Submarine Canyons and the Shelf along the North Coast of Molokai Island, Hawaiian Ridge[1]

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ABSTRACT: The north insular shelf of Molokai is a smooth plain, gently dipping seaward, with three slight steps, one occurring between the 30- and 60-foot isobaths, one between the 150- and 180-foot isobaths, and one near the 300-foot isobath. The shelf break occurs near the 500-foot isobath. Off East Molokai Volcano the shelf is cut by eleven submarine canyons; along West Molokai it is unbroken except for one canyon. About half the canyons have bowl-shaped heads; the remainder have V-shaped heads. The canyons originate about 1 mile offshore. Seismic reflection data show that the insular shelf is covered by a thin veneer of sediments, 0.005 to 0.025 seconds of reflection time, thickening seaward. The veneer is underlain by another series of reflectors, the deepest being 0.05 seconds 1 mile from shore and 0.25 seconds 3 miles from shore. The Molokai submarine canyons appear to have originated from subaerial erosion, which was followed by island subsidence with sediment deposition on the shelf and transport in the canyons. The geomorphology of the north slope of Molokai appears to have developed through erosion and deposition operating upon a subsiding volcanic island, rather than through the action of a giant submarine landslide.

DURING 1968 the U. S. Coast and Geodetic Survey Ship "McArthur" carried out detailed bathymetric surveys along the north coast of Molokai Island (Fig. 1). From the bathymetric data the author was able to contour the bathymetry at the same interval as the island topography and hence to study the geomorphology of the island in the transition into the shelf, and of the valleys into the submarine canyons. Using the University of Hawaii's R/V "Mahi," seismic reflection data were obtained to study the sedimentary regimes over the shelf (Fig. 1). The aim of this paper is to describe and discuss the relationship between the geomorphology of the island of Molokai and the submarine geology along the northern slope of the island.

The geology of Molokai Island was studied by Stearns and Macdonald (1947). Previous studies of the submarine canyons by Shepard and Dill (1966) described the topography and sediments of the canyons. Malahoff and Woollard (1966) carried out magnetic surveys of the study area, Strange et al. (1965) made some gravity observations, and Kroenke (1965) reported the results of two seismic reflection survey lines that were run near there.

GEOMORPHOLOGY OF MOLOKAI

Molokai comprises two major geomorphic provinces: West Molokai Dome, and East Molokai Dome (Stearns and Macdonald, 1947). The West Molokai Dome was built by late Tertiary volcanism and is generally flat and subdued compared with the East Molokai Dome. Volcanism took place along a southwest-trending rift zone that appears to extend out to sea along the crest of Penguin Bank and along a northwest-trending rift. Hoolehua Plain, lying between the domes, is a smooth plain built by lava flows from the East Molokai Volcano that were ponded against the West Molokai Dome. East Molokai Dome, the largest geomorphic province, is an upper Tertiary volcanic dome whose crest is now 4,970 feet high. The East Molokai volcanism appears to have originated from a center vent and from two rift zones, one

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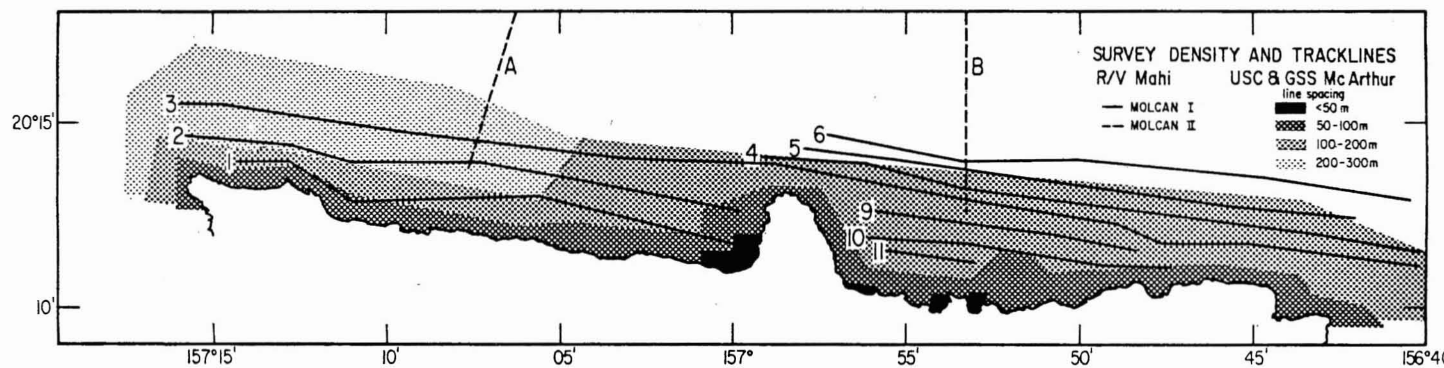


FIG. 1. Bathymetric survey line density and seismic reflection lines along the north coast of Molokai Island, Hawaii.

