Marine Pothole Erosion, Oahu, Hawaii[1]

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THE TERM "pothole" has been applied to a variety of depressions by many writers. The term is used here to describe depressions which are abraded and scoured by water and grinding tools under the influence of currents that produce a vortex motion. Elston (1918) referred to holes developed in this manner as "normal potholes," and Alexander (1932) used also the term "eddy holes" to describe depressions formed by this mechanism.

Fluvial and marine potholes and solution features found on the Hawaiian Islands have been described in general by Wentworth (1944). In the present study, marine potholes developed primarily by wave abrasion along the shorelines of Oahu are treated in greater detail. Our purpose is to demonstrate that wave scour in the drilling of marine potholes plays a significant role in the erosion and reduction of portions of Oahu's shores, and that the type of rock determines the type of pothole formed. Wiens (1957) was impressed by the significant role of mechanical abrasion in the erosion of shorelines of Pacific islands.

GENERAL SETTING

Localities selected for study provide a variety of conditions in rock type, structural attitudes, and exposure to wave attack. At seven locations around the perimeter of the island, the dimensions of more than 140 potholes were measured, and the relationship between the form of the pothole and the kind of rock was recorded (Tables 1, 2, and 3). These specific sections of coastline are shown in Fig. 1.

Three major rock types exposed along Oahu's coasts are being actively drilled. These rocks are basalt (Fig. 2), volcanic tuff (Fig. 3), and lithified carbonate sand beach deposits, called beachrock (Fig. 4).

MECHANISM OF DRILLING

The action of waves in producing potholes is quite similar to that of running water in a stream channel, although the stream-formed variety has received more attention in the literature. From observing wave action, it is evident that the incoming surge of the wave is the major energy source for swirling the pebbles around in the depressions. Some additional swirling takes place as the wave recedes, but this action is less vigorous. There is no reason to suspect that the behavior of the grinding pebbles is much different from that observed in laboratory experimentation by Alexander (1932, p. 318). Some potholes contain no grinders, and it appears likely that hydraulic action by heavy wave swash and cavitation (Barnes, 1956) are effective in forming potholes even though constant pebble abrasion is lacking (Fig. 5). Alexander (1932, p. 334) makes a point of this in speaking of stream-eroded potholes:

> The adhesion of water to rock is greater than the cohesion of water, from which it follows that all rocks are covered with a fixed layer of water. This layer of water not only protects the rock from the effect of water flowing over it, but also permits many varieties of algae to secure a "foothold." This algal growth which often covers the rocks in rapids [or in wave swash] still further protects them from wear. For erosion to occur the water itself must strike against the rock surface with sufficient force to break through the fixed layer, or it must dash or roll against the rock surface some solid particle which will break through and produce wear. A stream [waves] that does not carry tools therefore does not erode except under falls or in precipitous rapids [or heavy surf]. Much of the erosion in plunge pools and gouge holes is of the tool-less type, although tools when present greatly increase the effect.

GENERAL DESCRIPTION OF POTHOLES

Most individual potholes along the shoreline tend toward circular to elliptical shapes. In

