A Special Issue on Recombinant DNA

A special issue of *Science* to be dated 8 April 1977 will include a number of reports on recombinant DNA research. Deadline for receipt of manuscripts is 4 February. Reports providing new data relevant to the containment problem are especially welcome.

Reports

Chronology of Hawaiian Glaciations

Abstract. *Both potassium/argon and carbon-14 ages of lava flows and tephra layers interstratified with glacial deposits on Mauna Kea, Hawaii, indicate that four episodes of ice cap glaciation culminated about 20,000, 55,000, 135,000, and 250,000 years ago. These episodes are correlated with marine isotope stages 2, 4, 6, and 8, marking times of high global ice volume.*

Although the most dramatic environmental changes brought about by the Quaternary glacial ages occurred in northern middle latitudes where large continental ice sheets repeatedly formed and then disappeared, the effects of global climate change are also evident in tropical latitudes where smaller glaciers developed on some high mountain summits that now lack a perennial ice cover. During the latest glacial ages, a succession of small ice caps formed at the crest of Mauna Kea, the highest of Hawaii's volcanoes and the only known glaciated peak in the central Pacific Ocean basin. Because the massive shield of Mauna Kea was being actively constructed during this interval, glacial sediments are interstratified with lava flows and pyroclastic deposits on the upper slopes of the volcano. Recent radiometric dating of volcanic rocks and sediments directly associated with sheets of glacial drift makes possible an assessment of the ages of four recognized glaciations and provides a basis for comparing the resulting terrestrial glacial chronology with a record of late Pleistocene climatic fluctuations inferred from isotopic studies of deep-sea cores.

The exposed rocks on Mauna Kea are divisible into two lithologic groups, an older tholeiitic assemblage that constitutes the bulk of the volcanic pile and a younger differentiated alkalic suite that forms a thin carapace over the crest of the main shield (*1*). The older rocks, comprising the Hamakua Group, consist largely of thin but extensive pahoehoe flows of basalt and olivine basalt, whereas the younger rocks, included in the Laupahoehoe Group, are predominantly thick, type aa flows of hawaiite, with alkalic olivine basalt, ankaramite, and mugearite present in smaller volume. Pyroclastic cones and tephra layers form an important part of the Laupahoehoe section, especially along the principal rift zones (*2*).

Further subdivision of the stratigraphic sequence is based on the occurrence of glacial sediments within the volcanic pile. The recognition of four such horizons on the upper slopes of the mountain has led to the designation of seven formations (Figs. 1 and 2) (*1*). Clasts within the oldest exposed glacial drift, the Pohakuloa Formation, consist largely of vesicular olivine basalt of the Hamakua Group. The formation includes both diamicton and fluvial facies interpreted as till and outwash, respectively (*3*). It is exposed in several deep gulches on the south side of the volcano where basal sediments locally rest on abraded flows of the underlying Hopukani Formation.

Glacial sediments of the Waihu Formation form a belt of subdued end moraines that are exposed mainly in the southwest quadrant of the volcano at the 3000-m level; elsewhere they have been buried by younger lava flows. The drift includes clasts derived both from the Hopukani Formation and from the Liloe Formation which separates the Waihu deposits from the underlying Pohakuloa drift. The end moraines contain basal till and flow till as well as meltwater sediments, and they are associated with extensive outwash gravels that mantle the southwestern slope of the mountain above the Mauna Kea–Mauna Loa saddle. Abraded rock pavements are found locally beneath basal Waihu till and display striations oriented perpendicular to the gross topographic contours of the mountain. Surface boulders of Waihu age are deeply pitted or exfoliated, and tor-like pinnacles of indurated drift standing as much as 3 m above the surface of Waihu moraine crests suggest that the unit is substantially older than the comparatively unweathered and little-eroded drifts of Makanaka age.

