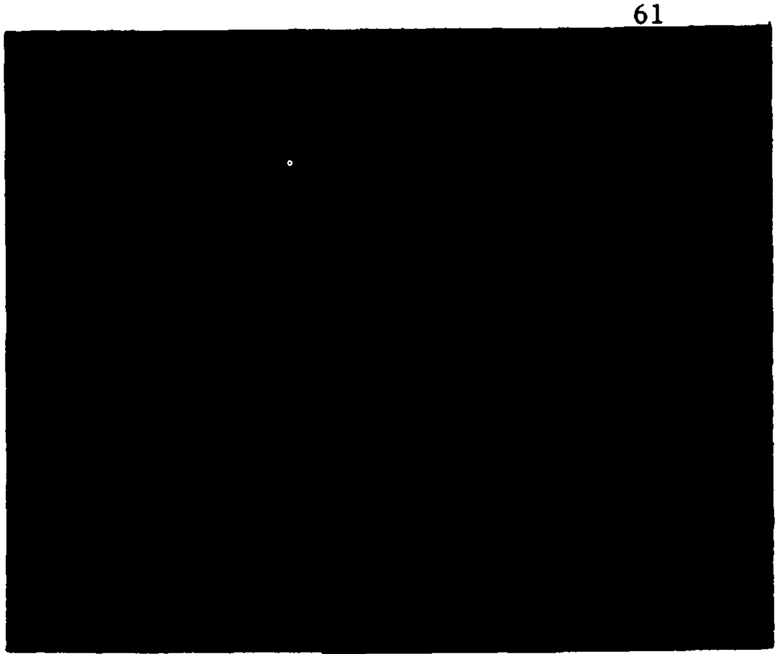
WELL INSPECTION BY TELEVISION. The first Hawaiian trial of down-hole television was made by Layne International, Incorporated in April 1960 for Kekaha Sugar Company, Kauai. Five old wells on the Mana plain where casings were obstructed were surveyed in an attempt to identify the nature of the obstructions.

Muddy water and oil limited visibility in two of the wells but the nature of the obstructions in the other three was indicated clearly on the television screen. Photographs of the screen (Figs. 15a, 15b, and 15c) show the obstructions in two of the wells. No surveys were made below the casings or in unobstructed wells.

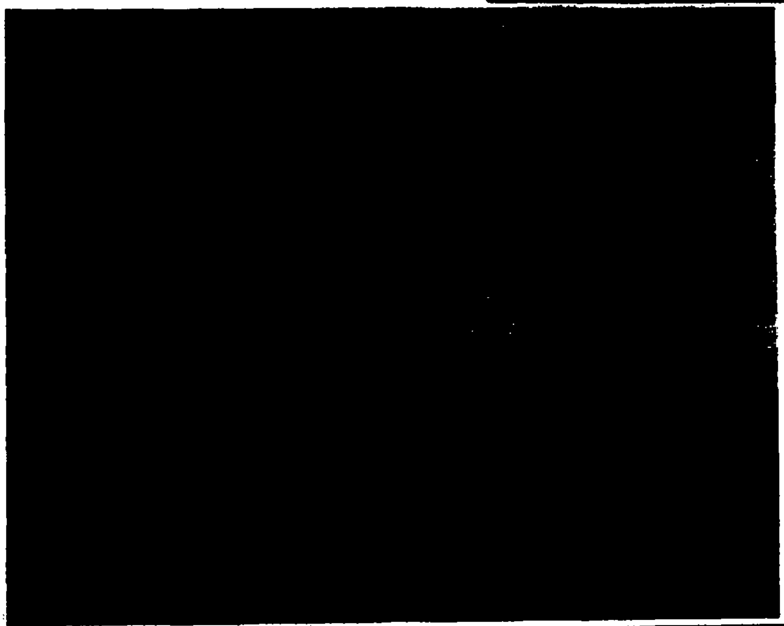
The Honolulu Board of Water Supply attempted television inspection of a leaky well casing at Beretania Pumping Station in July, 1968 and retained the services of Penetron Western, a firm then engaged in television inspection of sewers in Honolulu. Image quality during the brief transmission period was good, however, the attempt was unsuccessful owing to malfunction of the quartz-iodine lighting system. No further attempts were made with television. The casing inspection was subsequently completed with the Laval-type stereo well camera described in the following section of this report.

WELL INSPECTION BY PHOTOLOGS. A Laval-type well camera using a pair of matched lenses for stereo photography was used to photograph 22 wells on Oahu (electric logs were available for 9 of the wells). The work was performed for the Honolulu Board of Water Supply by Western Well Services of Hanford, California during the summer of 1968. The Water Resources Research Center logger was used to lower and to operate the camera and to monitor footage. Exposures were made every two feet to provide a slight photo overlap. A fast strobe light permitted continuous exposure of film without stopping the winch. A total of 2,759 feet of the basal aquifer were recorded.

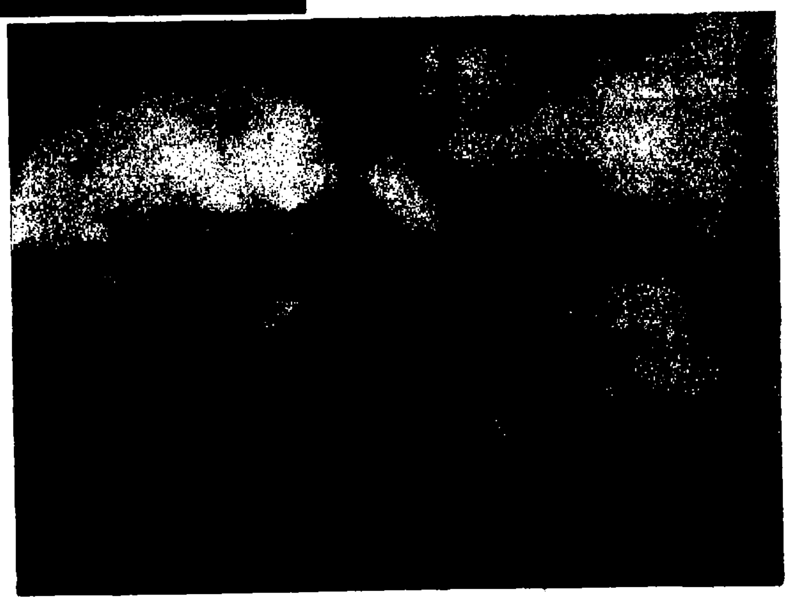
The images were recorded on 35 millimeter black and white negative film which was developed in the field in a daylight developing tank. Image quality was excellent in general and considerable detail could be discerned. Use of 35 mm focal-length lenses minimized but did not eliminate all problems of focus. However, the study of negative images is inconvenient in that considerable time is required for becoming accustomed to them. Furthermore, the camera was aimed downward because the well bores were too small to accomodate an attachment for taking pictures at right angles which would have made inter-



A. BOULDER OBSTRUCTING WELL NO. 44 AT MANA. DARK AREA TO THE LEFT OF BOULDER IS OPEN HOLE.



B. BOULDERS OBSTRUCTING WELL NO. 32A, AT KAUNALEWA.



C. IRON BAR DISCLOSED WHEN BOULDERS SHOWN IN B HAD BEEN DISLODGED BY THE TELEVISION CAMERA.

FIGURE 15. PHOTOGRAPHS OF TELEVISION IMAGES OF OBSTRUCTIONS IN WELLS ON MANA PLAIN, KAUAI.

pretation easier. Despite image excellence, determination of the type of lava in view is not always easy. Drilling sometimes obliterates rock textures and structures useful in identification. Color reversal film and a view normal to the well bore would make identification easier and more positive.

Nevertheless, positive and useful identification of flow types can be made. For example, pahoehoe flows frequently show curved color bands, or curved ribs projecting into the bore, or characteristically hemispherically shaped voids left by drainage of liquid lava. Clinker zones exhibit irregularly shaped bores of variable dimensions in which individual clinkers can be commonly distinguished. Vesicles appear frequently in dense flows. Very dense, thick flows show uniform bores of circular shape in which vertical jointing can be seen. Sometimes fracture cones occur where the drill bit passes from a dense flow into weaker rock and the hole "bells" out. Soft formations, such as weathered rock, or perhaps ash beds, on occasion, show cable striations from the drilling operation.

Correlation between the photologs and the electric logs is very good. An example of comparison of the driller's log, a photolog and electric logs is shown in Figure 16. Note that the electric log interpretation has lithologic character not normally obtainable from electric logs alone. This additional detail is supplied by the photolog and gives a more composite, comprehensive appraisal of the zone.

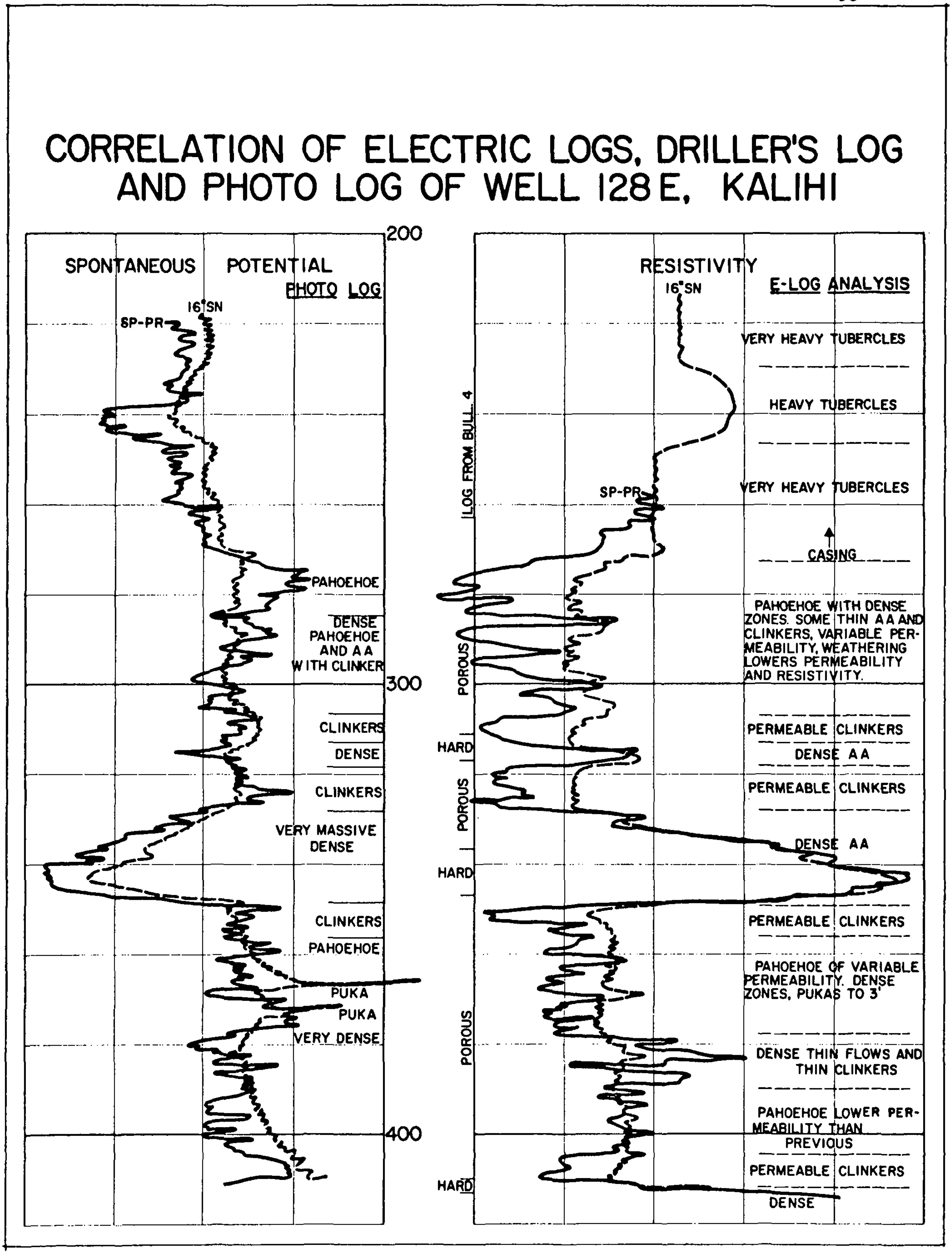


FIGURE 16. CORRELATION OF ELECTRIC LOGS, DRILLER'S LOGS AND PHOTO LOG OF WELL 128E, KALIHI, OAHU.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The problems of geophysical well logging, and in particular electric well logging, in Hawaii are unusual because of the relatively uniform composition of the basalts which constitute most of the aquifers and the complex relation of porosity to resistivity in basaltic aquifers and because logging usually is performed in water-filled boreholes.

