Glacial Chronology

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Glacial Chronology of Mauna Kea, Hawaii, as Constrained by Surface-exposure Dating

Since S. C. Porter completed his classic stratigraphic study (1979) of the glaciation of Mauna Kea, Hawaii, new surface-exposure dating techniques have been developed to estimate ages of Quaternary glacial events. Our rock varnish, cosmogenic ^{36}Cl buildup, ^{14}C dating of organics in silica skins, and in situ ^{14}C results affirm Porter's glacial sequence. The Makanaka glaciation lasted from ~40 ka to ~13 ka, but glacial retreat begun by ~18 ka was almost complete by ~15 ka. We place the Waihu glaciation during the early Wisconsin (oxygen-isotope stage 4) based on exposure ages of ~60 to 70 ka, and the Pohakuloa glaciation in oxygen-isotope stage 6 based on exposure ages of >132 to 163 ka.

Figure 1.
Pohakuloa till boulder at site 9.
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MAUNA KEA IS THE HIGHEST OF FIVE VOLCANOES that form the island of Hawaii (Figure 2). Its summit reaches 9 to 10 km above its base in the Hawaiian Deep; it is >4200 m above present sea level.[4] Volcanic rocks exposed at the surface of this massive volcano represent events covering the last 200000–250000 years (Figure 1).[34] The youngest flows are Holocene, as determined by ^{14}C ages on buried charcoal.[30,34]

Research on the glaciation of Mauna Kea started with R. A. Daly[8] who proposed that the summit had been glaciated. C. L. Wentworth and W. E. Powers[33] identified four glaciations: pre-Pohakuloa, Pohakuloa, Waihu, and Makanaka. H. T. Stearns[31] reexamined these deposits and concluded that only the Makanaka deposits were till, but that Waihu deposits might have related to subglacial volcanic eruptions.

S. C. Porter's study of Mauna Kea and its glacial history culminated in a series of papers and maps.[23–28] Porter defined four major glacial episodes: Pohakuloa (combining Wentworth and Power's pre-Pohakuloa and Pohakuloa deposits), Waihu, and early and late Makanaka. He initially correlated these with marine oxygen-isotope stages 8, 6, 4, and 2.[26]

New K–Ar and ^{14}C ages[34] have revised the numerical chronology first proposed by Porter. Based on some of the first of these new K–Ar results, Porter and colleagues[29] suggested that the Pohakuloa glaciation occurred during marine oxygen-isotope stage 6, the Waihu glaciation during the early part of stage 4, the late Makanaka glaciation during stage 2, and the early Makanaka glaciation during either the early part of stage 2 or stage 3. Although new mapping[34] has resulted in stratigraphic revisions, it has generally affirmed Porter's glacial sequence. However, E. W. Wolfe and coworkers[34] did not find evidence of a significant interglacial hiatus between the early and late parts of the Makanaka glacial episode. They view the Makanaka glaciation as essentially one episode that included some retreat and readvance of the glaciers. Even with new K–Ar dating, substantial uncertainties remain concerning the numerical ages of Mauna Kea glacial deposits. The focus of this study is to further constrain the chronology of glacial deposits on Mauna Kea using new surface-exposure dating methods.

The glacial chronology of Mauna Kea is significant for theoretical and applied studies and is a topic of physical geographic and geologic interest. Mauna Kea is an important link in reconstructing past glacial climates, and in turn the study of past climates yields valuable insights into the nature of global environmental changes. Mauna Kea is the only high