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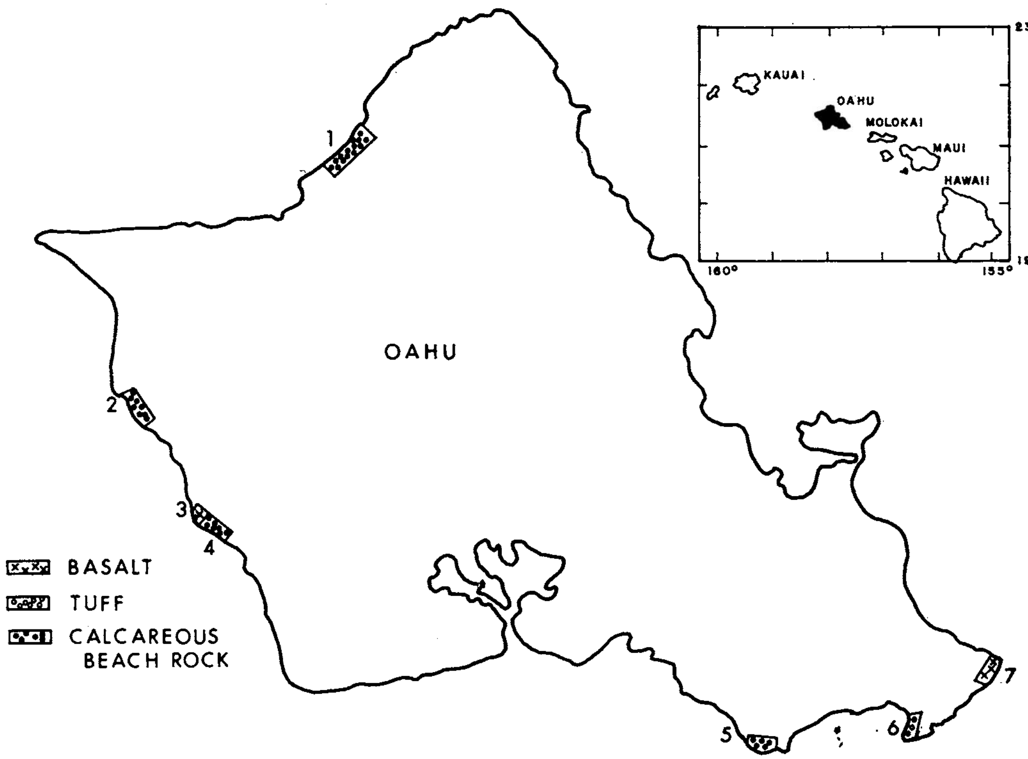

FIG. 1. Location map showing seven areas along Oahu's coastline where marine potholes were observed.

basaltic lava rock, the potholes occur as individual depressions with wide interareas (Figs. 6 and 7). In tuff or calcareous beachrock, the potholes frequently coalesce. By the process of coalescence an intricate network of potholes is developed to form an extremely irregular surface (Fig. 8). The remaining ridges separating the potholes which have not joined become very thin and, in general, lie parallel to the direction of surge motion which is usually perpendicular to the trend of the shoreline.

Some potholes are interconnected by shallow channels which serve as drainage outlets for excess water after the wave surge has receded (Fig. 8). Sand grains and small pebbles are found in some channels, suggesting that abrasion and scouring are important processes in the deepening and widening of these outlets. The channels vary in depth and width but generally maintain dimensions which are less than those of the connected potholes.

Elongate troughs, with potholes in the channel bottom (Fig. 9), are developing along the shore around Diamond Head and around Koko Head, (Honolulu Series tuff cones). These troughs commonly follow joints and fractures in the tuff. Once a channel has been enlarged along a fracture, the incoming wave swash follows a confined path. Much of the energy of the wave is concentrated in this trough each time a wave breaks over the shore. This concentration of energy establishes ideal conditions for pothole drilling in the channel bottom.

DEVELOPMENT ON DIFFERENT ROCK TYPES AND ATTITUDES

The shapes of potholes and the rate at which they are scoured are directly influenced by the rock types mentioned earlier. On Oahu's shores, potholes are most numerous per unit of area on calcareous beachrock deposits. Fewer potholes develop per unit area in basalt than in either beachrock or tuff. Tuff shows high susceptibility to the formation of potholes where the seaward dip of the tuffaceous beds is gentle, as is

FIG. 2. Pothole in massive basalt. Cobble of basalt is wedged in hole and cutting occurs around it. (Area 3.)

the case along the south coast of Diamond Head and along the southwest shore of Koko Head. But where the seaward dip steepens, as along the northeast shore of Koko Head and on the southwestern side of Diamond Head, pothole formation is poor or absent (Fig. 10).