Spontaneous potentials in local rocks are thought to result from electrochemical reactions and from fluid flow and probably primarily from the latter because of the uniformity of rock composition and the water-filled condition of the wells. Consequently, in Hawaiian basalts, positive SP's generally indicate zones with flow from the aquifer into the well. Negative SP's generally indicate the reverse condition, or zones with flow from the well into the aquifer. Spontaneous potential logs from wells in sedimentary formations commonly are used to locate permeable zones and to estimate formation water quality. In Hawaii, however, owing to the lack of chemical contrast in the rocks and because the fluid conductivity module measures water quality directly, SP logs are used primarily for correlation with resistivity, conductivity, and caliper logs.

The elaborate and sophisticated methods devised for the quantitative interpretation of formation resistivity logs in oil wells and in water wells in sedimentary rocks are generally not applicable in Hawaii. Furthermore, in Hawaii many of the devices such as neutron logs and borehole flow logs, which might have made the resistivity interpretation more quantitative, were not available to this investigation. Where logging does produce good results, the circumstances of water-filled wells and an imperfect knowledge of formation resistivity factors for Hawaiian basalts prevent the successful application of standard resistivity interpretation techniques for quantitatively reliable determination of porosity at present. Nevertheless, resistivity logging produced much important qualitative information and some quantitative information. Successful resistivity logging in Hawaii probably is due to a favorable ratio of resistivities of formation water to formation resistivity.

Electric logging and the other geophysical well-logging techniques tested in Hawaii in this study supplied much of the desirable geologic, hydrologic, and geometric information discussed in the section of this report on "Types of Well-Log Information in Hawaii." As indicated earlier, the geologic information desired from logging consists primarily of identifying rock characteristics and types. Both SP logs and resistivity logs from the few wells in Hawaiian sedimentary formations yielded useful information. Spontaneous potential logs commonly indicate permeable zones and resistivity logs are useful indicators of rock types and other rock characteristics. Resistivity logs from wells in basaltic aquifers indicate the location and thickness of each bed and the number and total thicknesses of permeable and less permeable formations and are extremely useful as indicators of water-yielding zones. High resistivities generally are indicative of dense impermeable basalts and low resistivities are indicative of porous permeable zones most likely to contribute water to the borehole. The highly variable thickness and lateral extent of individual lava flows, which results from topographic control, hampers correlation of the logs except where the wells are close together.

None of the electric logging techniques employed in this study can provide positive identification of rock types. However, the borehole photography used recently by the Honolulu Board of Water Supply provides identification of most Hawaiian rock types.

Hydrologic information desired from logging consists of measurements of rock porosity and permeability, head, flow velocity, water salinity or conductivity, and water temperature. Thus far, electric well logging and other geophysical well-logging methods employed in Hawaii have not provided quantitative measurements of rock porosity and permeability. However, as indicated above, considerable qualitative information on water yield from Hawaiian basalts is provided by resistivity logging. Quantitative estimation of porosities might be made possible by the use of computed correction curves for the diameter of and fluid-conductivity in the wells and should be facilitated by the addition of a radioactive logging capability.

Conductivity and temperature logs give a direct quantitative measure of water conductivity and water temperature, and provide considerable insight into the depth, thickness, quality, and temperature of waters contained in the wells of Hawaii. Furthermore, borehole conductivity and temperature data aid in the interpretation of complex dynamic Ghyben-Herzberg lens relationships.

Few reliable measurements of head, and no quantitative measurements of flow velocity were made during this study. It is hoped that future addition of a borehole flow-meter will provide measurement of flow velocity for use in quantitative estimates of water yields. Furthermore, caliper logging will enable the detection of sections of the borehole wall suitable for sealing with packers for possible head determinations.

Geometric information desired from logging consists primarily of measurements of well diameter as well as depth to the water and depth of the casing and the hole. Although the caliper module has not performed as well as expected and has been subject to non-linearity of readout and instability and frequent repairs, caliper logs give a direct quantative measure of well diameter. Recent alterations of the caliper module's design should allow the device to perform to its expected capability. Spontaneous potential and resistivity logs also provide direct measurements of depth to the water and depth of the casing and the hole.

Recommendations

In general, the goals of the well-logging program have been successfully met and the usefulness of the electric logging equipment in the study of Hawaiian aquifers has been affirmed over the past two years. However, a number of suggested recommendations to improve logging programs are listed below.

Equipment

1) Acquisition of a neutron module to allow determination of formation bulk porosity *in situ* which presently is not available from resistivity logs.
2) Addition of a borehole flow-meter unit to enable determination of velocities in well bores, and the location of horizons contributing and receiving water, as well as the location of leaky casings.

3) Conversion of the winch from mechanical to hydraulic drive to provide more efficient logging operations.
4) Periodic updating of the basic logging equipment to offset the decrease in reliability with age and to take advantage of advancements in the field of well logging by the purchase of new systems.

Logging Programs

1) Computer-calculated correction curves for different well diameters should be prepared for each resistivity logging sonde.
2) On future wells penetrating to salt water, consideration should be given to experimenting with drilling-mud makeup to obtain better logs.
3) Key wells should be monitored periodically for seasonal and long-term changes of salinity and temperature to provide greater understanding of the Ghyben-Herzberg lens (this program has already been initiated by the Honolulu Board of Water Supply).
4) The necessary chemical analytical data should be compiled so that departure curves can be made for the relationship of specific conductance to total dissolved solids in the various hydrologic units of Oahu.
5) Logs of wells drilled on other islands of the state should be obtained whenever possible.
6) Personnel from all interested agencies should be trained in the use of well-logging equipment to increase the manpower pool.

ACKNOWLEDGEMENTS

The authors wish to express their grateful appreciation and acknowledgements to the following people and agencies for having made possible this study.

L. S. Lau, Associate Director of the Water Resources Research Center, provided general guidance to the project, especially in the period from August 1966 to August 1967, when D. C. Cox was on sabbatical leave, and was instrumental in obtaining funds for the second year of the project.

The Honolulu Board of Water Supply provided financial support and active field support to the well logging project. The late E. J. Morgan, former manager of the BWS, and G. A. L. Yuen, his successor, provided encouragement through their interest in logging capabilities. S. P. Bowles, especially, assisted in the planning of the project, and both he and C. M. Murata participated in much of the logging operation. Glenn Masui and Joe Grance also assisted in logging. The Board of Water Supply further complemented the logging project by a program of down-hole photography the results of which are summarized in this report.

The Hawaii Department of Land and Natural Resources, Division of Water and Land Development provided not only financial support, but thanks to the interest of its Manager, R. T. Chuck, DOWALD also provided field assistance. Dan Lum, Harvey Young, and Stanley Shin assisted in logging DOWALD wells on Oahu, and Richard Teragawa assisted in logging DOWALD wells on Kauai and arranged for pickup and reshipment of the logging jeep.

Robert Dale and Isao Yamashiro of the U. S. Geological Survey provided assistance in logging some of the wells on Oahu.

The Kauai Board of Water Supply, especially Manager Walter Briant and Deputy Manager Larry Nishikawa made arrangements for logging of irrigation wells on Kekaha and Lihue plantations on Kauai.

The Craddick brothers, managers of the local division of Layne International, cooperated by allowing WRRC to fit logging into their otherwise tight well-drilling schedules. The local division of Roscoe Moss Company also cooperated similarly. Owners of agricultural wells on both Kauai and Oahu cooperated by arranging for access to their wells.

Graduate assistants G. T. Bandy, Tsegaye Hailu, and Melvin Caskey frequently assisted in logging, and Mr. Bandy and Mr. Hailu learned to operate the logger.

Paul H. Jones, well-logging expert of the U. S. Geological Survey, Baton Rouge Office, provided much appreciated encouragement and supplied several technical papers.

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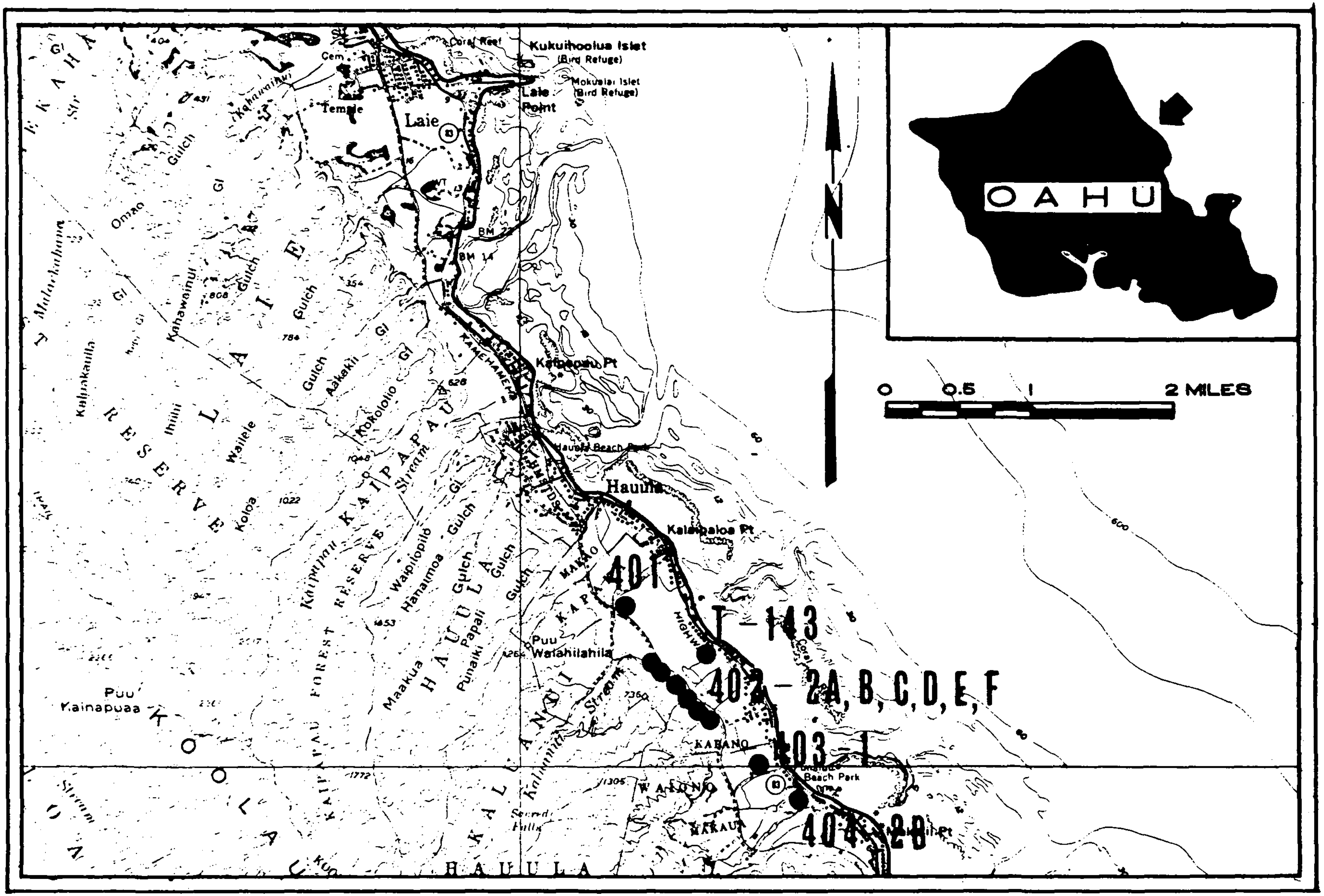
APPENDICES