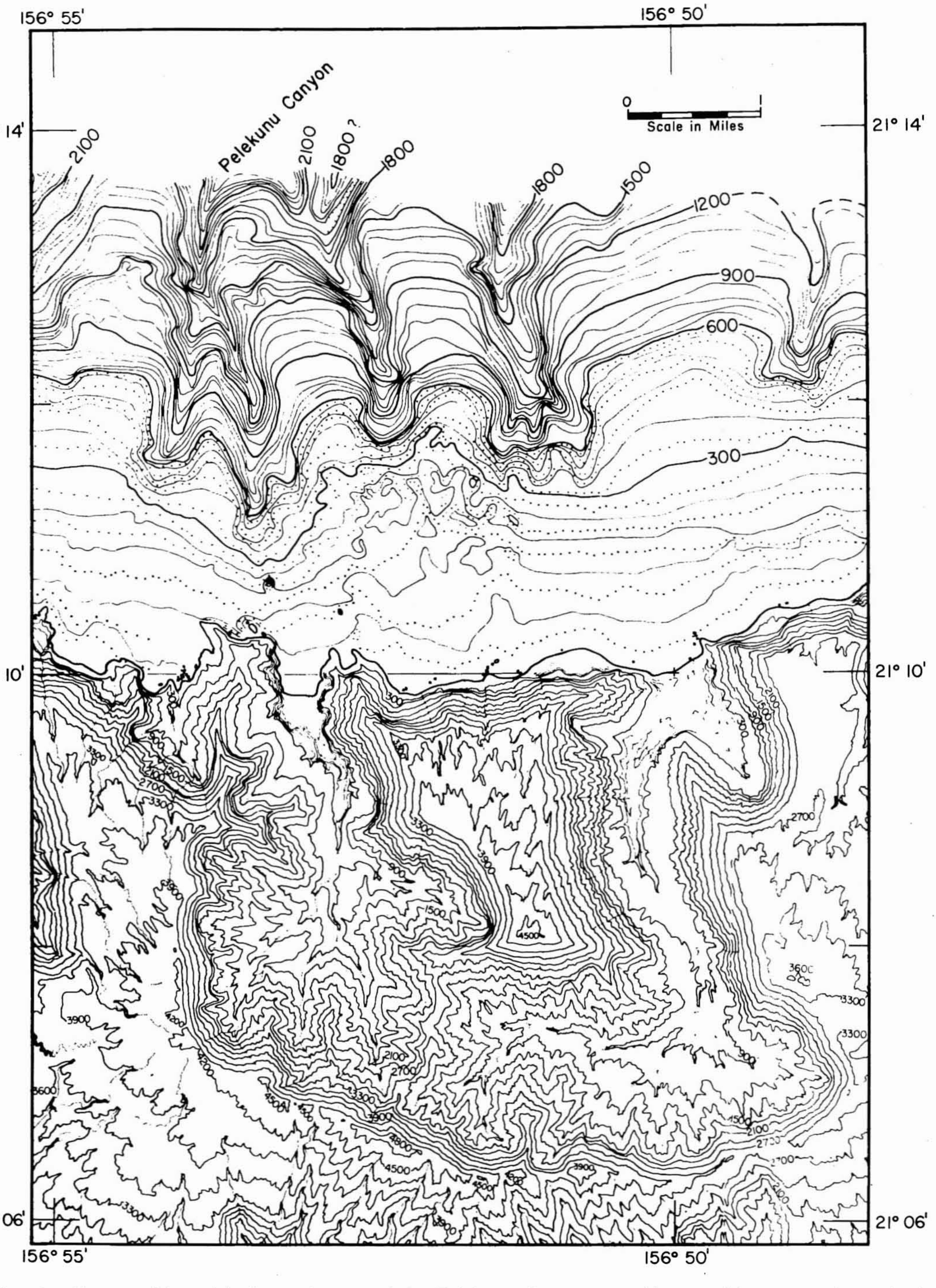


FIG. 2. Topographic and bathymetric map of the Pelekunu Canyon area. Topographic contour interval, 60 and 300 feet; bathymetric contour interval, 30 and 60 feet, corrected. After Mathewson (1969).

trending eastward and the other northwestward. Sea cliffs are found along the northern (windward) side of both domes. Those along East Molokai have a maximum relief of about 3,600 feet, whereas along West Molokai the maximum is about 500 feet.

The East Molokai Dome is an asymmetrical shield volcano with east-west elongation and thin-bedded basaltic aa and pahoehoe lava flows dipping from 2° to 15° away from the central caldera (Stearns, 1966). However, in the lower part of the high northern sea cliff, the beds dip

