served in the summit area during June and July, such as might accompany the movement of magma (2). An alternate explanation might be that magma intruded near the surface to form a conductive zone in which induction from magnetic micropulsations would take place. Magnetic micropulsations are taking place continuously, being characterized by fluctuations in the earth's magnetic field with amplitudes of a gamma or less, with periods of 10 seconds or longer. These fluctuations induce current flow in the earth in proportion to the conductivity of the earth. The secondary magnetic field resulting from these induced currents is normally directed in the horizontal plane, so that little or no effect would be noticed with a coil lying on the earth, such as we used in our observations. However, when there are strong lateral changes in conductivity, the secondary magnetic field may have a significant vertical component which might be detected (*3*). In either case, the fact that the unusual noise was not detected at recording sites a few kilometers away suggests that the source of the noise was shallow, probably less than a kilometer deep.

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References and Notes

1. D. W. Peterson, U.S. Geological Survey Map GO-667 (1967).
2. Written communication with the staff, U.S. Geological Survey Hawaii Volcano Observatory, Hawaii Volcanoes National Park.
3. I. D'Erceville and G. Kunetz, *Geophysics* **27**, 651 (1962); J. T. Weaver, *Can. J. Phys.* **41**, 484 (1963).
4. Publication authorized by the director, U.S. Geological Survey.

17 December 1971

Buried Caldera of Mauna Kea Volcano, Hawaii

Abstract. *An elliptical caldera (2.1 by 2.8 kilometers) at the summit of Mauna Kea volcano is inferred to lie buried beneath hawaiite lava flows and pyroclastic cones at an altitude of approximately 3850 meters. Stratigraphic relationships indicate that hawaiite eruptions began before a pre-Wisconsin period of ice-cap glaciation and that the crest of the mountain attained its present altitude and gross form during a glaciation of probable Early Wisconsin age.*

Mauna Kea (4205 m) is the highest of five massive shield volcanoes comprising the island of Hawaii, and it last erupted about 4500 years ago as determined by ^{14}C dating (*1*). The bulk of the mountain consists of primitive oceanic basalts of the Hawaiian tholeiite suite, but the top is thinly capped by a carapace of more alkaline lithologies, hawaiite being the predominant rock type. Unlike such recently active Hawaiian volcanoes as Kilauea and Mauna Loa, Mauna Kea possesses no obvious summit caldera. Instead, the crest of the mountain consists of a complex array of cinder cones and lava flows at the apex of three rift zones that trend west, south-southeast, and east-northeast. Geologists have long speculated on the possible existence of a caldera that may lie buried beneath the cap of young lavas and cones that mantle the summit area (*2–4*). Evidence gathered during current studies of the upper slopes of Mauna Kea points to the probable existence of a buried caldera and places limitations on its dimensions and age.

Detailed mapping and study of flow stratigraphy on the upper slopes of the volcano indicate that a relatively abrupt transition occurs from flows of olivine basalt and picrite basalt, which constitute the bulk of the exposed Hamakua Group, to overlying hawaiite lavas of the Laupahoehoe Group (*5*). Except along the three principal rift zones, where hawaiite flows and associated cinder cones comprise an unusually thick section, Laupahoehoe lavas and intercalated sheets of glacial drift seldom exceed 100 m in thickness. Nearly continuous exposures in Pohakuloa and Waikahalulu gulches on the south flank of the mountain show that Hamakua lavas extend high up the slopes of the volcano and that the entire Laupahoehoe section thins progressively downslope, being no more than several flows thick at the south base of the mountain (Figs. 1 and 2). At 3600 m in Pohakuloa Gulch the Laupahoehoe section is at least 110 m thick, but it thins to no more than 10 m at an altitude of 2200 m. Hamakua flows are exposed west of Pohakuloa Gulch in a large kipuka that extends upslope to about 2600 m, and seven other outcrops occur within and near Pohakuloa Gulch between 2800 and 3850 m. Two linear belts of outcrop also are found along Waikahalulu Gulch between 2700 and 3800 m.