APPENDIX A. LOCATION MAPS OF WELLS LOGGED ON OAHU AND KAUAI



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(Bird Refuge)
Mokuualai Islet
(Bird Refuge)
Coral Reef
Cem
Temple
Laie
Laie Point
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Gulch
Omao
Kahawainui
Gulch
BM 27
BM 14
KAMEHAMEHA
Kaipapau Pt
Aakakii
Gulch
Kokololio
Stream
Wailele
Ihiihi
Koloa
RESERVE
LAIE
KAIPAPAU
Hauula Beach Park
Hauula
Kalaipaloa Pt
Waipilopilo
Gulch
Hanaimoa
Gulch
Papali
Gulch
Maakua
Punaiki
Puu
Walahilahila
Puu
Kainapuaa
FOREST
RESERVE
HAUULA
KALUANUI
KOOLAU
Kaluanui
Stream
Sacred
Falls
KAPAKA
WAIONO
MAKAUA
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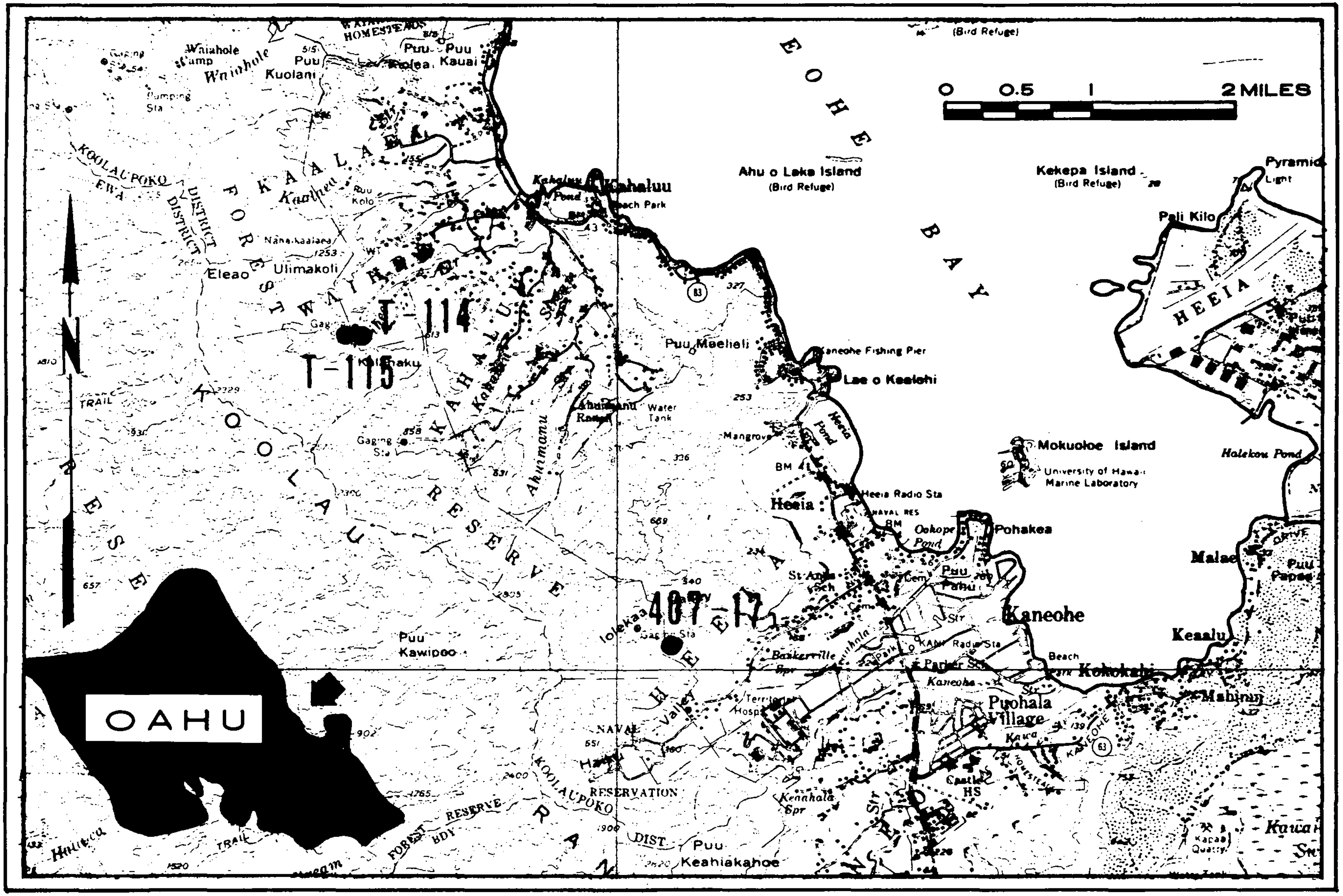
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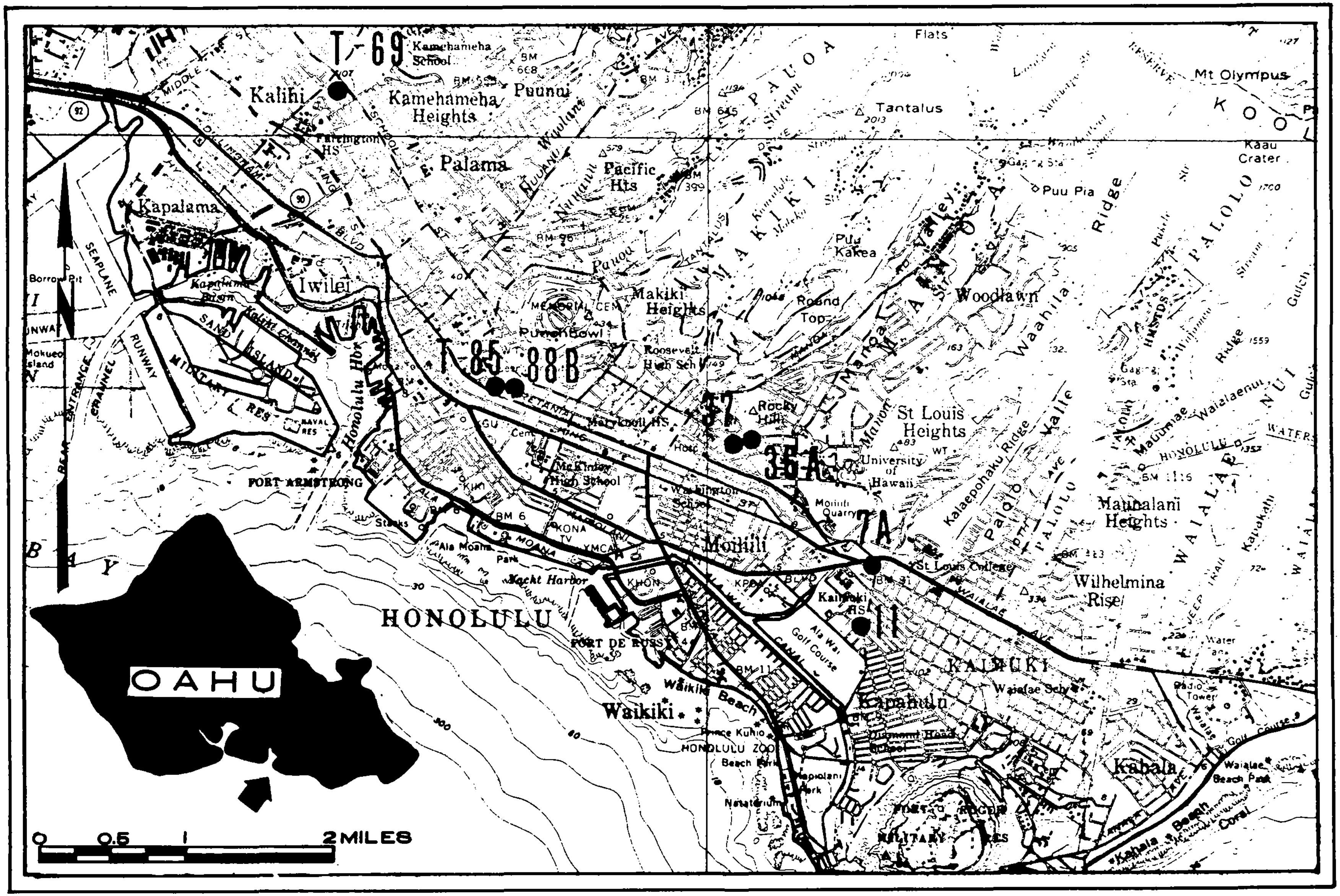
OAHU
T-114
T-115
407-17
KANEOHE BAY
Kaneohe
Kahaluu
Heeia
Ahu o Laka Island
(Bird Refuge)
Kekepa Island
(Bird Refuge)
Mokuoloe Island
University of Hawaii
Marine Laboratory
Lae o Kealohi
Kaneohe Fishing Pier
Heeia Radio Sta
Pohakea
Puu Maelieli
Puohala
Village
Castle
HS
Keaalu
Kokokahi
Malae
Pali Kilo
Pyramid
Light
Holekou Pond
HEEIA
Puu
Kawipoo
Puu
Keahiakahoe
Ulimakoli
Eleao
Kuolani
Waiahole
KOOLAU RESERVATION
FOREST RESERVE
KOOLAUPOKO
EWA
DISTRICT
NAVAL
RESERVATION
Kaneohe
Baskerville
Spr
Kenahala
Spr
Water
Tank
Mangrove
Gaging
Sta
Pumping
Sta
Beach
Kapaa
Quarry