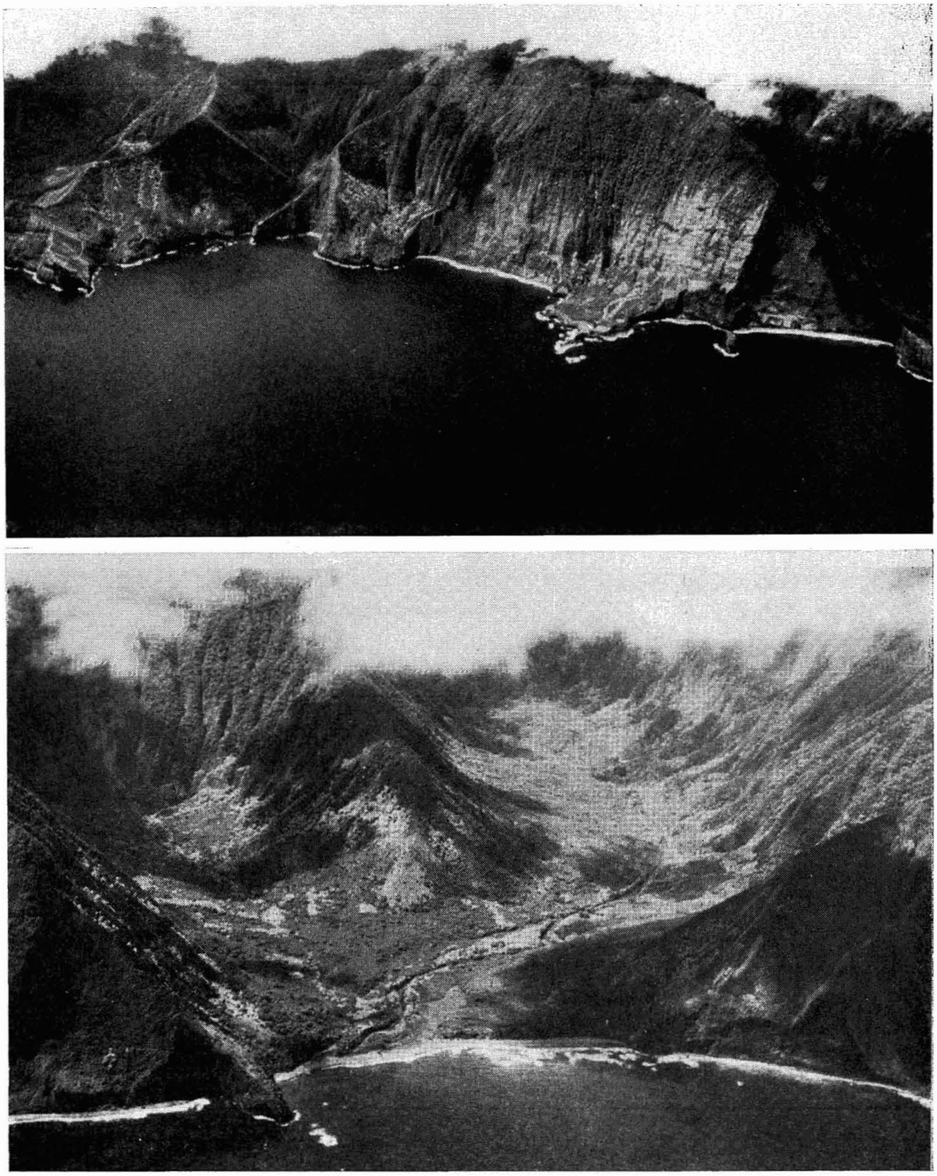


FIG. 3. Aerial photographs of the north coast of East Molokai. Upper photo shows the sea cliff (2,500 feet, from 2 miles offshore). Lower photo shows the U-shaped canyons (1,000 feet, from 0.5 mile), and the very steep gradient tributaries at the mouth of the canyons. The mountain tops are obscured by the clouds. Photographs by the author.