Along both gulches the contact between the Hamakua and Laupahoehoe groups slopes south at approximately 230 m/km (*6*). If this contact were projected upward beyond the highest outcrops of Hamakua lavas, it would reach an altitude of nearly 4400 m above the summit of the volcano (Fig. 2). Therefore, the basaltic core of the upper part of the mountain approximates a cone, truncated at about 3800 m and mostly buried by younger lavas. The underlying geometry of the top of the volcano is evident where the topography has not been masked by younger cinder cones. For example, in the reach between Douglas Cone and Puu Waiau, the land surface undergoes a marked and relatively abrupt change of gradient at about 3850 m, passing from 275 m/km downslope to about 90 m/km above. This summit plateau must reflect the basic underlying structure of the crest of the volcano and is compatible with the concept of a former caldera lying buried beneath the cap of late hawaiite eruptives.

Macdonald (*2*) called attention to the concentric alignment of certain

Table 1. Comparison of the dimensions of the inferred caldera of Mauna Kea with those of other Hawaiian volcanoes.

Caldera	Width (km)	Length (km)	Circumference (km)	Area (km^2)
Mauna Kea	2.1	2.8	8.0	4.5
Kilauea	3.1	4.2	12.6	10.7
Mauna Loa	2.6	4.4	15.3	9.3
Kohala (*3*)	3.2	4.8		

cinder cones on the upper slopes of Mauna Kea and speculated that they may point to the presence of one or more ring dikes at depth. Stratigraphic evidence assembled during the present investigation indicates that cones lying within the 3800-m contour are of two ages and were erupted when the summit of the mountain was mantled with glacier ice. Six of these cones (Douglas Cone, McCrae Cone, Puu Kea, Summit Cone, Goodrich Cone, and Puu Waiau) are located along an arc that coincides with the projected edge of the summit plateau and lie immediately above the highest outcrops of Hamakua lavas (Fig. 1). If the arc thus delineated is extended around the edge of the summit plateau, it describes an ellipse within which lie Puu Poliahu and various lava flows originating from it and from the encircling cones. The elliptical alignment of cones implies a series of late hawaiite eruptions that issued from vents located around the margin of the topographically defined summit plateau. Consequently, if these vents lie along deep-seated fractures that mark the margin of a buried caldera, the lava-filled conduits may now constitute one or more ring dikes, as envisaged by Macdonald.

The caldera, as reconstructed, measures approximately 2.1 by 2.8 km, being elongated in an approximately east-west direction. It has a shape somewhat similar to, but dimensions slightly smaller than, those of Kilauea, Manua Loa, and the inferred former caldera of Kohala volcano (Table 1).

On its south side, the caldera rim lies no lower than 3850 m, the altitude of the highest outcropping Hamakua lavas. Because Hamakua flows are not exposed elsewhere on the upper slopes of the volcano, the west, north, and east sides of the rim may lie somewhat lower than the south rim and thus may have permitted flows originating within the caldera to completely mantle its margin and the adjoining slopes of the volcano on those three sides.

Although no direct evidence bearing on the thickness of Laupahoehoe volcanics above 3850 m is currently available, limiting estimates can be obtained by assuming a buried caldera about as deep as the modern calderas of Kilauea and Mauna Loa. If there were no caldera, the total section of lava flows and pyroclastics beneath Summit Cone would have a maximum thickness of about 350 m. Away from the cinder cones, the lava pile would amount to no more than about 200 m. The rim of the Kilauea caldera currently ranges in height from 0 to 270 m, whereas the caldera of Mauna Loa is between 60 and 185 m deep. If a maximum depth of 200 m is assumed for the inferred Mauna Kea caldera at the time hawaiite flows began to fill it, the total thickness of Laupahoehoe volcanics capping the summit would be between 400 m (mean) and 550 m (maximum). Although these figures are admittedly speculative, the actual thickness probably lies within the extreme limits suggested.