Moraines of the Makanaka Formation, consisting largely of hawaiite clasts, can be traced almost continuously around the mountain at the 3500-m level. Where they border major gulches, the massive steep-sided lateral moraines reach heights of 50 m. Upslope from the end moraine belt extensive striated pavements are developed on aa lavas from which surface flow rubble has been stripped away by glacial ice. The Makanaka Formation is divisible into two units of glacial origin (Upper Member and Lower Member), separated by lava flows of the nonglacial Kemole Member. These lava flows are restricted largely to the principal rift zones where they are associated with numerous cinder cones and widespread tephra layers. End moraines of early Makanaka age commonly overlie lavas of the Hanaipoe Formation and extend only slightly beyond the more massive moraines of late Makanaka age. Only subtle differences in the degree of weathering are detectable between the two groups of moraines, suggesting that the Kemole interval probably was interstadial, rather than interglacial, in character. As many as five recessional moraines occur locally behind the late Makanaka terminal moraine, but they are difficult to correlate around the mountain because of their similar morphology and comparable degree of weathering.

The youngest lavas of Mauna Kea are included in the Waikahalulu Formation and crop out along the south rift zone (4). The postglacial age of the rocks is demonstrable on the upper slopes of the mountain where they overlie the late Makanaka terminal moraine and on the lower slopes where lava flows and tephra layers overlie a buried soil developed on late Makanaka outwash.

Certain lava flows and tephra cones lying largely inside the limit of late Makanaka glacial deposits are unique on Mauna Kea and are regarded as evidence of subglacial volcanic eruptions (5). Such features are restricted to the Waihu Formation and the Lower Member of the Makanaka Formation. The intraglacial lava flows exhibit steep and embayed margins locally as much as 90 m high, large palagonitized pillow structures that have well-developed radial jointing, glassy surfaces along ice-contact faces, and spiracles that extend as much as 2 m above the base of flows. Waihu tephra cones consist largely of bomb-bearing hyaloclastite, but they are capped by subaerially erupted cinders and bombs. Meltwater lakes into which the cones are inferred to have been built were as much as 150 m deep. Although hyaloclastite is not exposed in the little-eroded flanks of early Makanaka cones in the summit region, a seismic discontinuity within Summit Cone is believed to mark the contact between a core of hyaloclastite and overlying subaerially erupted cinders.

Lava flows within the lower part of the stratigraphic succession have been dated by the conventional K/Ar technique at the Quaternary Isotope Laboratory, University of Washington (6). The subaerial portion of Mauna Kea is at least 375,000 ± 50,000 years old, as shown by a date for a Hopukani lava flow exposed in lower Pohakuloa Gulch. Pohakuloa drift in Waikahalulu Gulch rests on an abraded flow of the Hopukani Formation that is 270,000 ± 35,000 years old; the Hopukani lavas probably accumulated rapidly during the tholeiitic phase of volcanism, and so very likely the drift is only slightly younger than the dated flow. Ice-contact lavas of the Waihu Formation have ages of 130,000 ± 7,000 and 136,000 ± 14,000 years and represent a time when the Waihu ice cap was close to its maximum extent and volume. A somewhat younger date of 113,000 ± 15,000 years was obtained for a volcanic bomb ejected during the final eruptive activity of Puu Waiau; because the sample was quite vesicular, Ar loss subsequent to crystallization may have resulted in an erroneously young age. Early Makanaka drift postdates a lava flow of the Hanaipoe Formation that is 85,000 ± 13,000 years old, whereas a