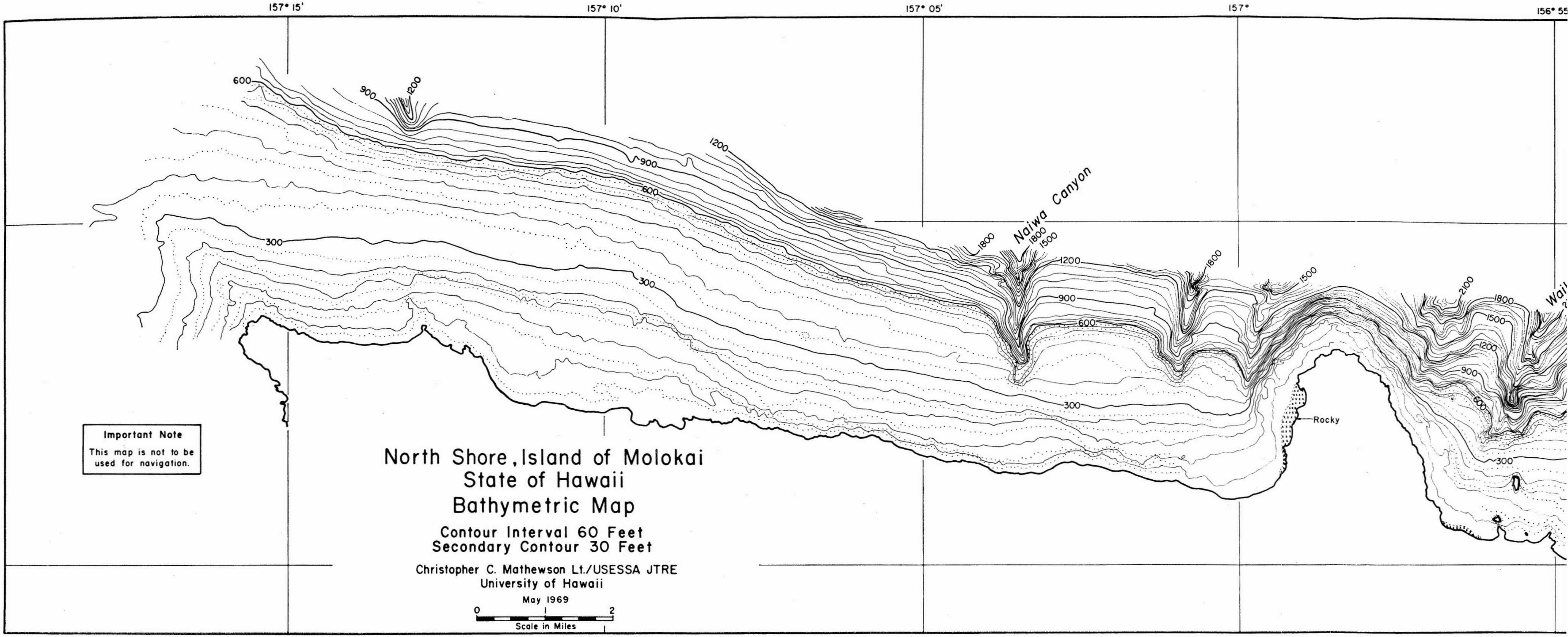
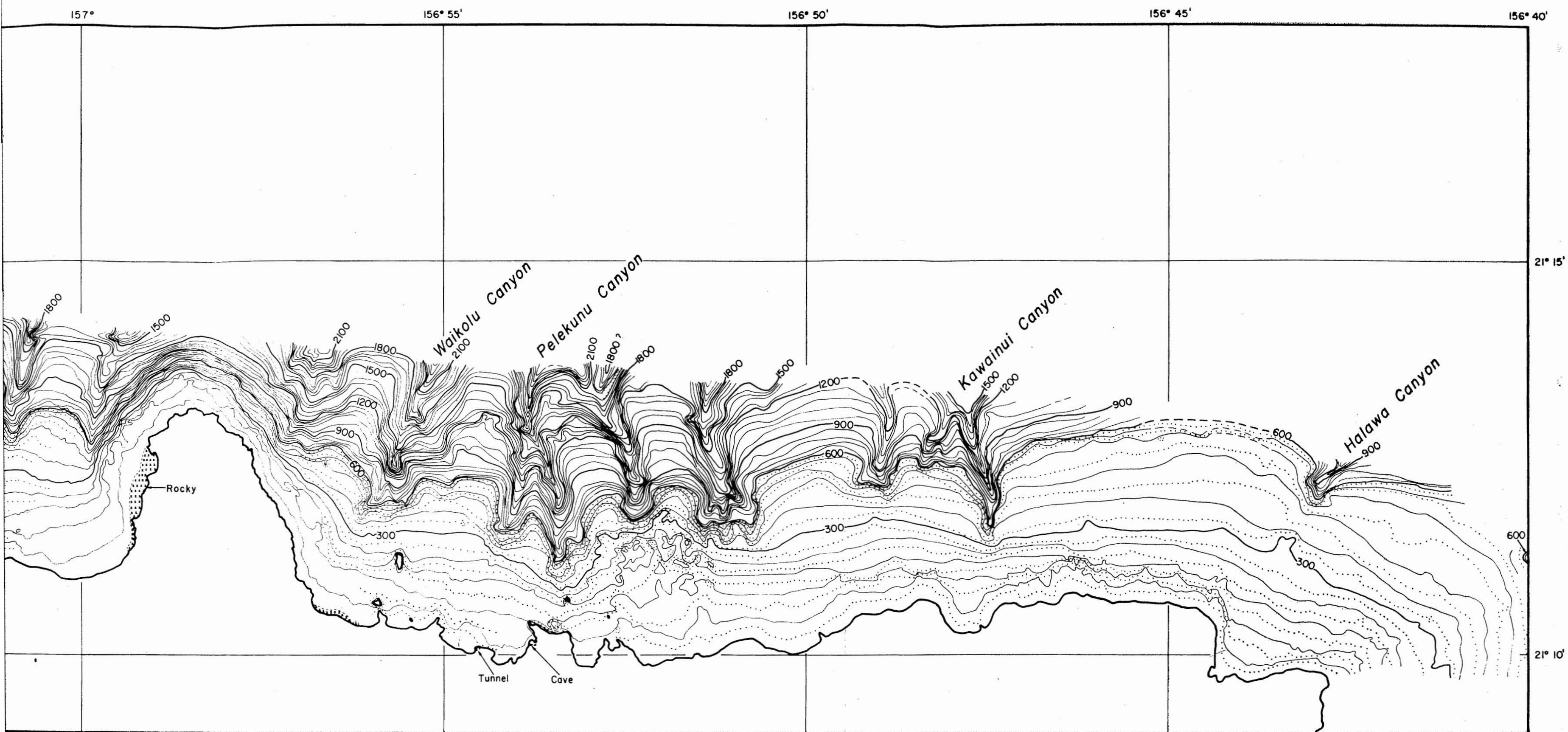


FIG. 4. Bathymetric map of the north insular shelf of Molokai Island, Hawaii.



ap of the north insular shelf of Molokai Island, Hawaii.

8° to 25° toward the south, suggesting that an early volcanic source may lie submerged on the insular shelf. The north side of the Dome is deeply incised by numerous northward-flowing streams (Fig. 2), with very steep gradients averaging about 1/3 (18° slope). The stream valleys are generally U-shaped throughout with very steep walls (Fig. 3). Near the mouths of major streams, the stream gradient abruptly reduces to about 1/30 (2° slope).

SUBMARINE GEOLOGY OF THE NORTH COAST

The Shelf

The north insular shelf of Molokai Island is a smooth plain gently dipping toward the sea with three slight steps (Fig. 4). The shelf dips at about 2° between the shoreline and the 30-/60-foot isobath step, then at about a 1° dip to the 150-/180-foot isobath step, which is a short segment of the shelf profile that also dips about 2°. Between this step and the 300-foot isobath the shelf dips at about 1°. At about the 300-foot isobath the dip of the shelf decreases slightly to about a 0.75° dip, continuing at this flatter dip to the shelf break, which occurs at about the 500-foot isobath.