A distinct wave-cut bench about 5 feet above present sea level extends along the Koko Head shorelines (Stearns, 1961, p. 7). In Hanauma Bay the bench truncates steeply dipping layers of tuff. Differential erosion on the bench resulted in a series of tiny parallel ridges and valleys which represent the edges of the truncated layers of tuff. The strike of these small ridges and intervening valleys approximately parallels the shoreline. Hence, when waves break and surge across the bench, the flow pattern is quite irregular. This dissipation of the energy associated with the inland-moving surge hinders pothole development. Where the dip of the layers of tuff or beachrock is gentle or nearly flat, as it is on the west side of Koko Head, potholes are fairly common (Fig. 6).

Along shores composed of beachrock, potholes and solution pits are very numerous (Wentworth, 1944). Unquestionably, pothole abrasion plus the chemical attack of salt water and salt spray operate together in producing cavities, holes, pits, pans, and depressions in the calcareous beachrock. In the zone of active wave surge, the insides of the holes are polished smooth as the result of pothole abrasion. Above this zone the insides of the holes are unpolished and rough and spiny (Figs. 11 and 12). The beachrock on the northwest shore of Oahu is riddled with potholes. One section (Fig. 1, Area 1) has several hundred potholes in a strip of shoreline 25 feet wide and approximately

FIG. 3. Pothole in volcanic tuff. Honolulu Volcanic Series on face of Diamond Head. Pebbles are coral and tuff. (Area 5.)

300 feet long. Many of the potholes are elongate, with the maximum axis oriented perpendicular to the trend of the beach.

GRINDING TOOLS

The lithology of the grinding tools is another important factor. On Oahu three types of rock serve as grinding tools in the potholes. These are (1) calcareous material, including fragments of coral reef and beachrock, (2) volcanic tuff, and (3) basalt. Although calcareous material rests in many potholes scoured in basalt, it is doubtful, because of its comparative softness, that it played a significant role in the drilling process. Pebbles of dense basalt found in all types of potholes in all types of rock undoubtedly provide the most effective grinding tools.

PROCESS OF DEVELOPMENT

For this study more than 140 potholes were measured in basalt, tuff, and calcareous beachrock. For each pothole, the diameter and depth were recorded and the diameter-depth ratio was computed. The purpose of these measurements was to determine whether lateral widening or vertical deepening in each of the three rock types is the dominant process in the drilling of the marine potholes. In elongated potholes, the maximum and minimum diameters were measured and an average circular dimension determined. Measurements and ratios are presented in Tables 1, 2, and 3.

In potholes in basalt (Table 1), the conclusions are not so well defined as in the other two rock types mentioned below. Ratios in basalt varied from 0.7 to 2.7. Of the potholes

TABLE 1

DIMENSIONS (IN INCHES) AND DIAMETER-DEPTH RATIOS OBTAINED FOR POTHOLES CUT IN BASALT; OAHU, HAWAII

CIRCULAR DIAMETER	MAXIMUM DIAMETER	MINIMUM DIAMETER	DEPTH	RATIO
		Area 3		
(8)*	9	6	3	2.7
11			5	2.2
7			7	1.0
9			9	1.0
6			3	2.0
5			2	2.5
9			9	1.0
(17)	21	13	9	1.9
11			6	1.8
11			10	1.1
7			6	1.1
6			4	1.5
9			11	0.8
(20)	24	15	23	0.9
10			12	0.8
(13)	13	12	15	0.9
9			11	0.8
18			18	1.0
9			11	0.8
(7)	7	6	6	1.1
5			6	0.8
(10)	11	8	14	0.7
(12)	15	9	14	0.9
15			21	0.7
(20)	21	20	20	1.0
		Area 7		
19			15	1.3
35			31	1.1
14			13	1.1
20			23	0.9
(26)	32	21	25	1.0
(14)	16	12	11	1.3
34			29	1.2
8			8	1.0
18			20	0.9
11			13	0.9
21			16	1.3
15			18	0.8
18			19	0.9
17			18	0.9
19			27	0.7
(14)	17	10	17	0.8
13			15	0.9
11			11	1.0
20			19	1.1
7			10	0.7
30			28	1.1
60			66	0.9
Average ratio = 1.1				

* ( ) = Circular diameter computed.