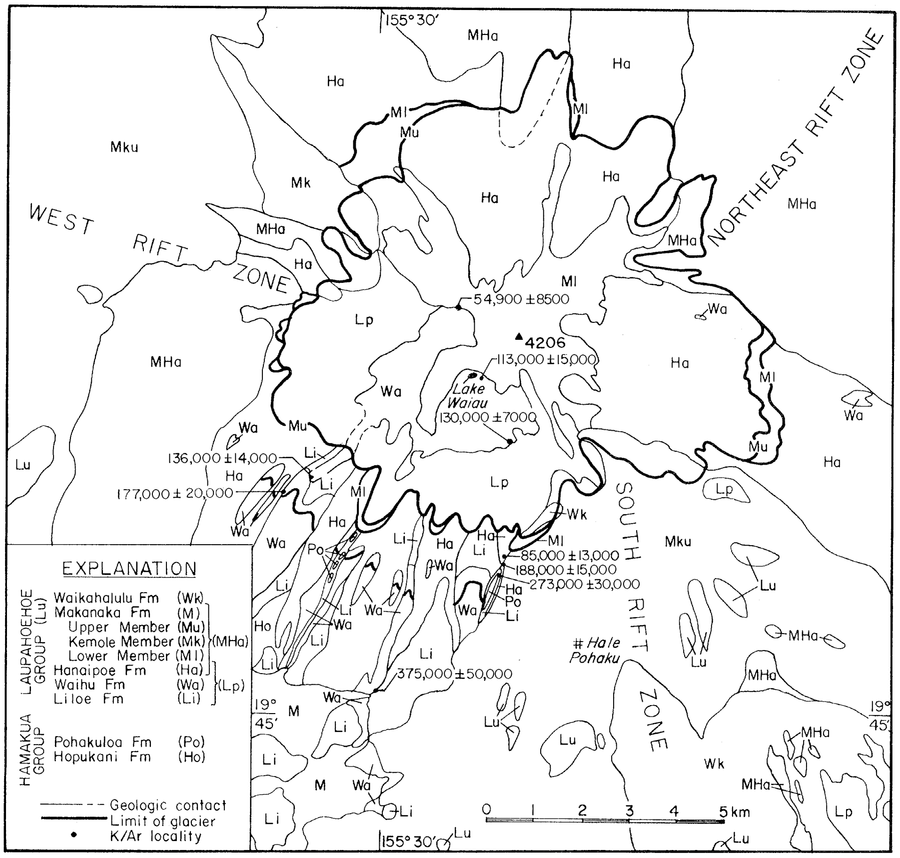

Fig. 1. Geologic map of the upper slopes of Mauna Kea showing the location of K/Ar sample localities.

Rock-stratigraphic units			K/Ar years B.P.	^{14}C years B.P.
LAUPAHOEHOE GROUP	WAIKAHALULU FORMATION			•4500† •9080±200
	MAKANAKA FORMATION	UPPER MEMBER		
		KEMOLE MEMBER		
		LOWER MEMBER	•54,900±8,500	•22,150±250 •29,700±500 •37,200±1,400
	HANAIPOE FORMATION		•85,000±13,000	
	WAIHU FORMATION		•113,000±15,000 •130,000±7,000 •136,000±14,000	
	LILOE FORMATION		•(177,000±20,000)* •(188,000±15,000)*	
HAMAKUA GROUP	POHAKULOA FORMATION			
	HOPUKANI FORMATION		•270,000±35,000 •273,000±30,000 •375,000±50,000	

*Anomalous dates constituting minimum ages for samples
† Average of 7 dates

Fig. 2. Rock-stratigraphic units and associated radiometric dates; B.P., before the present.

flow that erupted from a vent beneath the early Makanaka ice cap toward the end of that glaciation has an age of 54,900 ± 8,500 years.

Ages for units in the upper part of the stratigraphic section are provided by radiocarbon dates of organic matter related to tephra layers and to glacial drift (Fig. 2) (*7*). Two bodies of dune sand on the lower west rift zone are separated by three tephra layers of Kemole age, and the younger sand has a post-Makanaka soil profile developed on it. The dune sands probably were derived largely by deflation of active outwash surfaces in the adjacent Mauna Kea–Mauna Loa saddle during the early and late Makanaka glaciations. Charcoal and wood found between and below the tephra layers range in age from 29,700 ± 500 to 37,200 ± 1,400 years and provide both a lower limiting age for the Upper Member and an upper limiting age for the Lower Member. An isolated tephra layer farther down the rift zone overlies charcoal 22,150 ± 250 years old and is mantled by loess of probable late Makanaka age. This tephra may record the youngest intra-Makanaka eruption and provide a closer limit on the maximum age of the Upper Member.

The late Makanaka ice cap had disappeared from the summit by 9080 ± 200 years ago, the age of basal algal mud in Lake Waiau (3968 m). An additional 8 m of undated sediment underlies the sampled horizon (*7*); thus deglaciation of the lake basin may have occurred as much as several thousand years earlier.

The latest eruptions of Mauna Kea resulted in the deposition of widespread tephra layers and lavas on the lower south rift zone. Seven radiocarbon dates of charcoal obtained from soil buried by lava and cinders indicate that the eruptions occurred close to 4500 years ago.