The three steps are remnants of ancient terraces of Molokai. A total of six submerged terraces, representing former sea level stands, have been identified around the Hawaiian Islands: the Koko at 15 feet, the Waipio at 60 feet, the Penguin Bank at 180 feet, the Mamala-Kahipa at 300 feet, the Lualualei at from 1,200 to 1,800 feet, and the Waho at 3,600 feet below sea level (Easton, 1965; Ruhe et al., 1965; Stearns, 1966, 1967). The submerged 15-foot, 60-foot, 180-foot, and 300-foot ancient terraces are apparent in bathymetric profiles across the North Molokai Shelf (Fig. 5).

An anomalous bathymetric area off East Molokai, about 1.5 miles north of Pelekunu Bay and about 6 miles east of Kalaupapa Peninsula, is characterized by numerous small, steep-sided pinnacles (Fig. 6). These small features have a relief of about 75 feet and are probably submerged stacks. The area occupied by the pinnacles corresponds to a +270 mgal Bouguer gravity anomaly maximum reported by Strange et al. (1965), and to an inflection point in the magnetic anomaly (Malahoff and Woollard,

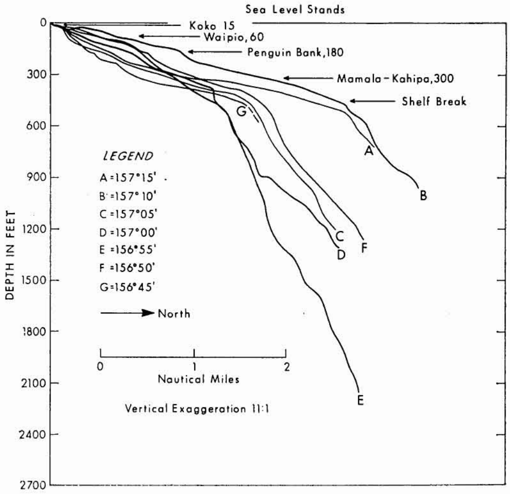


FIG. 5. North-south bathymetric profiles across the north shelf of Molokai Island, showing the ancient stands of sea level.

1966) related to the North Molokai Volcanic Pipe Zone. From these geophysical data it would appear that the pinnacles mark the center of volcanism of the East Molokai Volcano.

The entire shelf is covered by a thin veneer of recent sediments which are highly reflective and conformable to the basement reflector and characteristically appear as two distinct reflectors, with a total thickness of about 0.005 seconds[3] (12.5 feet) near shore, thickening to about 0.025 seconds (62.5 feet) offshore. The veneer is underlain by another series of reflectors that also increase in thickness with increasing distance from shore. The deepest reflector is the lower limit of the veneer near the shore and is 0.23 seconds (575 feet) below the surface of the veneer about 3 miles offshore (Fig. 7).[4]

The Submarine Canyons

The East Molokai Shelf lying off the East Molokai Dome, is cut by eleven submarine canyons, whereas the West Molokai Shelf off the West Molokai Dome is cut by only one.

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[3] Sediment thickness based on round-trip travel times as measured on the seismic reflection record and an assumed velocity of sound in the sediments of 5,000 feet per second.

[4] Cruises MOLCAN I and MOLCAN II were supported by the Joint Tsunami Research Effort (JTRE), ESSA, at the University of Hawaii.

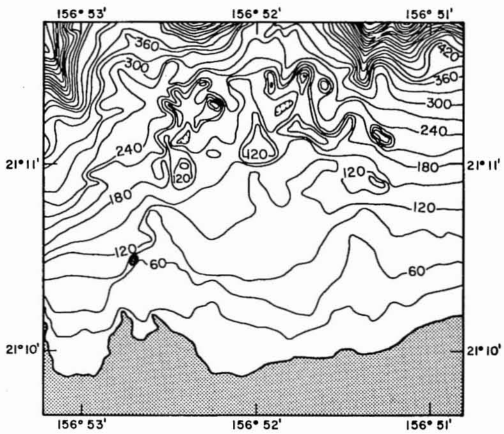

FIG. 6. Detailed bathymetric map of the North Molokai Volcanic Pipe Zone. Contour interval 30 feet, corrected.

This study shows that, except for the two canyons off Kalaupapa, the East Molokai submarine canyons originate about 1 mile offshore, that the West Molokai submarine canyon originates about 3 miles offshore, and that the shelf between the canyon heads and the shoreline is generally smooth. About one half of the canyons have typical bowl-shaped heads, the remainder have V-shaped heads. Some of the canyons with bowl-shaped heads actually have two or more small, less than 0.1 mile long, V-shaped or U-shaped canyons as tributaries (Fig. 3). These tributaries acting together form the general bowl-shaped head of the major canyon. The study by Shepard and Dill (1966), extending farther offshore than the surveys by the USC&GS Ship "McArthur," shows that the East Molokai canyons have typical V-shaped profiles and no indication of broad flat floors; that they appear to be fairly straight, of rather even gradient, and terminate at depths of about 6,000 feet; and that a direct relationship between the submarine and subaerial portions of each canyon system appears to exist. This canyon/submarine canyon correspondence appears to hold for Pelekunu, Halawa, Kawainui, Waikolu, and Naiwa submarine canyons. East-west profiles across the Pelekunu subaerial submarine canyon system (Fig. 8) appear to confirm this connection between the subaerial canyon and the submarine canyon which can be traced across the shelf between the shore and the canyon head. The long profile of the Pelekunu Canyon system is smooth and does not show any distinct nick points. Kalaupapa Peninsula, north of Waihanau Canyon, has two submarine canyons that begin within 0.25 mile of the peninsula shoreline. It is possible that these two submarine canyons were filled during the eruption of