T-69
T-85
88B
57
35A
7A
11
Kalihi
Kamehameha School
Kamehameha Heights
Puunui
Palama
Farrington HS
Pacific Hts
Kapalama
Iwilei
Kapalama Basin
Sand Island
Kalihi Channel
Honolulu Hbr
Punchbowl
Memorial Cem
Makiki Heights
Roosevelt High Sch
Maryknoll HS
McKinley High School
Washington School
Moiliili
Moiliili Quarry
Tantalus
Mt Olympus
Kaau Crater
Puu Pia
Puu Kakea
Round Top
Rocky Hill
Woodlawn
St Louis Heights
University of Hawaii
St Louis College
Kalaepohaku Ridge
Maunalani Heights
Wilhelmina Rise
Kaimuki
Kaimuki HS
Kapahulu
Waialae Sch
Kahala
Waikiki
Waikiki Beach
Ala Moana Park
Yacht Harbor
Ala Wai Golf Course
HONOLULU
FORT ARMSTRONG
FORT DE RUSSY
Honolulu Zoo
Kapiolani Park
Natatorium
Diamond Head School
Kahala Beach
Waialae Beach Park
Radio Tower
Borrow Pit
Seaplane
Runway
Mokuleo Island
Military Res
Manoa Valley
Palolo Valley
Paloa
Waahila Ridge
Waialae Nui
Makiki
Manoa
Palolo
OAHU
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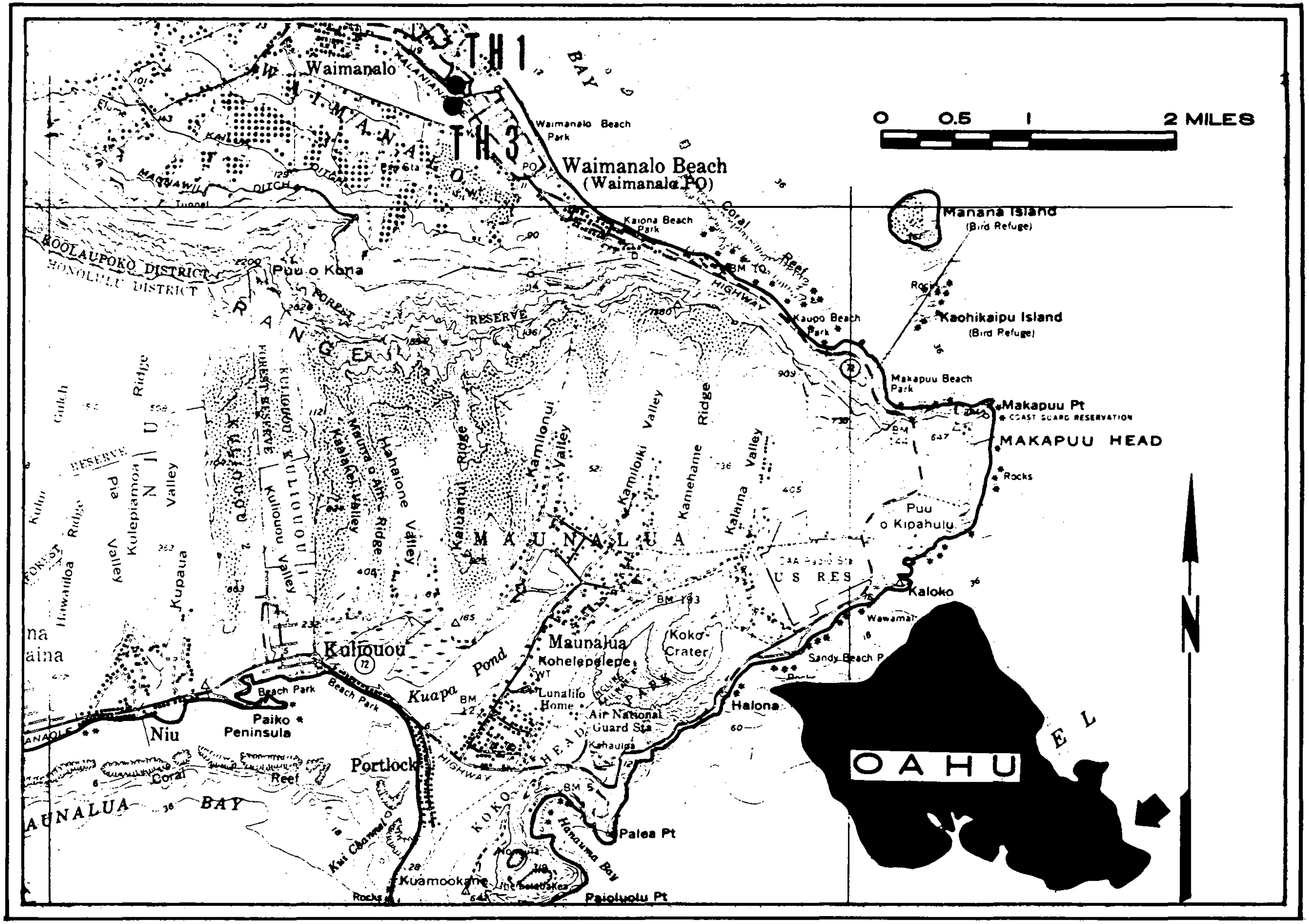
TH1
TH3
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Waimanalo
Waimanalo Beach Park
Waimanalo Beach
(Waimanalo PO)
Kaiona Beach Park
Coral Reef
HIGHWAY
Manana Island
(Bird Refuge)
Kaohikaipu Island
(Bird Refuge)
Kaupo Beach Park
Makapuu Beach Park
Makapuu Pt
COAST GUARD RESERVATION
MAKAPUU HEAD
Rocks
Puu o Kipahulu
Kaloko
Wawamalu
Sandy Beach P
Halona
KOOLAUPOKO DISTRICT
HONOLULU DISTRICT
Puu o Kona
FOREST RESERVE
RANGE
MAUNALUA
Kamilonui Valley
Kamiloiki Valley
Kamehame Ridge
Kalama Valley
Kaluanui Ridge
Hahaione Valley
Kuliouou Valley
Kupaua
Pia Valley
Niu Valley
Kulepiamoa Ridge
Hawaiiloa Ridge
Kuliouou
Maunalua
Kohelepelepe
Koko Crater
Lunalilo Home
Air National Guard Sta
Kahauloa
Kuapa Pond
Beach Park
Paiko Peninsula
Niu
Portlock
Coral Reef
MAUNALUA BAY
Kui Channel
Kuamookane
Rocks
KOKO HEAD
Hanauma Bay
Palea Pt
Paiolyolu Pt
US RES
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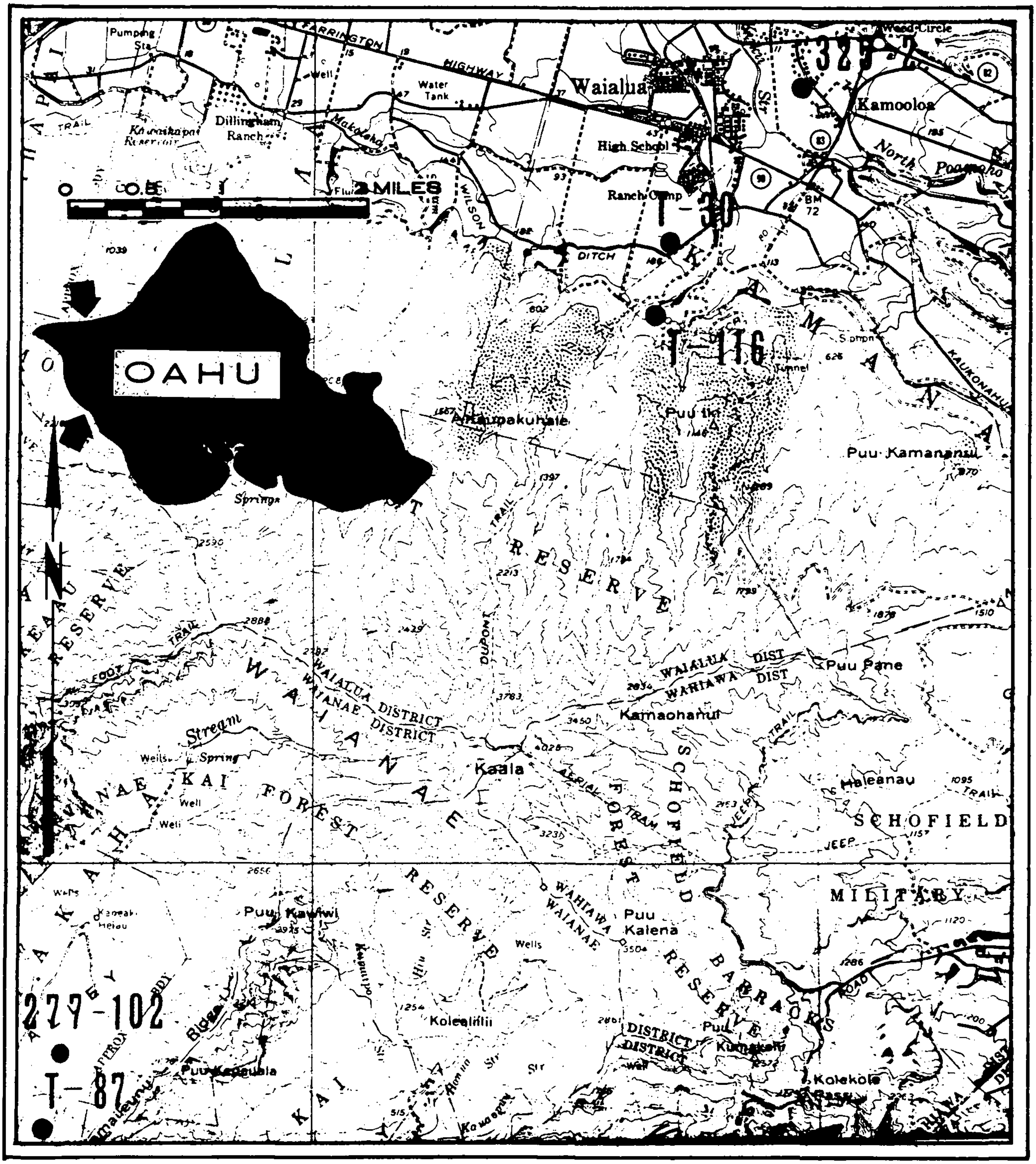
OAHU
N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Ranch Camp
Dillingham Ranch
Kamoolo
North Poamoho
FARRINGTON HIGHWAY
Water Tank
Pumping Sta
T-30
T-116
325
Puu Iki
Puu Kamananui
Kaala
Kamaohanui
Puu Pane
Haleanau
SCHOFIELD
MILITARY
BARRACKS
Puu Kalena
Puu Kawiwi
Kolealiilii
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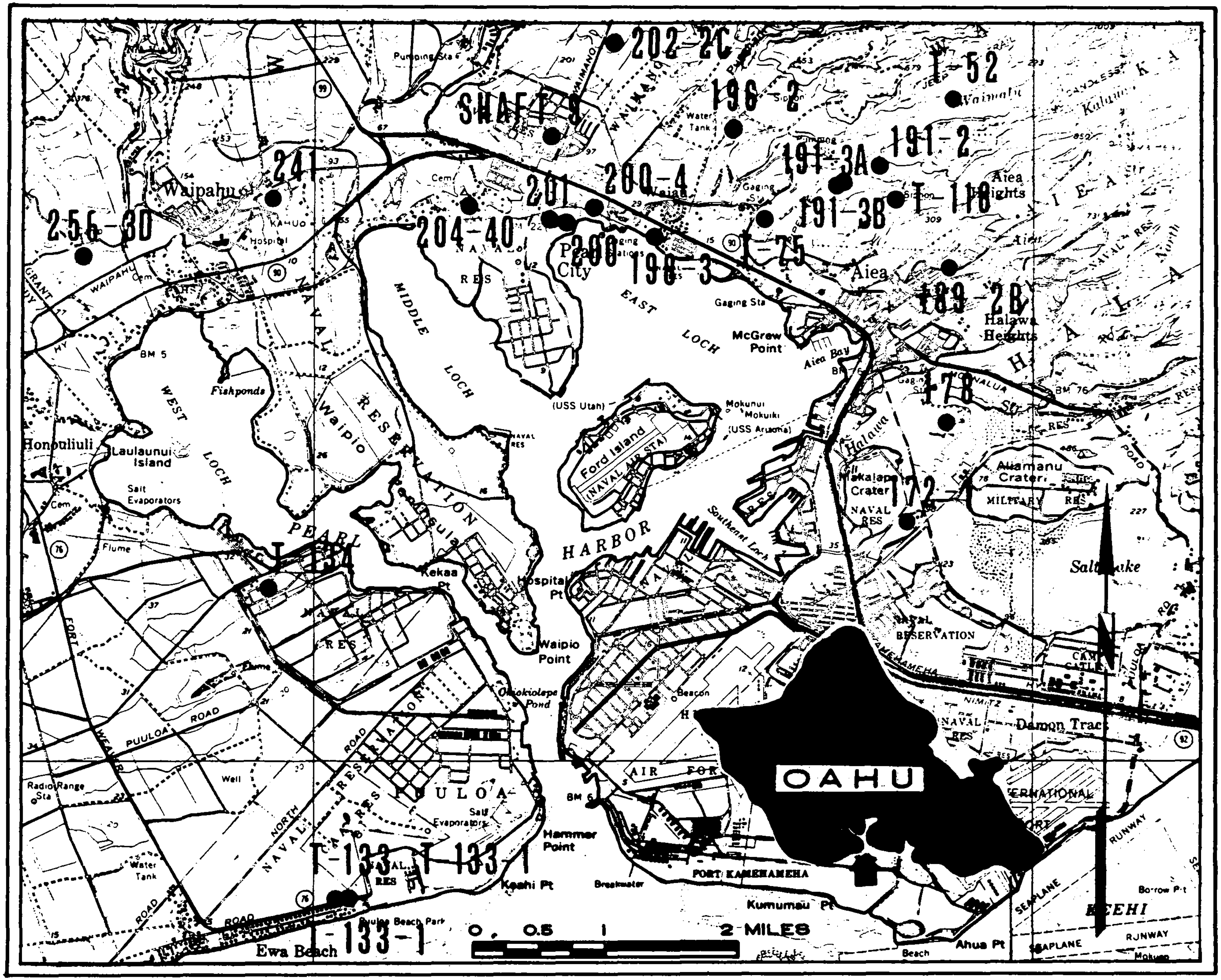
Kolekole Pass
WAIANAE KAI FOREST RESERVE
WAIALUA DISTRICT
WAIANAE DISTRICT
WAHIAWA
277-102
T-87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T-118
Waipahu
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191-3B
256-3D
204-40
200
T-75
Pearl City
198-3
Aiea
189-2B
Halawa Heights
WAIPAHU
NAVAL
MIDDLE LOCH
EAST LOCH
McGrew Point
Gaging Sta
Aiea Bay
BM 5
WEST LOCH
Fishponds
Waipio
RESERVATION
(USS Utah)
Mokunui
Mokuiki
(USS Arizona)
Ford Island
(NAVAL AIR STA)
178
Honouliuli
Laulaunui Island
Salt Evaporators
Halawa
Aliamanu Crater
Makalapa Crater
172
NAVAL RES
MILITARY RES
PEARL
HARBOR
Southeast Loch
Salt Lake
Flume
T-131
Kekaa Pt
Hospital Pt
NAVAL RESERVATION
Waipio Point
PUULOA ROAD
Ohiokiolepe Pond
Beacon
KAMEHAMEHA
NIMITZ
NAVAL RES
Damon Tract
OAHU
Radio Range Sta
Well
PUULOA
BM 6
Salt Evaporators
Hammer Point
INTERNATIONAL
RUNWAY
T-133
T-133-1
Water Tank
Keahi Pt
Breakwater
PORT KAMEHAMEHA
Kumumau Pt
Borrow Pit
SEAPLANE
KEEHI
Puuloa Beach Park
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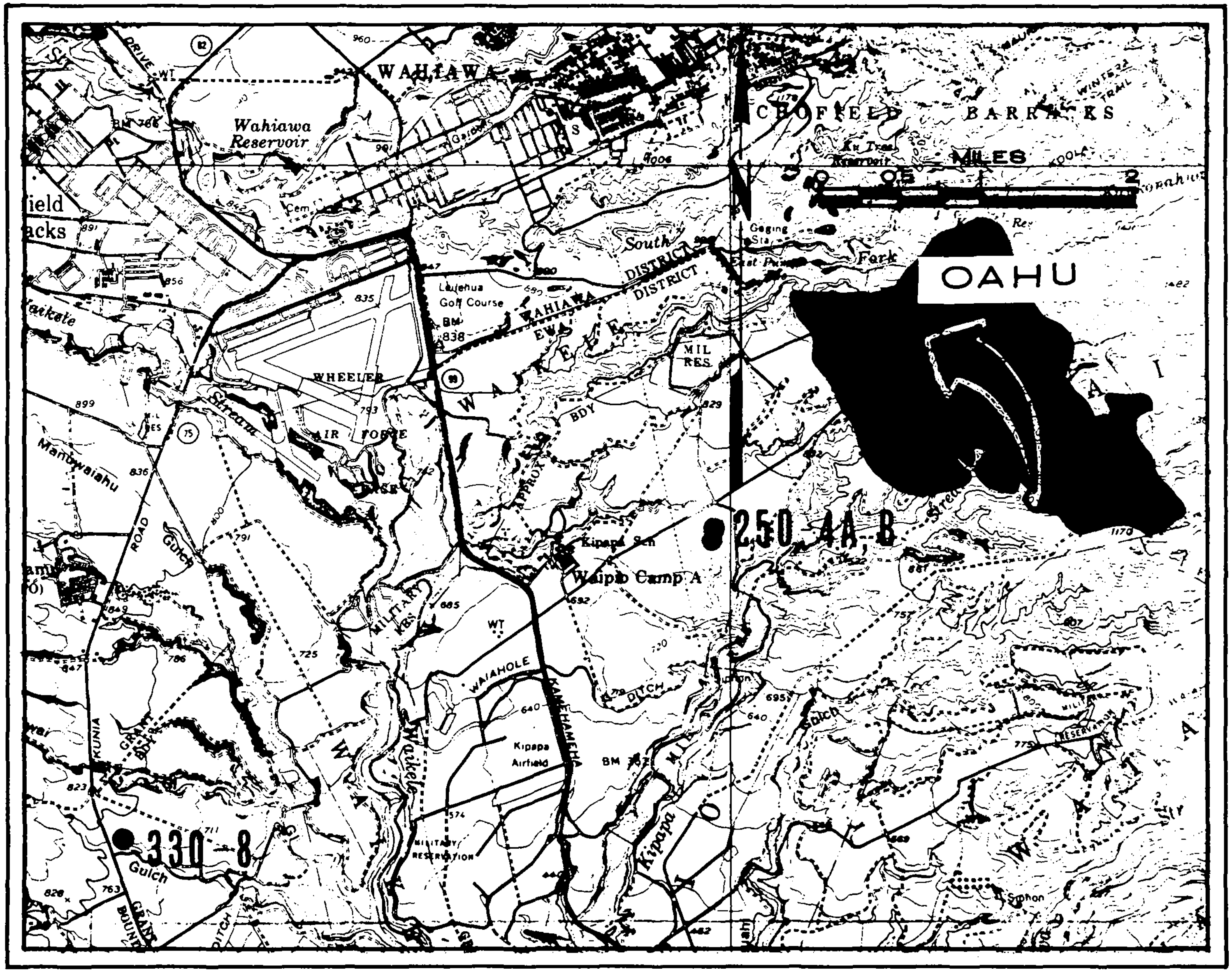
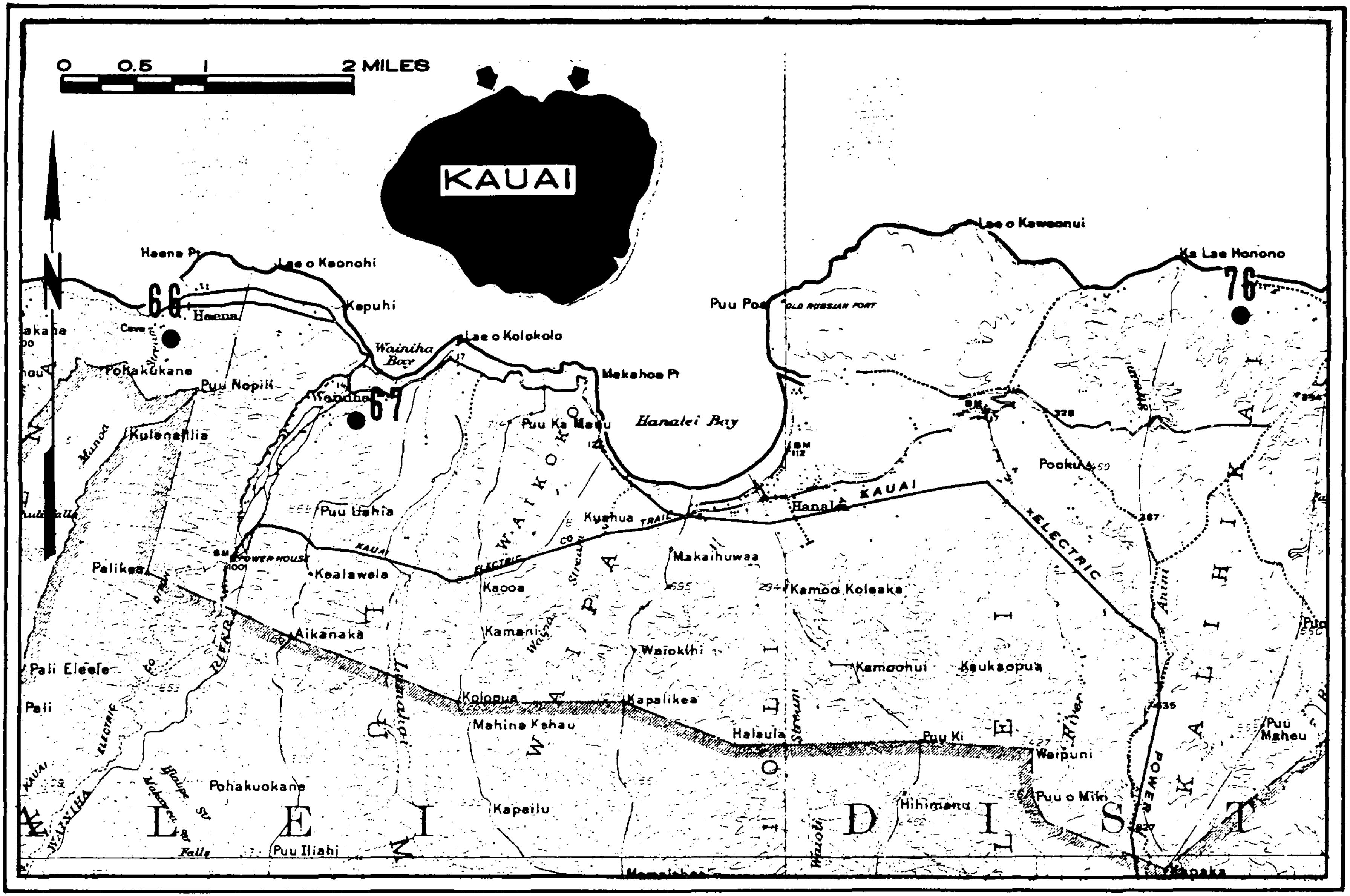
Ewa Beach
Beach
Ahua Pt
SEAPLANE RUNWAY
Mokuea