The age of the inferred caldera and the time of caldera filling can be deduced from stratigraphic relationships of lava flows, cinder cones, and glacial deposits in the summit area. The uppermost unit of the

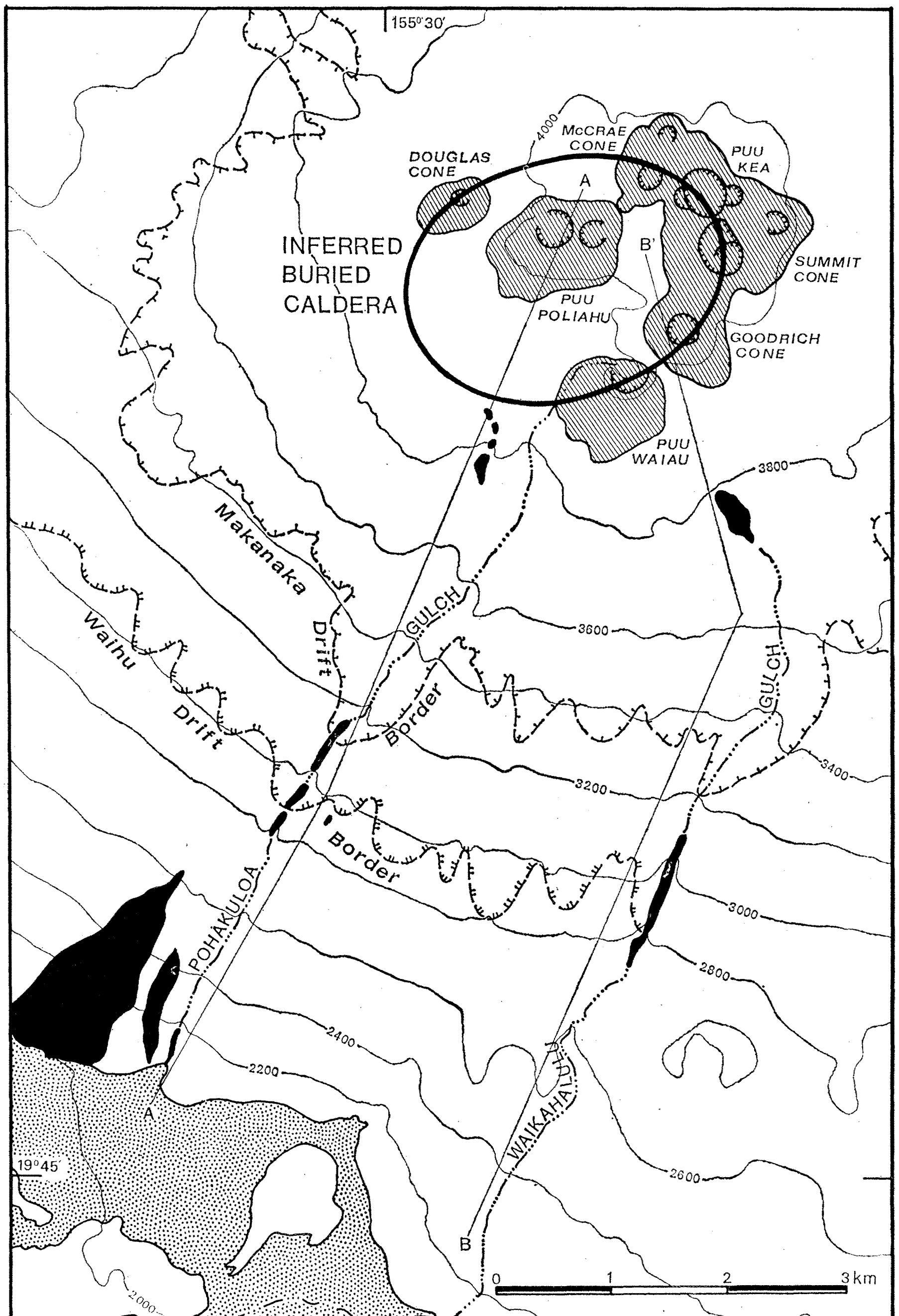

Fig. 1. Map of the south slope of Mauna Kea showing the position of the inferred caldera, outcrops of Hamakua lavas (black), pyroclastic cones on the summit plateau (shaded), and the limits of the Makanaka and Waihu ice caps. Outwash gravels at the base of the mountain are indicated by the stippled pattern. The contours are in meters.