TABLE 2

DIMENSIONS (IN INCHES) AND DIAMETER-DEPTH RATIOS OBTAINED FOR POTHOLES CUT IN TUFF; OAHU, HAWAII

CIRCULAR DIAMETER	MAXIMUM DIAMETER	MINIMUM DIAMETER	DEPTH	RATIO
		Area 5		
(30)*	42	18	12	2.5
(17)	22	13	8	2.1
14			9	1.5
7	9	5	4	1.8
18			12	1.5
(12)	18	7	6	2.0
28			14	2.0
(18)	23	14	11	1.7
14			13	1.1
15			12	1.3
(16)	20	12	10	1.6
22			14	1.5
(30)	36	24	18	1.7
(14)	16	12	7	2.0
(19)	20	18	14	1.4
28			24	1.2
12			7	1.7
(22)	24	18	20	1.1
12			8	1.4
18			18	1.0
		Area 6		
40			24	1.6
13			9	1.4
12			12	1.0
19			15	1.3
Average ratio = 1.6				

* ( ) = Circular diameter computed.

measured in basalt, 45 per cent had diameters less than their depth, 40 per cent had diameters greater than their depth, and 15 per cent had diameters approximately equal to their depth. All ratios combined for potholes in basalt show an average value of 1.1.

Similar measurements and ratios were obtained from potholes in volcanic tuff. The diameter exceeded the depth in all holes except two, where the depth and diameter were approximately equal (Table 2). The range of ratios extends from 1.0 to 2.5, with an average value of 1.6. As is the case in beachrock, the rate of lateral cutting seems to exceed the rate of deepening.

Data from potholes developed on calcareous beachrock (Table 3) show that in every hole

TABLE 3

DIMENSIONS (IN INCHES) AND DIAMETER-DEPTH RATIOS OBTAINED FOR POTHOLES CUT IN BEACHROCK; OAHU, HAWAII

CIRCULAR DIAMETER	MAXIMUM DIAMETER	MINIMUM DIAMETER	DEPTH	RATIO
		Area 1		
(11)*	13	10	5	2.2
(11)	14	9	4	2.8
6			4	2.5
(12)	14	10	5	2.4
7			3	2.3
12			4	3.0
11			6	1.9
9			5	1.8
6			3	2.0
9			4	2.2
(11)	14	9	5	2.2
(13)	16	11	8	1.6
6			3	2.0
(11)	13	9	3	3.7
6			3	2.0
10			4	2.5
(16)	18	14	7	2.3
(9)	11	8	4	2.2
8			3	2.7
9			6	1.5
10			6	1.7
(16)	19	13	9	1.8
8			5	1.6
12			7	1.7
(12)	14	10	6	2.0
		Area 2		
(24)	28	20	9	2.5
23			11	2.1
(27)	30	24	12	2.3
11			5	2.2
14			7	2.0
(17)	21	14	9	1.9
18			11	1.6
18			11	1.6
(24)	26	21	9	2.7
12			7	1.7
(22)	24	19	13	1.7
23			13	1.8
(19)	22	15	11	1.7
23			11	2.1
22			15	1.5
(23)	28	18	11	2.1
(16)	20	11	11	1.4
8			3	2.7
(24)	26	19	6	4.0
14			7	2.0
9			5	1.8
(8)	9	7	5	1.6
7			2	3.5

* ( ) = Circular diameter computed.