WAHIAWA
Wahiawa Reservoir
MILES
OAHU
Leilehua Golf Course
WHEELER
AIR FORCE
WAHIAWA DISTRICT
EWA DISTRICT
MIL RES
Kipapa Stn
Waipio Camp A
250 4A B
330 8
WAIAHOLE
DITCH
Kipapa Airfield
MILITARY RESERVATION
KUNIA
ROAD
Gulch
Siphon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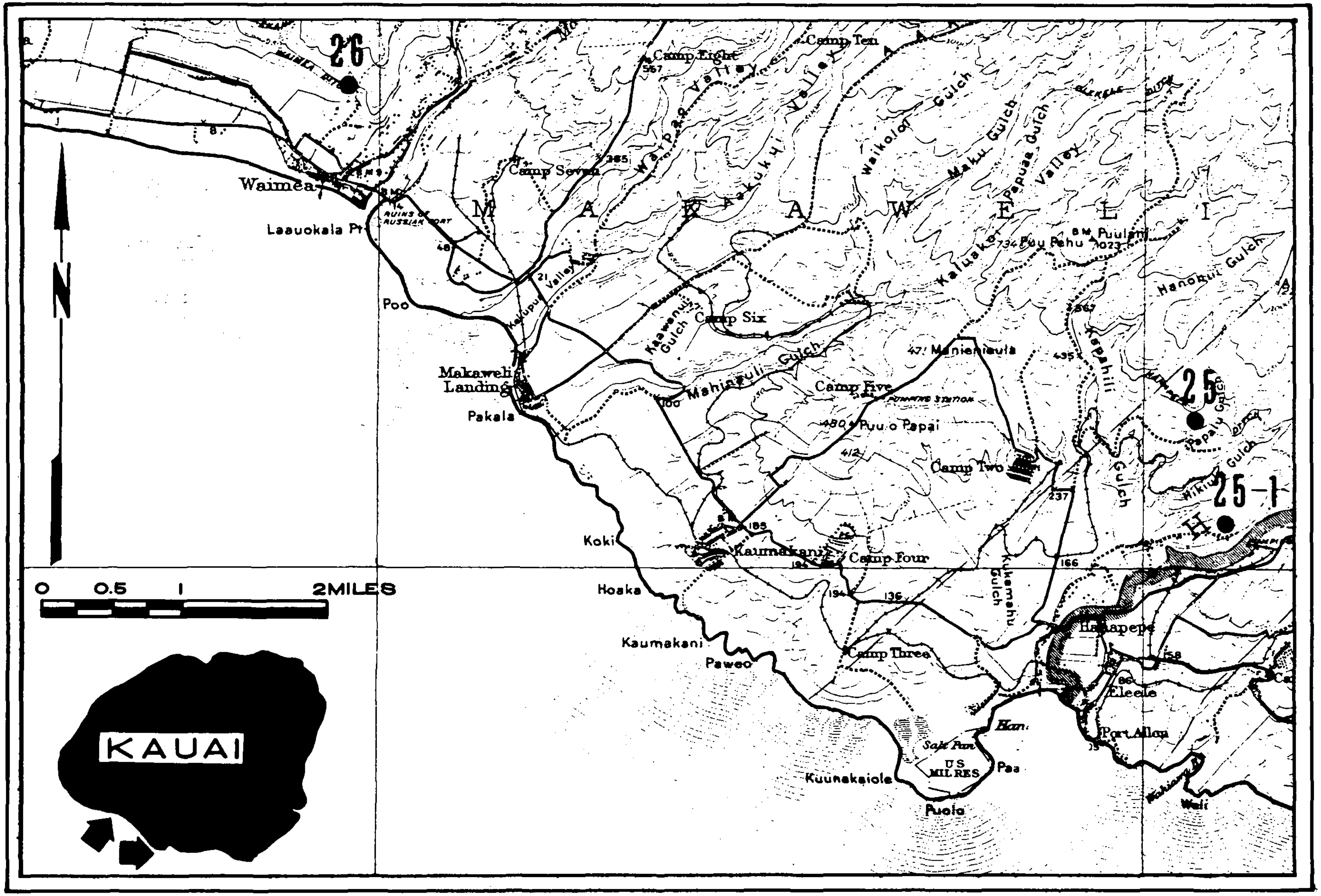
KAUAI
Haena Pt
Lae o Keonohi
Kepuhi
Haena
Cave
Pohakukane
Puu Nopili
Kulanaililia
Wainiha Bay
Lae o Kolokolo
Makahoa Pt
Hanalei Bay
Puu Ka Manu
Puu Poa
OLD RUSSIAN FORT
Lae o Kaweonui
Ka Lae Honono
66
67
76
Puu Uahia
Kuahua
TRAIL
KAUAI ELECTRIC CO
Hanalei
Pooku
POWER HOUSE
Palikea
Kealawela
Kaooa
Makaihuwaa
Kamoo Koleaka
Aikanaka
Kamani
Waiokihi
Kamoohui
Kaukaopua
Pali Eleele
Pali
Kolopua
Kapalikea
Mahina Kehau
Halaula
Puu Ki
Waipuni
Puu Maheu
Pohakuokane
Kapailu
Hihimanu
Puu o Miki
Puu Iliahi
Falls
POWER
Kapaka
WAIPA
WAIKOKO
HALELEA DIST
Hanalei River
Waioli Stream