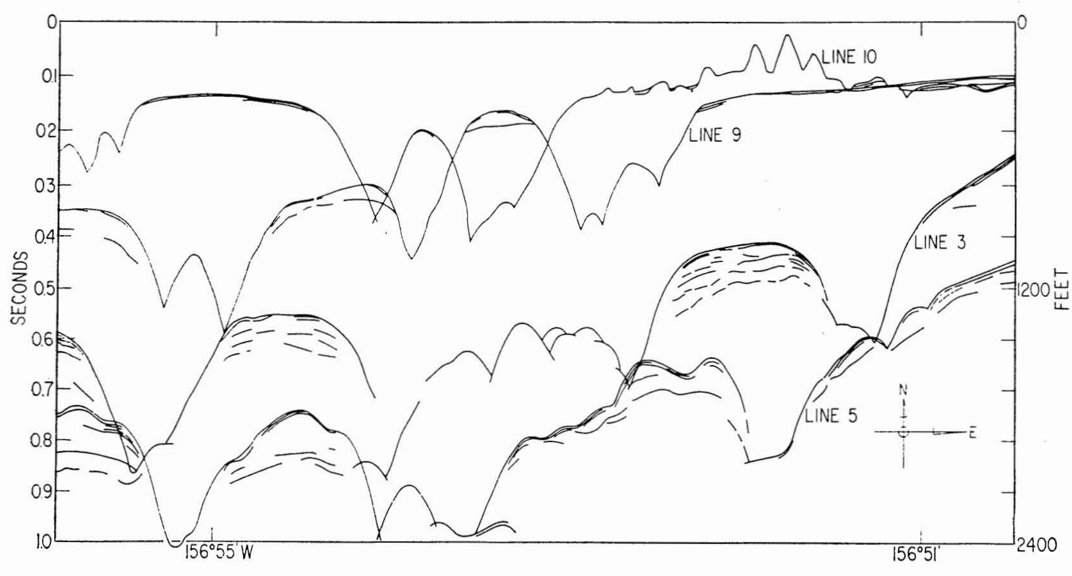

FIG. 7. Tracings of the seismic reflection records obtained along lines 3, 5, 9, and 10, cruise MOLCAN I, superimposed so that the sedimentary sequences can be related. See Figure 1 for line positions.

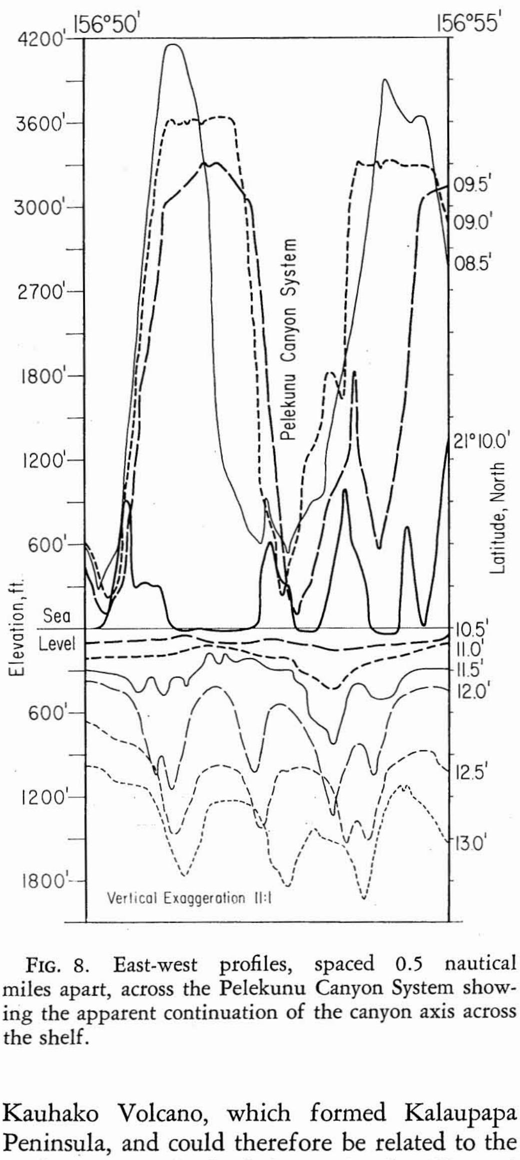

FIG. 8. East-west profiles, spaced 0.5 nautical miles apart, across the Pelekunu Canyon System showing the apparent continuation of the canyon axis across the shelf.

Kauhako Volcano, which formed Kalaupapa Peninsula, and could therefore be related to the land canyons inland of the peninsula (Shepard and Dill, 1966).

There appears to be no evidence of sediments deposited along the axis of the submarine canyons (Fig. 7), suggesting that the canyons are primarily sediment-transport areas, while the shelf is a depositional area. The submarine canyons probably carry most of the material that is transported into the sea from the subaerial canyons through turbidity currents, eventually settling in the Hawaiian Deep. Periodic turbidite flows may act to keep the submarine canyons clear of sediments delivered by the bottom currents from the island shoreline.