The areal extent and thickness of the late Makanaka ice cap has been determined from ice limit data, and the topographic configuration of the ice cap has been reconstructed (*1*). This information was then used to derive the equilibrium-line altitude (ELA) of the ice cap. Similar reconstructions, although based on less reliable data, permit assessment of ELA's for the earlier ice caps. The ELA's, after correction for isostatic subsidence of the volcano, can be plotted as a function of time to illustrate long-term climatic fluctuations for Hawaii (Fig. 3). The resulting curve may then be compared with a record of oxygen isotopic variations of planktonic foraminifera in the equatorial Pacific spanning the Brunhes polarity epoch (*8*), the last half of which covers the interval of the recognized Hawaiian glaciations. The isotopic time series reflects both temperature and the intergrated fluctuations of global ice volume, with even-numbered stages representing times of maximum ice volume (glaciations) and odd-numbered stages intervals when the ice volume was similar to that of today (interglaciations). The chronology of the isotope curve is not firmly established, for ages are inferred largely by interpolation between the top of the core and the Brunhes/Matuyama boundary (about 0.7 million years). With the exception of stage 2, the inferred ages of earlier cold stages (stages 4, 6, and 8) may be in error and are subject to different interpretations (*9*). Two of the possible time scales (*D* and *E*) differ in the vicinity of stage 5 by nearly 20 percent.

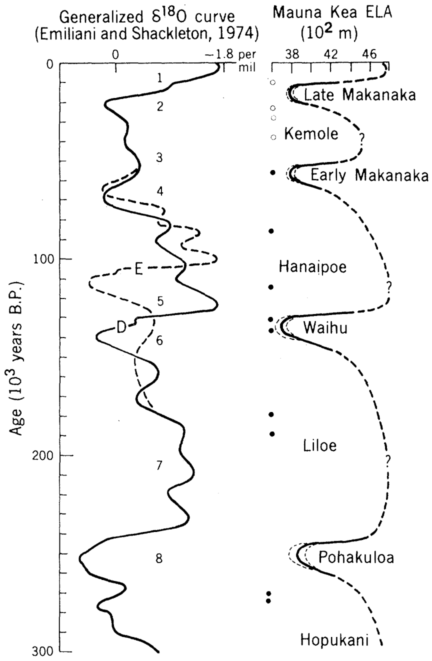

Fig. 3. Curve of snow-line fluctuations on Mauna Kea compared with a generalized curve of marine oxygen isotope variations. The long (*D*) and short (*E*) chronologies for isotope stages 5 and 6 are derived from Emiliani and Shackleton (*9*). Open circles indicate ^{14}C dates; closed circles are K/Ar dates.

A close similarity is seen between the isotopically dated Hawaiian glacial record and the major peaks of the marine isotope curve (Fig. 3). The late Makanaka glaciation correlates broadly with stage 2, whereas the early Makanaka glaciation, which is less than 85,000 years old and probably is close to 55,000 years old, apparently correlates with stage 4. The ages of the two subglacially erupted Waihu lavas (130,000 and 136,000 years ago) suggest that the Waihu glaciation correlates with isotope stage 6. These dates are in agreement with marine isotope chronology *D* of Fig. 3 and also are compatible with numerous radiometric dates for raised coral reefs in the tropical Pacific and Caribbean that indicate an age of 120,000 to 125,000 years for the earliest and warmest peak (5e) of the preceding interglacial stage (*10*). Although the Pohakuloa glaciation is not closely bracketed by K/Ar dates, its inferred age of somewhat less than 270,000 years makes a correlation with isotope stage 8 probable. This stage is the only interval of significant ice volume between 188,000 and 270,000 years, the two available limiting dates for the Pohakuloa glaciation.

The restricted number of radiometric dates and the large standard errors of the K/Ar dates precludes making a close estimate of the length of each glacial episode. However, because an ice cap can form on Mauna Kea only if the snow line is lowered many hundreds of meters below its present level, each successive Hawaiian glacier probably was short-lived and its development most likely coincided with the culmination of a glacial age when continental glaciers achieved their maximum dimensions and ^{18}O concentrations in planktonic foraminifera reached their highest values. Consequently, the dates obtained for the Hawaiian glaciations provide an important independent check on the accuracy of the marine isotope chronology.

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6. The K_2O content of the lavas was between 0.7 and 1.8 percent, and the radiogenic ^{40}Ar content ranged from 0.7 to 7.6 percent of the total ^{40}Ar content. Technical details of measurements will be discussed elsewhere (M. Stuiver, in preparation). Calculations of standard deviations follow the accepted method of A. V. Cox and G. B. Dalrymple [*J. Geophys. Res.* **72**, 2603 (1967)].
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