26
Camp Ten
Camp Eight
Waimea
Laauokala Pt
Ruins of Russian Fort
Camp Seven
Waipao Valley
Kaakuku Valley
Waikoloi Gulch
Maku Gulch
Papuaa Gulch
Valley
M A K A W E L I
Puu Pehu
Puulani
Hanohui Gulch
Poo
Camp Six
Kaawanui Gulch
Mahinauli Gulch
Manienieula
Makaweli Landing
Pakala
Camp Five
Pumping Station
Puu o Papai
Camp Two
Kepahili Gulch
25
Papalu Gulch
25-1
Koki
Kaumakani
Camp Four
Kukamahu Gulch
Hoaka
Hanapepe
Kaumakani
Paweo
Camp Three
Eleele
Port Allen
Salt Pan
US MIL RES
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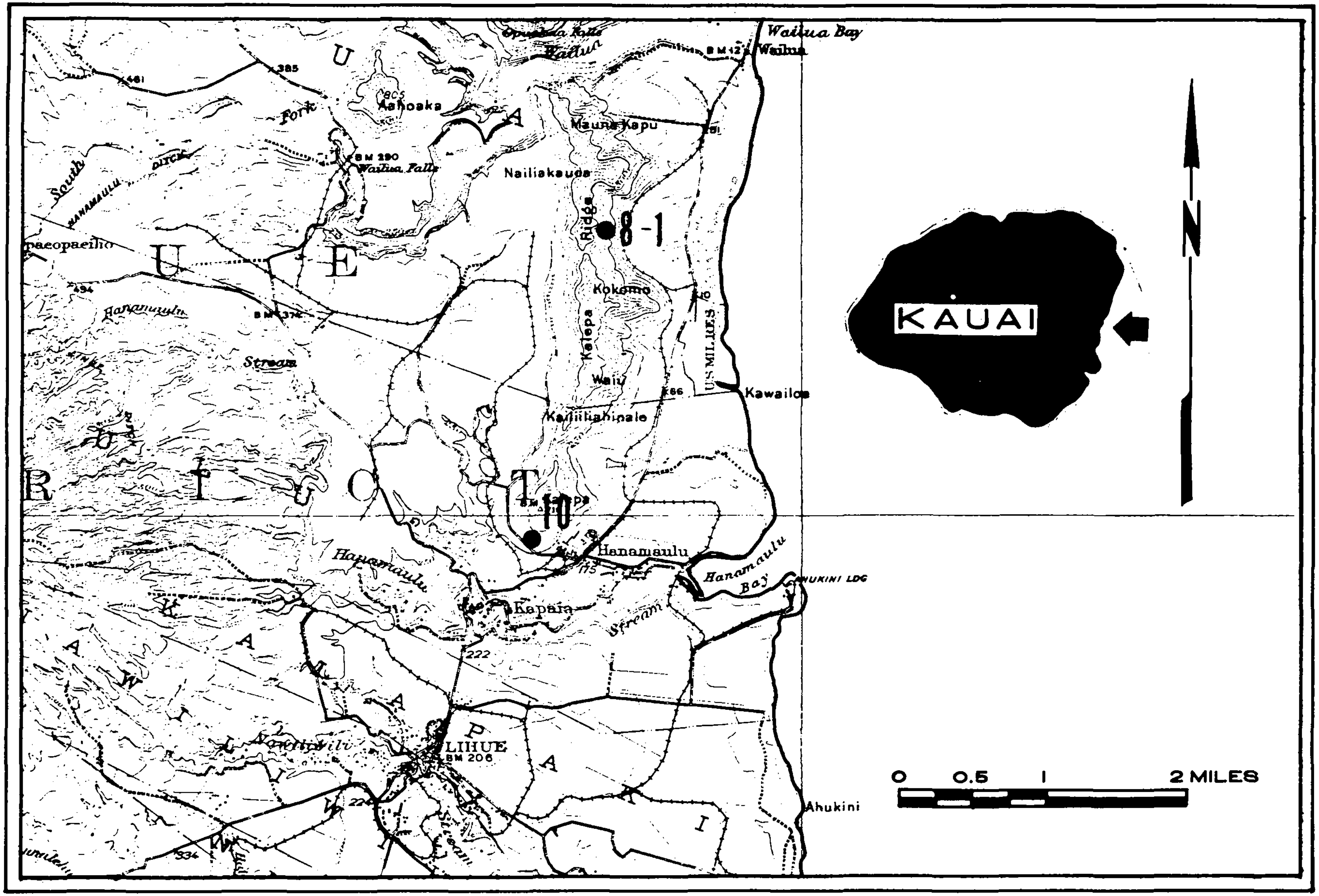
Puolo
Wahiawa
0 0.5 1 2MILES
N
KAUAI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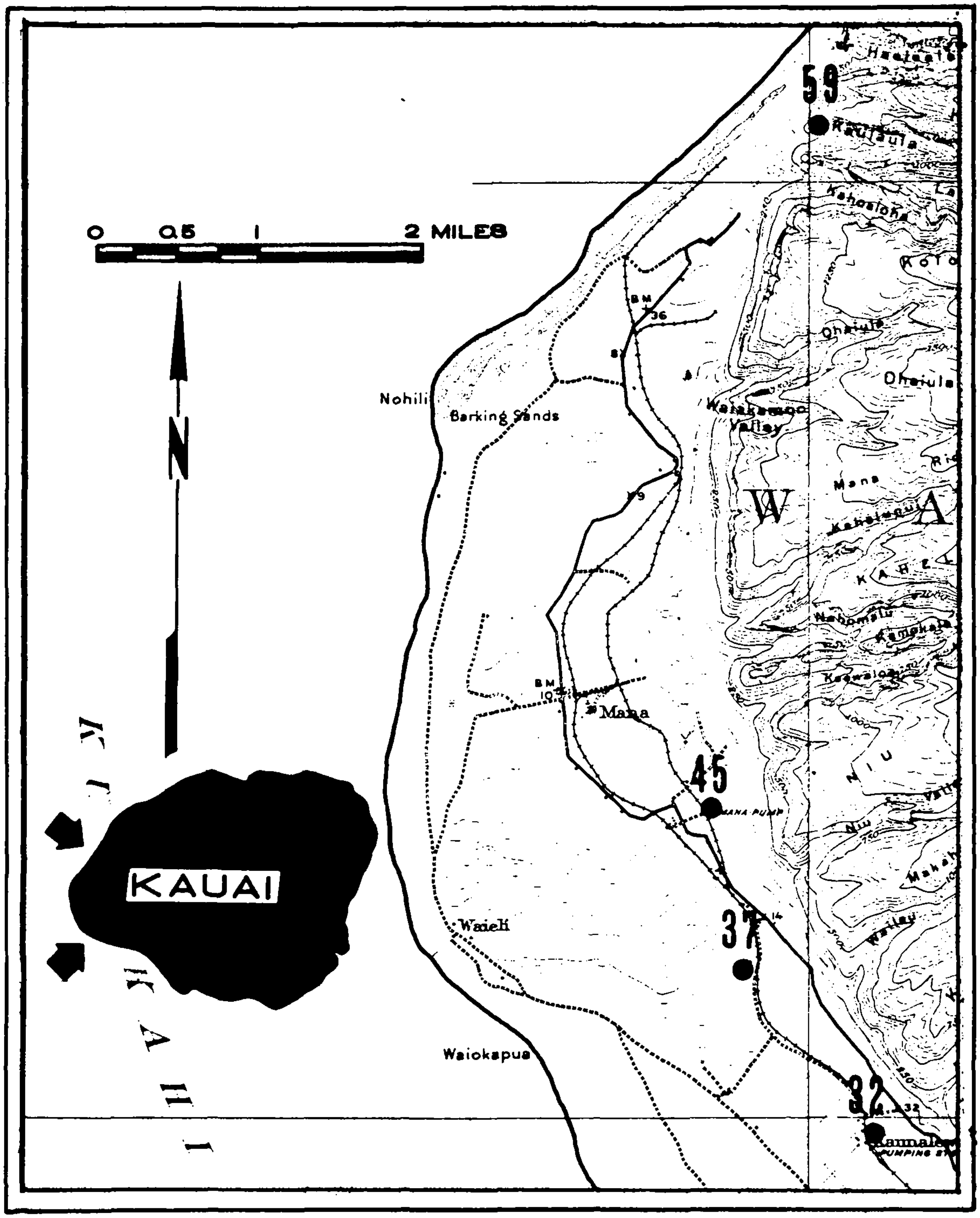
Mauna Kapu
BM 290
Wailua Falls
Ridge
8-1
Kokomo
Kalepa
Waiu
Kawailoa
Hanamaulu
10
Hanamaulu Bay
Kapaia
Stream
LIHUE
BM 206
Ahukini
KAUAI
N
0 0.5 1 2 MILES



0 0.5 1 2 MILES
N
KAUAI
59
Kaulaula
Kahoaloha
Ohaiula
Nohili
Barking Sands
Waiakamoo Valley
Mana
W A
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45
MANA PUMP
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Waieli
Waiokapua
32
PUMPING STA

APPENDIX B-1. SUMMARY OF FUNCTIONS LOGGED.

	WELL	DATE LOGGED	SP	PR	16"SN	64"LN	6'LAT	COND	TEMP	CALIPER	REMARKS
								O A H U			
AIEA	189-2B	5-4-66	X		X						GOOD 5' ZONE 14' FROM BOTTOM.
BERETANIA	T-85	6-26-67	X	X	X	X	X				FORMATIONS POORLY DEFINED BELOW TRANSITION ZONE.
BERETANIA	T-85	6-30-67						X	X		TRANSITION ZONE DEFINED.
BERETANIA	T-85	1-30-68						X	X		SALINITY PROFILE OF LENS PLOTTED.
BERETANIA	T-85	4-5-68	X	X	X	X	X				FORMATIONS POORLY DEFINED BELOW FRESH WATER.
BERETANIA	T-85	4-8-68						X	X		
BERETANIA	88B	4-7-67	X	X	X		X	X	X	X	NOISY LOCATION, LOCATED CASING BREAK.
EWA BEACH	T-133	6-25-66	X	X	X	X	X				BASALT DEFINED FROM CORAL AND CLAYS.
EWA BEACH	T-133-1	5-18-66	X	X	X	X	X				AQUIFER AND WATER QUALITY RELATION.
FORT RUGER	11	3-14-67	X	X	X	X	X				FORMATIONS DEFINED.
HOAEAE	256-3D	5-4-66	X	X	X	X	X				LITTLE UNCASED HOLE, NOISY RECORDS.
IOLEKAA	407-17	10-17-66	X	X	X	X	X				FORMATIONS WELL DEFINED, THIN.
IOLEKAA	404-2B	10-26-67	X	X	X	X	X				FORMATIONS WELL DEFINED.
KAIMUKI	#7A	11-27-67	X	X	X	X	X	X	X	X	FORMATIONS WELL DEFINED, SALINITY INCREASE WITH DEPTH.
KALAUAO	T-118	2-2-67	X	X	X	X	X				SEASONAL CHANGE IN WATER QUALITY INDICATED IN LOGS, IRRIGATION RETURN WATER.
KALAUAO	T-118	8-2-67						X	X		IRRIGATION RETURN WATER ON TAP.
KAONOHI	191-2	5-25-66	X	X	X	X	X				FORMATIONS DEFINED.
KAONOHI	191-3A	2-24-67	X	X	X	X	X				FIRST RUN.
KAONOHI	191-3A	8-30-67	X	X	X	X	X	X	X		LARGE FORMATION UNITS, IRRIGATION RETURN WATER.
KAONOHI	191-3B	1-10-67	X	X	X	X	X				FORMATIONS DEFINED.
KAONOHI	191-3B	8-30-67						X	X		IRRIGATION RETURN CONFIRMED.
KUNIA	330-8	12-19-66	X	X	X	X	X				HIGH NOISE LEVEL FOR PR & 6' LATERAL.
MAKAHA	277-102	6-19-68	X		X	X	X	X	X		DIFFERENT THAN OTHER MAKAHA WELL T-87.
MAKAHA	T-87	10-19-67	X	X			X	X	X		TEMPERATURE OF DIKE WATER HIGHER THAN BASAL WATER.
MANANA SHAFT	#9	6-1-66	X	X	X	X	X				UNIFORM FORMATIONS SHOWS EFFECT OF SHAFT.
MILILANI	250-4A	11-8-67	X		X	X					MUD FILLED TO TOP OF HOLE, THICK UNITS, SOIL TO 130' DEPTH.
MILILANI	250-4B	4-4-68	X	X	X	X	X				
MOKULEIA	T-116	9-27-66	X	X	X	X	X				UNIFORM CONDITIONS, ONE ZONE BEST.
MOKULEIA	325-2	10-5-66	X	X	X	X	X	X	X		SINGLE DENSE FLOW IN SHORT, UNCASED SECTION.
PEARL CITY	198-3	10-17-66	X	X	X	X	X				FORMATIONS WELL DEFINED.
PEARL CITY	200	10-7-66	X	X	X	X	X				FORMATIONS WELL DEFINED.
PEARL CITY	200-4	10-7-66	X	X	X	X	X				GOOD MATCH WITH DRILLERS LOG.
PEARL CITY	202-2C	10-6-66	X	X	X	X	X	X	X		IRRIGATION RETURN WATER EFFECTS.
PUNAHOU	37	1-16-67	X	X	X	X	X				DETECTED BREAK IN CASING AND WATER-QUALITY CHANGE
PUNAHOU	37	3-17-67	X	X	X	X	X				EXTREMELY NOISY RECORD.
PUNALUU	T-143	7-25-67	X	X	X		X				LOGS OF SEDIMENTS BEFORE CASED.
PUNALUU	T-143	8-31-67						X	X		8-31 MIXING ZONE MUCH THICKER THAN 10-2.
PUNALUU	T-143	10-2-67						X			8-31 MIXING ZONE MUCH THICKER THAN 10-2.
PUNALUU	T-143	10-3-67	X	X			X				PERMEABLE ZONES CORRELATE WITH ENLARGED PORTION OF BORE.
PUNALUU	T-143	10-4-67	X		X	X					PERMEABLE AND DENSE ZONES DEFINED.

APPENDIX B-1. SUMMARY OF FUNCTIONS LOGGED (CONT'D).