GEOMORPHOLOGICAL HISTORY OF THE NORTH SLOPE

Moore (1964) suggested that the Oahu-Molokai seamount group, located about 60 miles north of Molokai, was formed through two giant landslides, one from the northeast coast of Oahu and the other from the north coast of Molokai. This study does not lend support to that contention, since the evidence outlined above suggests that the north slope of Molokai has developed through island subsidence accompanied by subaerial erosion, wave erosion, sediment deposition, and sediment transport.

It is well known that high islands in tradewind regions interrupt the normal tradewind pattern and cause heavy rainfall on the windward sides of the islands. East Molokai Dome may have been as much as 15,000 feet high before erosion. Heavy rainfall on the relatively steep northern slope of Molokai Island could therefore be expected to have formed many straight subaerial canyons having steep gradients. Similarly, such an island would also interrupt the normal wind-driven wave systems, resulting in heavy wave erosion along the windward shoreline, and wave erosion could also be expected to have cut back into the lava and thus have developed the insular shelf. With continued subsidence of the island, the subaerially formed canyons would eventually become submarine canyons, and the submerged wave-cut bench or shelf would begin to collect sediments, as appears to be the case along the north shore of Molokai. Sediments transported down the subaerial canyons would probably continue to move down the submarine canyons in the form of turbidity currents and be deposited in the Hawaiian Deep.

From the data presented in this study, from data obtained on two north-south profiles of the north slope of Molokai (Fig. 9), and from the study by Shepard and Dill (1966), a structural profile of the north slope of Molokai was constructed (Fig. 10). The suggestion that the submarine canyons were subaerially formed is supported by the long profile of the canyon axes. The flatter gradient in the waterline sec-

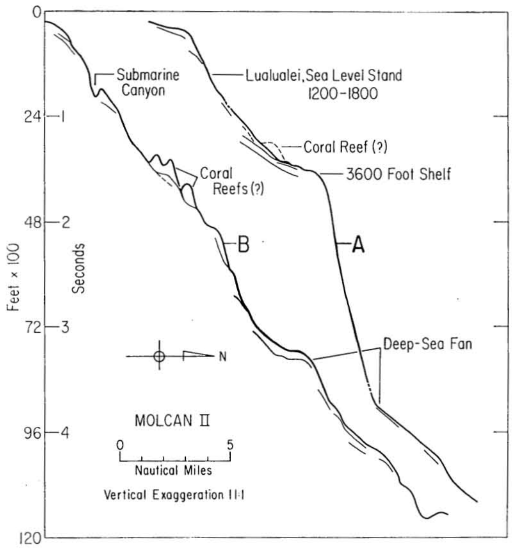

FIG. 9. Tracings of the seismic reflection records obtained on two north-south lines during cruise MOLCAN II. See Figure 1 for line positions.

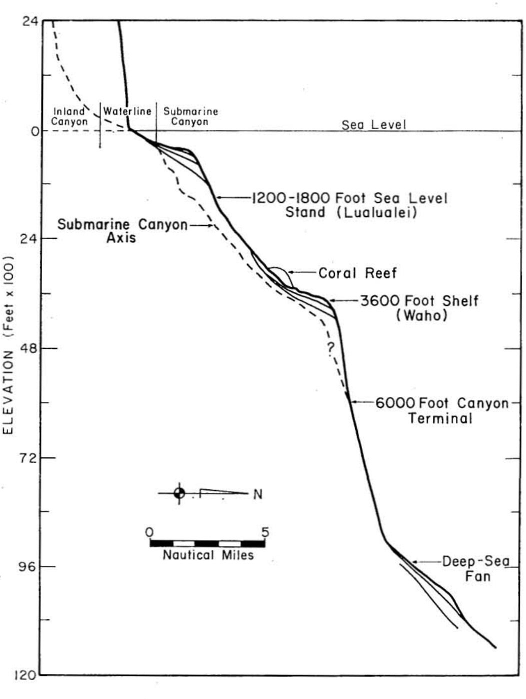

FIG. 10. Composite profile of the present north slope of Molokai Island showing the sedimentary sequences as inferred from the seismic reflection data, and the average axis of the submarine canyons as obtained in these bathymetric surveys and from Shepard and Dill (1966). Vertical exaggeration: 11 to 1.

tion of the profile is probably the result of subaerial erosion that has now nearly reached equilibrium and the result of wave erosion and sediment deposition that has occurred during stages of island submergence. The continuation of this gradient along the surface of the shelf without a nick point suggests that submarine erosion is not significant. The similarity between this profile and the profile through the 3,600-foot shelf suggests that their origins are also similar. The canyons terminate at about a 6,000-foot depth, which is about 2,000 feet less than the amount of inferred island subsidence (Furumoto and Woollard, 1965; Strange et al., 1965), suggesting that the entire canyon system was developed subaerially and then drowned.

Support for the suggestion that the submarine canyons are now only turbidity current channels is seen in the seismic reflection data. Sediments do not appear in the axis of the canyons, whereas they do appear as conformable layers in the intracanyon areas. The intracanyon sediments thicken with increasing distance from the shore and therefore increase the canyon wall heights. The primary source of these sediments appears to be the entire eroded coast of Molokai which has acted, and still is acting, as a line source. These sediments are probably derived through wave erosion from the shore and transported offshore by bottom currents, in that way producing the conformable sedimentary sequences that cover the entire shelf. Since there appear to be no sediments in the canyon axes, the canyons must therefore be sediment transport channels.