TABLE 3 (*continued*)

CIRCULAR DIAMETER	MINIMUM DIAMETER	MAXIMUM DIAMETER	DEPTH	RATIO
		Area 2 (*continued*)		
9			4	2.2
12			5	2.4
11			5	2.2
10			5	2.0
13			6	2.1
(8)	9	7	6	1.3
15			7	2.1
(14)	17	11	9	1.5
11			8	1.4
11			7	1.6
13			7	1.8
18			7	2.6
15			6	2.5
20			8	2.5
16			5	3.2
11			7	1.6
14			10	1.4
		Area 4		
(35)	39	31	18	1.9
19			13	1.4
(21)	23	18	9	2.3
11			9	1.2
19			11	1.7
20			11	1.9
13			10	1.3
31			16	1.9
22			10	2.2
(19)	25	14	11	1.7
14			10	1.4

Average ratio = 2.1

* ( ) = Circular diameter computed.

the diameter exceeded the depth. The ratio of diameter to depth ranged from 1.3 to 4.0, with an average value of 2.1. This suggests that in beachrock lateral undercutting of the pothole walls occurs more commonly than downcutting.

These observations indicate that the diameter-depth ratio is controlled by lithology—bearing out the conclusions of Alexander (1932, p. 329). Potholes along a shoreline containing very gently seaward-dipping stratified rocks generally have a greater diameter-depth ratio than is found in massive basalt. The apparent explanation is that, in the process of lateral extension of the pothole walls, in finely stratified rocks such as tuff and beachrock, the grinding tools attack the strata edgewise where some are less resistant. The dense, more uniform, unstratified

FIG. 4. Pothole in calcareous beachrock; flakes and grains of carbonate rock resting in hole. (Area 4.)

FIG. 5. Potholes in beachrock, formed largely by hydraulic action of heavy surf; few if any grinding pebbles present. (Area 4.)

FIG. 6. Potholes in basalt. Note wide spacing. Cobble of basalt and fragments of coral rest in larger hole. (Area 3.)

FIG. 7. Potholes in basalt. (Area 3.)

FIG. 8. Potholes scoured in volcanic tuff. Note polishing of interiors and coalescence. Pebbles are composed of tuff, coral, and basalt. (Area 5.)