Hamakua Group consists of interbedded gravels and diamicton layers that originated on the upper slopes of the volcano. The formation is extensively exposed in Pohakuloa Gulch, for which it is named, and consists of detrital clasts of olivine basalt and picrite basalt in an indurated finer-grained matrix (*7*). Because no hawaiite clasts have been found in the unit, one can infer that hawaiite lavas were not exposed on the upper south flank of the mountain at the time the clastic sediments were deposited. If a caldera was then in the process of being filled by hawaiite lava flows, none had yet overtopped the south wall of the caldera, and apparently no cones or flows of hawaiite had yet been erupted upon the caldera rim on the south side of the summit plateau. Flows overlying the Pohakuloa sediments consist largely of hawaiite lavas that erupted prior to the ensuing Waihu Glaciation (*7*). Because these flows can be traced upslope onto the summit plateau, they indicate that any preexisting depression had been filled prior to the generation of a Waihu ice cap. By the beginning of the Waihu Glaciation, little, if any, Hamakua lava was cropping out in the summit area, for exposed Waihu drift consists almost entirely of hawaiite clasts.

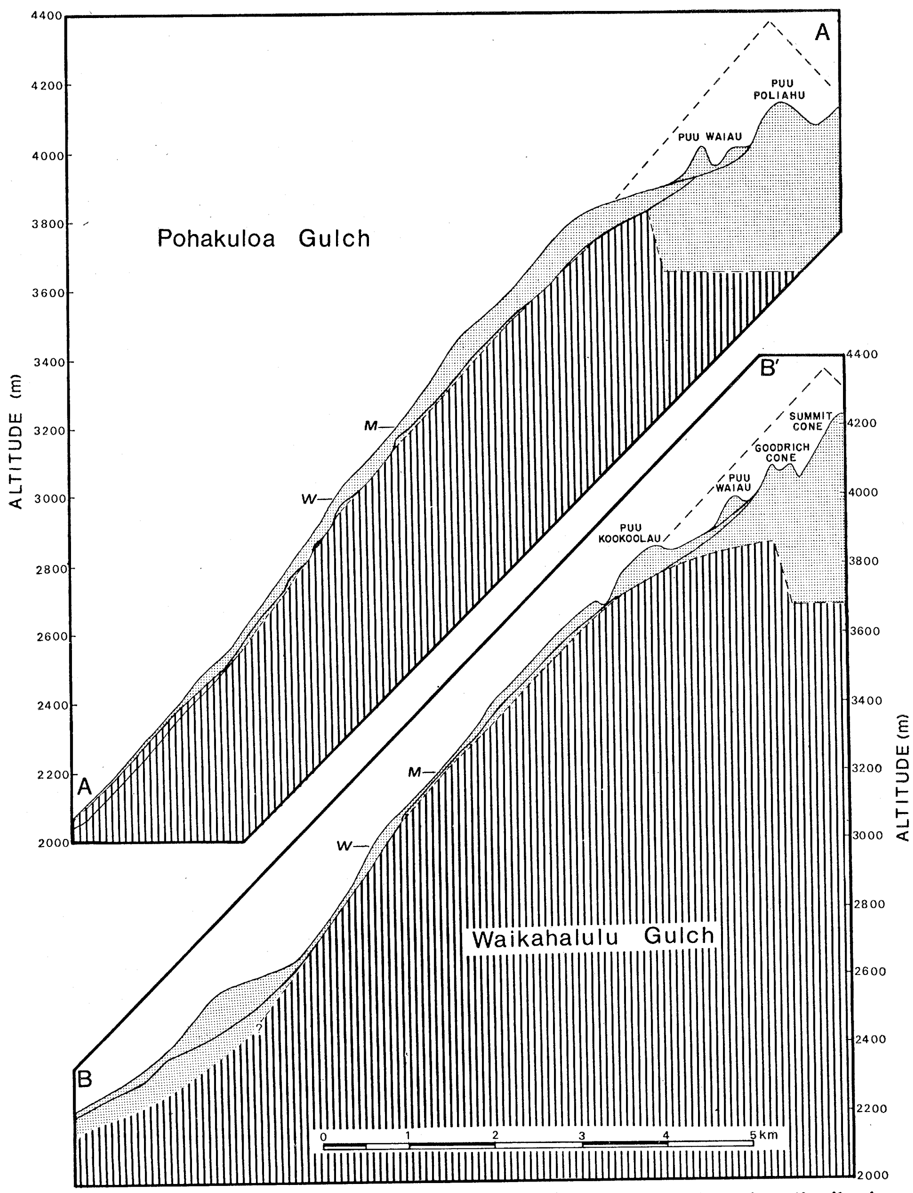

Fig. 2. Sections along Pohakuloa and Waikahalulu gulches showing the distribution of Laupahoehoe (stippled) and Hamakua (shaded) lavas. The limits of the Waihu (*W*) and Makanaka (*M*) glaciers are indicated. The projection of the Laupahoehoe-Hamakua contact above the summit plateau is shown by dashed lines.

Lava flows and pyroclastic cones now exposed at the summit of the mountain were erupted during two separate intervals, both coinciding with periods of ice-cap glaciation. Puu Waiau, Puu Poliahu, and their associated lava flows were erupted during the Waihu Glaciation, as attested by stratigraphic position and by extensive ice-contact flow margins characterized by pillow-palagonite breccias. These flows and pyroclastics rest on largely unexposed post-Pohakuloa hawaiite flows, which must lie at or above