The slope of North Molokai suggests that subsidence may have continued at a uniform rate until the —3,600-foot level, when the first apparent stand of sea level occurred. This stand appears to have lasted for a long period of time because a shelf about 2 to 4 miles wide was formed in the interval. Seismic reflection evidence suggests that coral reefs may have formed on this shelf. Age estimates of the shelf range from 2 to 50 million years (Mathewson and Malahoff, 1969). During that period erosion continued to cut the subaerial canyons which are now drowned, while deposition continued to increase the submarine canyon wall heights and to build out the shelf and slope. Turbidity currents continued to flow down the canyons into the Hawaiian Deep.

With the advent of a rise in sea level or renewed island subsidence, or both, the slope above the Waho shelf began to form. The present —1,200- to —1,800-foot terrace was formed during this period when island subsidence probably halted for a short period of time. The present geomorphology of the island and the shelf was probably formed through a complex series of island submergences and emergences, as is suggested by the numerous elevated and submerged stands of sea level reported in Stearns (1966). The sediments derived from the island through wave erosion are probably the sediments that form the sedimentary veneer seen in the seismic profiler records and the deeper reflectors detected on the outer shelf. The sediments derived from the land canyons probably still continue to travel to the Hawaiian Deep as turbidity currents flowing through the submarine canyons. The inner shelf now appears to be covered only by a thin sedimentary veneer (0.005 seconds reflection time thick at 0.5 mile offshore), suggesting that this area is within or at least near the wave erosion zone.

CONCLUSIONS

From bathymetric and seismic profiler evidence the geomorphology of the north slope of Molokai Island appears to have developed through the processes of erosion and deposition operating upon a subsiding volcanic island with a steep north slope. The canyon systems were apparently cut by subaerial erosion prior to the sinking of the island, and after submergence the submarine canyons acted as turbidity current channels. At the present time subaerially eroded material continues to travel down the canyons and out into the Hawaiian Deep as turbidity currents. Wave erosion, operating along the entire north shore, cut the sea cliffs and acts as a line sediment source supplying sediment to the entire shelf. The sediment is then transported along the sea floor and deposited on the outer shelf. These sediments, which are seen in the seismic reflection profiler data, have built up the submarine canyon walls. The geomorphology of the present day shelf and the submerged 3,600-foot shelf suggests that the geologic processes operating on the north coast of Molokai have been uniform throughout most of the history of the area.

ACKNOWLEDGMENTS

The officers and men of the USC&GS Ship "McArthur" carried out the bathymetric survey, and Commander R. L. Newsom made the data available to the author. The officers and men of the R/V "Mahi" and many graduate students in Oceanography assisted in the collection of the seismic reflection data. The figures reflect the skills of Gary Kajiwara. Janet Mathewson spent many hours working on the data. Ethel McAfee gave editorial guidance in the preparation of the paper for publication. Dr. James Andrews and Dr. Alexander Malahoff critically reviewed this paper. To all, the author expresses his appreciation.

LITERATURE CITED

EASTON, W. H. 1965. New Pleistocene shore lines in Hawaii. Geological Society of America Cordilleran Section, 61st Annual Meeting, Program, p. 21.

FURUMOTO, A. S., and G. P. WOOLLARD. 1965. Seismic refraction studies of the crustal structure of the Hawaiian Archipelago. Pacific Science, vol. 19, no. 3, pp. 315–319.

KROENKE, L. W. 1965. Seismic reflection studies of sediment thicknesses around the Hawaiian Ridge. Pacific Science, vol. 19, no. 3, pp. 335–338.

MALAHOFF, A., and G. P. WOOLLARD. 1966. Magnetic surveys over the Hawaiian Islands and their geologic implications. Pacific Science, vol. 20, no. 3, pp. 265–311.

MATHEWSON, CHRISTOPHER C. 1969. Bathymetry of the north insular shelf of Molokai Island, Hawaii from surveys by the USC& GSS "McArthur." Data Report No. 14, Hawaii Institute of Geophysics Report HIG-69-21, 9 pp., 5 figs., 1 map.

MATHEWSON, CHRISTOPHER C., and ALEXANDER MALAHOFF. 1969. Ancient shelf along the Hawaiian Ridge (Abstract). Fall Meeting (San Francisco), A.G.U., December 1969.

MOORE, J. G. 1964. Giant submarine landslides on the Hawaiian Ridge. U. S. Geological Survey, Professional Paper 501-D, pp. D95–D98.

RUHE, R. V., J. M. WILLIAMS, and E. L. HILL. 1965. Shorelines and submarine shelves, Oahu, Hawaii. Journal of Geology, vol. 73, pp. 485–497.

SHEPARD, F. P., and R. F. DILL. 1966. Submarine canyons and other sea valleys. Rand McNally and Co., Chicago. 381 pp.

STEARNS, H. T. 1966. Geology of the State of Hawaii. Pacific Books, Palo Alto, California. 266 pp.

——— 1967. Geology of the Hawaiian Islands. State of Hawaii Dept. of Land and Natural Resources, Bulletin 8; supplement by G. A. Macdonald.

STEARNS, H. T., and G. A. MACDONALD. 1947. Geology and groundwater resources of the island of Molokai, Hawaii. Hawaii Division of Hydrography, Bulletin 11. 113 pp. (geologic map enclosed).

STRANGE, W. E., G. P. WOOLLARD, and J. C. ROSE. 1965. An analysis of the gravity field over the Hawaiian Islands in terms of crustal structure. Pacific Science, vol. 19, no. 3, pp. 381–389.