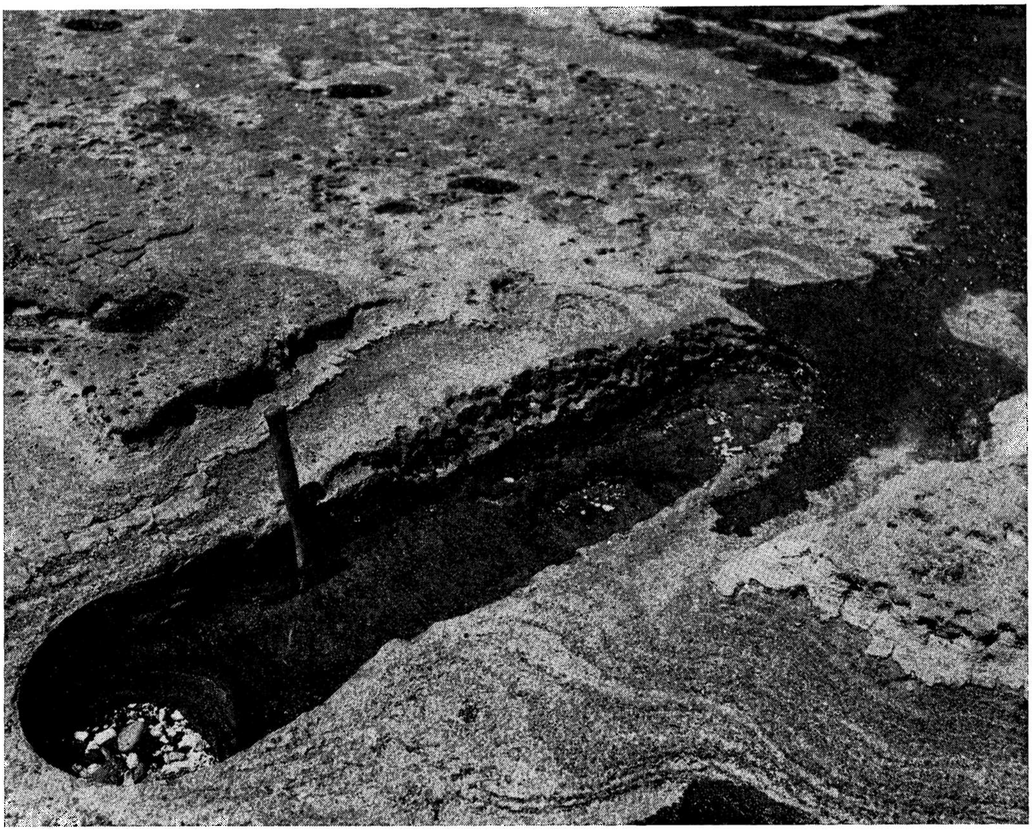

FIG. 9. Elongate trough following joint in gently dipping volcanic tuff. Pothole at landward end of trough. Pebbles are composed of coral, tuff, and basalt. (Area 6.)

FIG. 10. Comparison of active potholing in flat-lying, light-colored beachrock in foreground with no pothole action in more steeply dipping dark-colored volcanic tuff in background. (Area 5.)

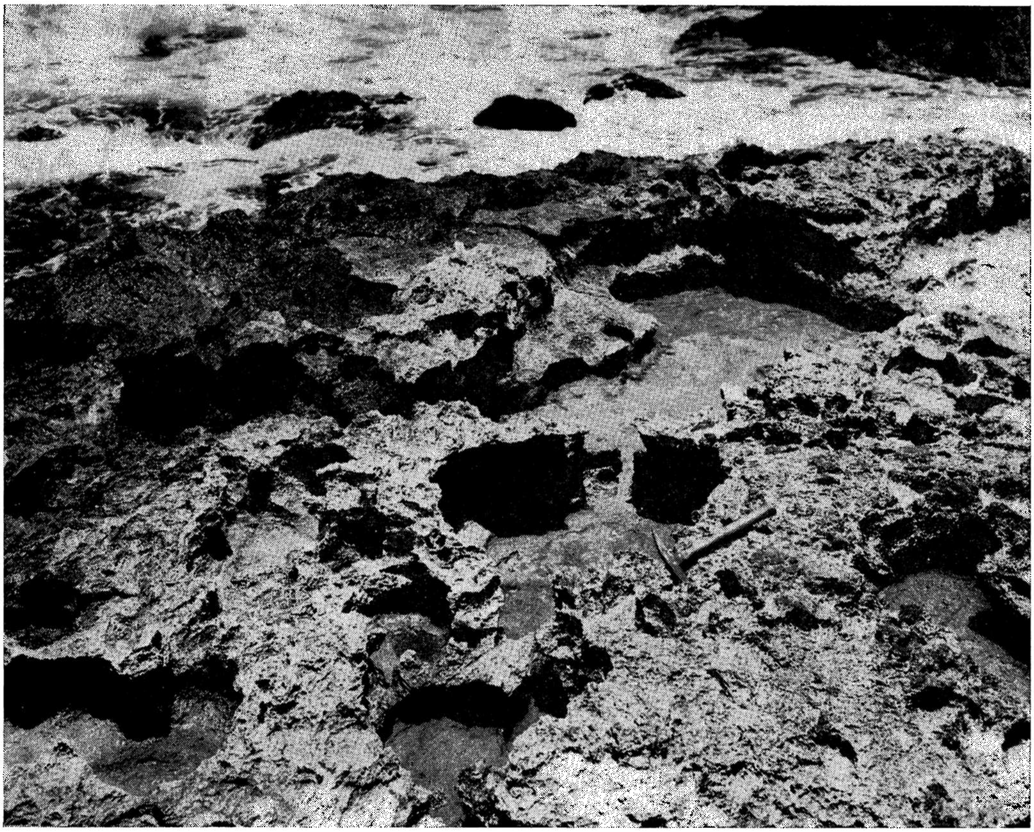

FIG. 11. Above constant surf zone in beachrock, combined action of solution processes and potholing to form cavities. (Area 4.)