	WELL	DATE LOGGED	SP	PR	16"SN	64"LN	6'LAT	COND	TEMP	CALIPER	REMARKS
PUNALUU	T-143	11-24-67								X	SAME AS ABOVE.
PUNALUU	T-143	2-27-68						X	X	X	TRANSITION ZONE AND HOLE DIAMETER.
PUNALUU	401	6-2-66	X	X	X	X					FORMATIONS WELL DEFINED.
PUNALUU	402-2A	6-2-66	X	X	X	X	X				FORMATIONS WELL DEFINED, DIFFICULT TO GET CURRENT INTO GROUND.
PUNALUU	402-2B	6-2-66	X				X				SOME VERY THICK UNITS NEAR BOTTOM.
PUNALUU	402-2B	1-16-67	X	X	X	X	X				MOSTLY THIN FLOWS.
PUNALUU	402-2C	6-19-67	X	X	X	X	X	X	X	X	FLOWS THICKER THAN 402-2B.
PUNALUU	402-2D	6-19-67	X	X	X	X	X	X	X	X	CALIPER ONLY QUALITATIVE.
PUNALUU	402-2E	7-28-67	X	X	X	X	X	X	X		TEMPERATURE KICK OPPOSITE PERMEABLE ZONE FLOWS THICKER, TWO PROMINENT DENSE, FLOWS SIMILAR TO 402-2B.
PUNALUU	402-2F	6-20-67	X	X	X	X	X	X	X		FORMATIONS WELL DEFINED, THIN FLOWS.
PUNANANI	196-2	8-31-67								X	QUALITATIVE.
PUNANANI	196-2	10-2-67	X	X	X	X	X				FORMATIONS WELL DEFINED DESPITE HIGH SALINITY.
PUNANANI	196-2	12-28-67								X	QUALITATIVE.
PUNANANI	196-2	1-12-68 (3-4-68) (3-7-68)						X	X		TRANSITION ZONE.
PUNANANI	196-2	3-13-68						X	X		IRRIGATION RETURN WATER, TRANSITION ZONE.
PUNANANI	196-2	3-20-68						X	X		
PUNANANI	196-2	5-16-68	X	X	X	X	X			X	NOISY RECORDS, SP REVERSED.
PUULOA	T-134	7-9-66	X	X	X	X	X				PERMEABLE ZONES ON LOGS CONFIRMED BY CORE.
SALT LAKE	172-1	5-6-68						X	X		POORER QUALITY WATER BEGINS IN SPECIFIC FLOW.
SALT LAKE	172-1	5-7-68	X	X		X	X				THICK PERMEABLE AND IMPERMEABLE ZONES EASILY IDENTIFIED.
SALT LAKE	178	6- 68									WELL DEFINED FORMATIONS.
WAIALUA	T-30	10-5-66	X	X	X	X	X				FORMATIONS WELL DEFINED.
WAIAWA	204-40	3-29-67	X	X			X				PR SURVEY SHOWS FORMATIONS, 6'L NOISY.
WAIHEE	T-114	10-14-66	X	X	X	X	X				FLOWS WELL DEFINED BUT RATHER TIGHT.
WAIHEE	T-115	10-14-66	X	X	X	X	X				FLOWS WELL DEFINED BUT TIGHT.
WAIMALU	T-52	4-11-68	X	X				X	X		IRRIGATION RETURN WATER ON TOP.
WAIMALU	T-75	8-30-67						X	X		WATER QUALITY WORSENS WITH DEPTH.
WAIMALU	T-69	9-8-67						X	X		WATER QUALITY WORSENS WITH DEPTH.
WAIMANALO	TH #1	8-4-66	X	X			X				CORAL AND CLAY STRATA DEFINED.
WAIMANALO	TH #3	9-27-66	X	X			X				FAIRLY UNIFORM LITHOLOGY.
WAIMANU	201	5-10-66	X	X	X	X	X	X	X		DEFINITE FLOW ZONES OF VARIABLE QUALITY.
WAIPAHU	241	6-14-66	X	X	X	X	X				GOOD DEFINITION OF FORMATIONS.
WILDER AVE.	36A	2-1-67	X	X	X	X	X				WELL CORED TO WITHIN FEW FEET OF CASING, THIN-BEDDED FLOWS.
							K A U A I				
ANINI (PRINCEVILLE RANCH)	76	4-25-68	X	X			X	X	X		WELL CAVED TO WITHIN APPROXIMATELY 50' OF SURFACE.
HAENA	66	4-25-68	X	X	X	X	X	X	X		CASED TO BOTTOM, UNIFORM WATER.
HANAPEPE	25-1	4-23-68	X	X			X	X	X		WELL CASED TO BOTTOM.
HANAPEPE	25	4-23-68	X	X			X	X	X		WELL CASED TO BOTTOM.

APPENDIX B-1. SUMMARY OF FUNCTIONS LOGGED (CONT'D).

	WELL	DATE LOGGED	SP	PR	16"SN	64"LN	6'LAT	COND	TEMP	CALIPER	REMARKS
KALEPA	10	4-22-68	X	X	X	X	X	X	X		LOGS SHOW WATER FROM BOTTOM 10'.
KAUNALEWA	32	4-26-68	X	X			X	X	X		
KEKAHA	37	4-26-68	X	X	X	X	X	X	X		
KEKAHA	45	4-26-68						X	X		OBSTRUCTED CASING AT 33'.
POLIKULE	59	9- 67	X	X			X	X	X		CASED NEARLY TO BOTTOM SHOWED SLIGHTLY SALTIER WATER AT BOTTOM.
WAILUA	8-1	9-25-67	X	X	X	X	X	X	X		LOCATED RETURN IRRIGATION WATER, RECOMMENDED SEALING HORIZON.
WAIMEA	26	9- 67	X	X			X	X	X		
WAINIHA	67	4-26-68	X	X	X	X	X	X	X		SMALL, SHARP INCREASE OF SALINITY NEAR BOTTOM.

APPENDIX B-2. SUMMARY OF SP'S, APPARENT RESISTIVITIES, CONDUCTIVITIES, AND TEMPERATURES MEASURED.

WELL LOCATION		SP*	RESISTIVITY (IN OHMMETERS) PR	16" SN	64" LN	6' L	SPECIFIC CONDUCTIVITY (IN MICRO-MHOS)	TEMPERATURE (IN °C)
					O A H U			
AIEA	189-2B							
BERETANIA	T-85	70	440-480	350-530	390-460	440-480	185-44,000	19.8-23.6
BERETANIA	88B		610-710	450	370	370	160- 200	
EWA BEACH	T-133	125				490-505		
EWA BEACH	T-133-1							
FORT RUGER	11	100	635-775	400-455	405-605	480-490		
HOAEAE	256-3D							
IOLEKAA	407-17							
IOLEKAA	404-2B	20	390-405	325-380	380-395	315-330	13,000-31,500	21.5-22.0
KAIMUKI	7A	130	290-515	310-370	325-375	290-340	265- 305	20.1-20.5
KALAUAO	T-118	40	730-910	450-470	385-430	485-490	145- 240	20.0-21.3
KAONOHI	191-2							
KAONOHI	191-3A	180	700-970	450-485	370-470	490-495	125- 225	19.8-21.5
KAONOHI	191-3B	200	80-380	470-475	440-465	470-475	120- 225	19.4-21.1
KUNIA	330-8	100	585-690		485-540	460-480		
MAKAHA	277-102	250		380-560	465-565	250-390	475- 485	23.7-23.8
MAKAHA	T-87	25	500-?			410-?	350- 370	25.1-25.2
MANANA SHAFT	9							
MILILANI	450-4A	95		375-420	335-425			
MILILANI	450-4B	200	654-745	60-280	0-120	315-465		
MOKULEIA	T-116	10	775-875	235-245	235-275			
MOKULEIA	325-2		675-?			480-490		
PEARL CITY	198-3	65	700-810		475-?	455-585		
PEARL CITY	200	45	665-685	480-490	460-490	475-505		
PEARL CITY	200-4	30	735-835	495-515	500-585	505-560		
PEARL CITY	202-2C		40-740	460-510	350-595		290- 620	22.6-23.7
PUNAHOU	37	7200	770-875	465	485-495	500-505		
PUNALUU	T-143	100	420-530	310-460	340-435	270-380	170-49,000	19.5-23.3
PUNALUU	401							
PUNALUU	402-2A	750	1000-1380	485-490	58-595	515-565		
PUNALUU	402-2B	100	760-1000	470	425-525	500-530		
PUNALUU	402-2C	80	890-1140	480-525	485-?	500-505	250- 480	21.0
PUNALUU	402-2D	125	950-1200	445-?	430-520	500-505	195- 25	20.0
PUNALUU	402-2E	175	650-695	435-540	475-550		130- 140	19.0-19.7
PUNALUU	402-2F	100	590-620	430-530	480-520	425-560	220	18.9-20.3
PUNANANI	196-2	7200	550-630	285-485	320-530	475-525	260-35,000	20.0-24.1
PUULOA	T-134	85	545-580	485-495	495-500	490-500		
SALT LAKE	172-1	75	225-300	305-430	355-405	130-165	650- 1,580	20.9-21.2
SALT LAKE	178							
WAIALUA	T-30	25	600-645	645-695	475-485	480-490		

APPENDIX B-2. SUMMARY OF SP'S, APPARENT RESISTIVITIES, CONDUCTIVITIES, AND TEMPERATURES MEASURED (CONT'D).

WELL LOCATION		SP*	RESISTIVITY (IN OHMMETERS)				SPECIFIC CONDUCTIVITY (IN MICRO-MHOS)	TEMPERATURE (IN °C)
			PR	16" SN	64" LN	6' L		
WAIAWA	204-40	400				445-475		
WAIHEE	T-114	10	870-?	485-505	490-515	490-530		
WAIHEE	T-115	15	815-1115	490	500-510	500-520		
WAIMALU	T-52	100	625-645				180- 285	19.1-19.9
WAIMALU	T-75						195- 310	19.0
WAIMALU	T-69						338- 360	19.9-20.0
WAIMANALO	TH #1							
WAIMANALO	TH #3							
WAIMANU	201							
WAIPAHU	241	140	0-100	485-555	485-?	480-680		
WILDER AVE.	36A	50	670-720			490	320- 460	20.7-21.1

*DIFFERENCE BETWEEN MAXIMUM AND MINIMUM IN MILLIVOLTS.

APPENDIX C. LIST OF EQUIPMENT

Item	Description
Recorder	Log-Master Model LMR-D dual-channel recorder and selector panel. Self-balancing potentiometric D. C. millivolt recorder. Simultaneous recording of spontaneous potential and resistivity. Individual recording of temperature, specific conductance, caliper surveys, and other logs.
Depth Measurement System	Selsyn generator at cable hoist-head controls synchronous motor-driven odometer and chart paper system.
Hoist Unit	Log-Master Model LMH-15-POE. Drum driven by an electric motor through gear reducer and variable speed transmission. Drum capacity of 1500 feet of 3/16" O. D. stainless reverse laid 3-conductor cable. Quick-change cable head.
A. C. Generator or A. C. Alternator	2500 watt, 115 VAC, 60 cycle gasoline-powered generator. 1250 watt, 115 VAC, 60 cycle gasoline-powered alternator. Minimum recommended size.
Point Resistivity Electrode	Log-Master Model LME-2A. Used for Spontaneous Potential and Point Resistivity surveys.
6' Lateral Electrode	Log-Master Model LME-2-LN. Used for SP-PR and 6' Lateral resistivity surveys.
Cable Electrode Assembly	Log-Master Model LME-2-CE. Used in conjunction with 6' Lateral electrode to obtain 16" Short Normal and 64" Long Normal resistivity surveys.
Caliper tool	Neltronic Instrument Corporation Model MO. 3-arm borehole caliper measuring minimum diameter of hole. Retractable arms.
Specific Conductance and Temperature Sonde	Beckman Instruments Model DWSM-2. Deep well solubridge for Specific Conductance Surveys of water in well. Selectable ranges using cell constants of 0.2, 2.0, and 20, temperature compensated output. Temperature recorded as separate but not simultaneuous function.

APPENDIX D. OPERATIONAL PROCEDURES

It is not the intent of this section to repeat information already contained in the manufacturer's instruction manual for the logger. The discussion will dwell on procedures that were found to facilitate logging or to be necessary from local experience in Hawaii.

General Check-Out

A check of the recorder is always in order before commencing logging to verify that the power hookups and cable hookups are proper and the recorder is operating and calibrated.

The selsyn sheave should be centered over the well to minimize catching of the cable head or sonde on the walls of the bore and to avoid problems brought about by eccentricity. In particular, failure to center the caliper tool in the bore may result in erroneous readings. All of the arms are linked together and drive a single potentiometer. If the sonde is eccentrically supported in the hole so that its weight causes unequal compression of the arms, the diameter indicated by the sonde is smaller than the actual well diameter.

In resistivity surveys, the use of a ground electrode is required. In some situations the ground electrode may have to be shifted to obtain the greatest signal-to-noise ratio. Usually, placement of the ground close to the well casing produces the best results. If the water level in the well can be reached with the electrode, this usually is desirable. In dry areas with very porous soils, difficulty may arise in keeping the electrode immersed in fluid; therefore, an adequate supply of water must be kept on hand. Experience has shown that pouring water on the electrode produces a dynamic potential which causes a change in the setting of the base. To avoid this, enough water must poured into a hole to last the duration of logging. A mud slurry can be used to retain water. No ground electrode is needed to make caliper, temperature, or conductivity surveys as the signal voltage travels on a single wire and the armored cable serves as ground.