the upper rim of the buried caldera. Douglas Cone, McCrae Cone, Puu Kea, Summit Cone, Goodrich Cone, and several unnamed cones in the Summit Cone cluster, together with their associated lava flows, were erupted during an early phase of the subsequent Makanaka Glaciation, as indicated both by stratigraphic relationships and by widespread ice-contact flow margins. Therefore, the summit of Mauna Kea reached its present altitude and attained its present form during the early part of the last glaciation, tentatively correlated broadly with the Early Wisconsin ice advances of North America. Erosional modification of the summit during the Late Makanaka Glaciation and postglacial time has been relatively insignificant.

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References and Notes

1. S. C. Porter, *Science* **172**, 375 (1971).
2. G. A. Macdonald, *Amer. J. Sci.* **242**, 210 (1945).
3. H. T. Stearns and G. A. Macdonald, *Hawaii Div. Hydrogr. Bull. 9* (1946).
4. G. A. Macdonald and T. Katsura, *Geophys. Monogr. Amer. Geophys. Union* **6**, 187 (1962); G. A. Macdonald, *Pac. Sci.* **19**, 320 (1965); ——— and A. T. Abbott, *Volcanoes in the Sea* (Univ. of Hawaii Press, Honolulu, 1970).
5. As used here, the Hamakua and Laupahoehoe groups are essentially equivalent to the Hamakua and Laupahoehoe volcanic series of Stearns and Macdonald (*3*). These units will be redefined in a subsequent report on volcanic and glacial stratigraphy of Mauna Kea, currently in preparation.
6. This slope is steeper than the upper slopes of Kilauea (40 m/km) and Mauna Loa (150 to 200 m/km), which may indicate that late Hamakua lavas, owing either to lesser volume or higher viscosity of flows, did not travel as far downslope as early Hamakua tholeiitic lavas, which comprise the bulk of the main shield.
7. C. K. Wentworth and W. E. Powers, *Geol. Soc. Amer. Bull.* **51**, 542 (1943); H. T. Stearns, *ibid.* **56**, 267 (1945).

8. This work was supported by NSF grant GA-20320. Gordon A. Macdonald and Bates McKee kindly reviewed an early draft of the manuscript.

16 December 1971; revised 2 February 1972