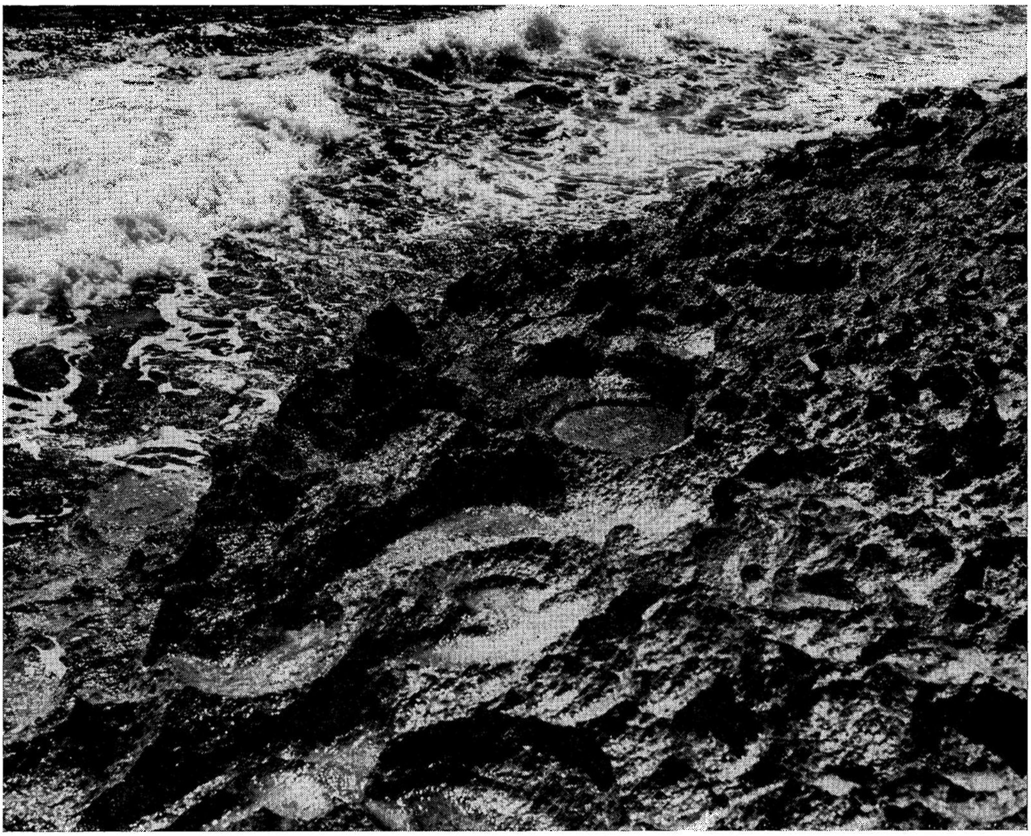

FIG. 12. Pothole abrasion predominant in surf zone; solution cavities predominant to the right of hammer. (Area 2.)

basalt wears away slightly faster at the bottom of the pothole where downcutting pebble abrasion exceeds lateral cutting.

SUMMARY

Along certain sections of the shorelines of Oahu, erosion is being hastened by wave-induced pothole drilling. Most potholes occur in the active wave-surge zone and are drilled in basalt, volcanic tuff, and calcareous beachrock. Rock type is an important factor in controlling the diameter-depth ratio. In basalt the average is 1.1, in volcanic tuff it is 1.6, and in beachrock 2.1.

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