In resistivity logging, it may be difficult to establish and maintain an adequate current through the ground. Certain geological conditions, oil on the sondes, or a poor ground contact may cause the current, as indicated on the meter, to drop below recommended values. If only the 6' lateral is affected, then the other logs probably will be satisfactory. If no current can be induced downhole, this is a certain indication of an open circuit in the logging-line connections, usually in the cable head or the slip-ring assembly. If the recommended values of current are not maintained, the range of current should be recorded because the value of resistivity depends upon this current ($V_1 - V_2 = \frac{Ie\frac{1}{r}}{4\pi}$ or $e = \frac{V}{I}4\pi\frac{1}{r}$). Otherwise, the calibration is not valid, *i.e.*, one inch on the chart will not be 5, 10, 25, 50, or 100 ohmmeters. The alternative is to select a given lower maintainable value of current and refer back to the table in the manufacturer's manual for the particular logging function being used. The indicated chart scales will then be some constant proportion of the nominal value.

Safety Precautions

The following safety precautions especially should be observed when operating the logging equipment:

1) The ground connection at the jumper cables should be double checked when running conductivity, temperature, or caliper surveys as high voltage is used to activate motors in these devices. Unless a good connection to ground is obtained the operator may suffer an uncomfortable electrical shock upon activation of these motors.
2) The rotary switch should be *off* when resistivity sondes are being changed or a shock will result if the uninsulated portion of the sondes are touched. Furthermore, the Rotary Switch must be off when running conductivity, temperature, and caliper surveys.
3) If it is necessary to guide the logging cable onto the winch by hand to obtain even rewinding, care should be taken not to get fingers, hands, or clothing between the winch drum and

the line as severe injury could result, especially when the heavier tools are in the well.

Preliminary Operations

After all components have been checked and found to be functioning properly, and the control panel has been set up for the desired logging survey, the next step is to position the top of the cable head at a known reference such as the top of the well casing. For logs of conductivity, temperature, and caliper or any other added capability, the left hand jumper wires should be removed from the tip and ground positions and the proper leads from the control module should be plugged in. No ground electrode is required for these surveys.

DEPTH MEASUREMENT. The depth measurement system on the recorder records footage going in or coming out of the well. Contrary to what the manual appears to indicate, it is not possible to reverse the counter as it operates only in the forward position. No way has been found to set depth reference footages per the instructions. Rather than starting the records at the depth indicated on the footage counter, the reference footages should be added to this depth and the pens placed accordingly, which results in the proper vertical footages. Unless extreme or compressed vertical details are desired, the most useful gear ratio is one inch of chart to a twenty-foot depth.

RANGE AND BASE. After the most suitable range, or sensitivity, has been selected for most of the run, the base sometimes will change when the sonde reaches the bottom. This may result from a change of hole geometry, from bottom effects, or from the change of position of the upper potential pickup in the cable electrode assembly when the cable goes slack in the well.

Sometimes the base is different going down the hole than when coming up, which may cause the record to run either off the chart or into the left channel. In either case, the base should be reset, and the sonde relowered into the hole and started up again for another run. In addition, for the sake of maintaining sensitivity, it may be desirable to change the setting of the base or range somewhere in the record.

APPENDIX E. TROUBLE-SHOOTING PROCEDURES

This section has been subdivided into (1) mechanical and (2) electrical troubles and included to help locate trouble sources so repairs can be effected quickly. On-the-spot repairs can save much time as wells are often located some distance from where the bulk of repair equipment is kept. Only a minimum ability in the manual arts is assumed necessary to diagnose and complete repairs to all but the most complex systems.

Mechanical

A. C. ALTERNATOR. If the crankcase oil is changed regularly and clean gasoline is used, this unit ordinarily is trouble free. Hard starting usually is caused by a dirty spark plug, improperly gapped spark plug, or an accumulation of carbon in the head. A weak spark or lack of spark usually can be traced to the magneto system where the breaker points should be checked for proper gap, pitting, sticking and cleanliness. Also, the capacitor should be checked for open and shorted conditions and the coil for shorts and continuity. These tests on the ignition system are easily accomplished with a multitester which should be carried as standard equipment for servicing the logging gear.

Poor running in the idle position can be usually traced to the carburetion system. Checks should be made to see that the choke is fully open, the fuel bowl, tank, and lines are free of sediment, and the needle jets for idle and running are adjusted for maximum efficiency.

Sometimes the alternator will perform poorly under loads when the hoist mechanism is actuated and drawing maximum power. The above checks should be performed first. If the trouble is not alleviated, then the voltage output of the alternator should be checked to see if it is within the suggested limits of 115 to 120 volts. If not, the governor position should be reset accordingly. If the unit still malfunctions, the cylinder compression should be checked with a suitable gauge. Compression of 90 psi and below, together with undue oil consumption and oil fouling of the spark plug, indicates that a general overhaul is necessary.

If the power source checks out, then the trouble is located in the capacitor "start" portion of the electric winch motor. See the following section.

CABLE HOIST. This unit is prone to frequent breakdown owing to the high stresses imposed by the weight of logging tools and cable and also because of some inherent design deficiencies in the variable-speed transmission unit. The transmission should be checked periodically during logging of deep wells for overheating. The first indication of distress is grinding noises. When grinding noises begin, a breakdown is imminent. The weakest components in the transmission are: (1) the ring gear which is made of non-hardened metal, (2) the three pinion gears which rotate and drive the ring gear, and (3) the three bearings carrying the roller cones. Spares for these parts should be kept on hand. The proper oil level must be maintained at all times. The oil should be changed periodically in accordance with instructions, and oftener if the oil becomes dirty. Only the specified oil should be used.

Stalling or stopping the hoist with the variable-speed control should be avoided. Rapid stops or starts of the hoist should also be avoided, as these place undue strain on the transmission components. With practice, smooth engagements and disengagements of the brake coordinated with control of the motor can be learned. Extremes of speed, either low or high, should be avoided. Logging speeds should not exceed thirty feet per minute. There are two brakes on the hoist. The high ratio brake, which has been added, is easiest to apply, but the low ratio brake is more efficient under heavy loads.

The starter section of the electric motor has given trouble several times. When this occurs the high current consumption of the starting capacitors overloads the power since the motor overheats. The trouble has been traced to the contact points failing to open when the motor has reached speed. The flat copper spring only requires a slight tension to keep the points closed in the non-operating condition. After the motor is started, the points open to cut out the capacitor section, and the motor continues under reduced power consumption. Action of the points can be observed through the ventilation and inspection ports on the unattached end of the motor.

Electrical

RECORDER AND CONTROL PANEL. Because the control panel contains only mechanical switches, potentiometers, and a milliameter, it is not prone to failure. However, the brushes on the rotary switch should be checked for wear. The recorder is much more complex and consists of two separate tube-type amplifiers. Proper functioning of the recorder amplifiers should be the first check in the case of any malfunction of the logger. The recorder is easily isolated from the other components by placing the test-log switch in the "test" position and noting whether the recorder responds normally to the base control changes and to standard calibration procedures. If either or both channels are inoperative, the most obvious checks are the AC power to the recorder, the use in each amplifier, and the tubes in each section. Remove the screws holding the component to the recorder housing and check to see if the tubes light up. If all the tubes in one amplifier are out, check the fuse. If only one or a few are out, replace them with new tubes after all of the tubes are pulled out and checked on a reliable tube checker. Defective and weak tubes should be discarded. If this does not correct the trouble then the entire amplifier circuit must be checked. An electronics repairman may have to do the work if the logging operator doesn't have the necessary background.

The 45-volt pen-drive battery also should be checked for proper voltage under load conditions and replaced if the voltage falls below 45 volts. Two 1.5-volt batteries supply reference voltages for each channel. Both the pen-drive battery and the reference batteries should be checked periodically, and more frequently when the batteries are nearing the end of usefulness. The recorder may still respond to basing and calibration procedures even if the batteries are substantially below par. However, under load, the pens gradually will drift outwards from the center of the chart showing a christmas tree effect.

If the recorder fails to respond when using the conductivity or the caliper sonde, check to be certain that, for the channel involved, one end of the cable connecting the recorder to the control panel is disconnected. Otherwise, the incoming signal bucks the internal reference voltage and is thus negated.

Wiggly lines in the record not due to formation changes usually are caused by the gain control being set too high. This may be difficult to separate from rapid changes in the formation such as may be induced by drilling-mud invasion in thin-bedded flows or strong random transient electrical fields from power lines or transformers. Cyclical noise of lower frequency which repeats itself every few feet or more has been traced to the slip-ring assembly on the hoist. Irregularity of the slip-ring surfaces and eccentricity of the slip rings with respect to the main shaft of the winch to which it is attached were causes of noise peaks recorded every four feet. The signal frequently was strong enough to mask out any changes produced by the formation. The slip ring assembly was removed and turned on a lathe to a perfectly smooth surface. Next, in attaching the assembly back to the shaft, the allen screws were carefully adjusted until there was no perceptible eccentricity noted by the rise and fall of the spring contacts as the winch was turned. Be certain the allen screws are tight and also tighten them only when the brake has been applied to the winch drum; otherwise, when the brake is applied the force is also applied to the slip rings which tends to slide the assembly along the shaft. Magnetization of the logging cable and winch armature should also be checked as this can be a small periodic noise equal to πD showing up on the logs.

In obtaining logs that might go off scale, a lower range or sensitivity should be used or the signal and record will be lost for the interval the pen is off scale. The continued straining of the pen against the stop will result in wear of the pen-drive clutch surfaces.

CALIPER TOOL. Beyond checking for burned out fuses, the complexity of the circuit indicates that the unit should be serviced by a competent electronics repairman. If the ground lead is left disconnected and the caliper motor activated, the operator will receive an electric shock as he provides the ground path. Before beginning a logging run the tightness of the caliper arms should be checked. Periodic checks of the module in the high and low positions of the arms and the calibrating switch is recommended.

SPECIFIC CONDUCTANCE AND TEMPERATURE SONDE.. This equipment has been relatively trouble free after initial problems were corrected by the manufacturer and the electronics shop of the Hawaii Institute of Geophysics. A leaky O-ring seal where the conductivity cell unit plugs into the instrument body at the bottom was initially very troublesome. The replacement O-ring, smaller than the original, has prevented leaks for a year and shows no signs of impending leakage. The only other source of trouble with this device is the occasional failure of the batteries to hold a charge. Although the instruction manual does not state this, the body of the sonde must be grounded to the command set when charging, otherwise, the batteries in the downhole portion will not charge properly. While charging, the tip of the charging wire and the port in the sonde must be clean and making good electrical contact which can be verified by a spark when the ground wire is touched to the command set. At present, the charging part has been bypassed by running a wire inside the sonde which can be pulled out from the top when needed. Troubles with this sonde and also the caliper sonde can be isolated from the logging line and recorder sections by simply using short jumper cables and noting whether the command module still indicates the proper signals.

SP-RESISTIVITY LOGGING SONDES, ELECTRODE CABLE ASSEMBLY, LOGGING CABLE AND CABLE HEAD. Except for the cable head, the other components are relatively trouble free but the same trouble-shooting procedures used for the cable head also apply to them. Broken or high resistance connections easily can be located with an ohmmeter. Because of the large stresses on the cable at the cable head and because water does enter into the upper side of the head, the cable has to be reheaded periodically. Failure to do so will result in an inability to obtain a proper log. The manufacturer suggests that vaseline be used to pack the cable head, but experience has shown emulsification and consequent deterioration occurs soon after. Silicone grease is more expensive, but longer lasting and more reliable. The outside of the cable head should be thoroughly wiped clean before re-wrapping, or the tape will not adhere tightly. The first layer of wrapping should be self-vulcanizing rubber tape. Plastic electrician's tape should be wrapped over the rubber tape as the final layer. A neat job of wrapping insures a water-proof cable connection. A permanent solution would be to fill the inspection part of the cable head with butyl rubber and put the cable wires and connectors into a simple waterproof unit.

If the recorder section checks out, the fault is usually in the downhole components. If trouble is indicated in the downhole portion of the logger, that is, from the control panel through the winch, logging line, and sonde, the following order or trouble shooting is suggested:

1) Remove the cover from the slip rings and check to see that the slip ring assembly has not slipped on the winch shaft and broken any of the four wires leading from the logging line to the slip rings.

2) Check the cable from the slip ring to the recorder for continuity with an ohmmeter by pulling the jumper wires from the right hand side of the panel and checking through these wires to the bands on the slip rings.

3) If the logging tools are out of the hole, a quick check of the leads in the cable head can be made to see whether they have parted or not. Although there is an ample strain loop for each conductor wire at the cable head, this component seems surprisingly fragile.

4) Continuity should be checked from the tip, band, body, and ground of the sonde to the corresponding pull-out leads on the recorder.

This procedure should isolate the wire which is causing the difficulty. The proper phonoplugs and jacks can be substituted for the sondes as well.