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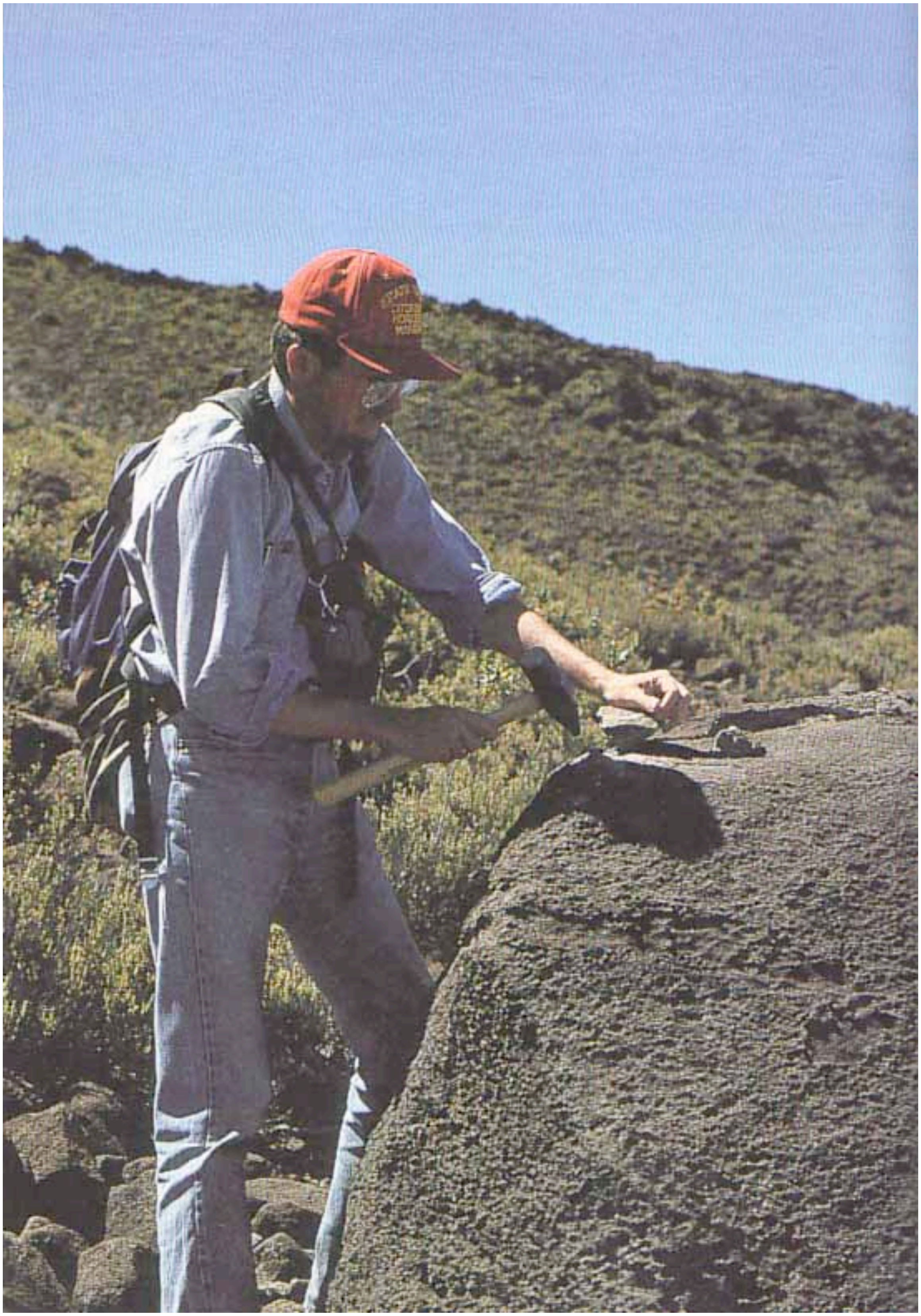

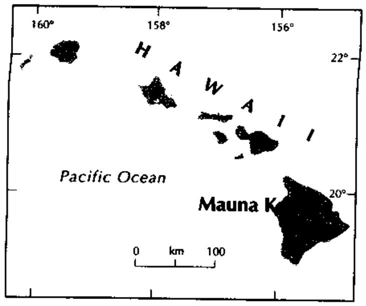

Figure 2.
The study site, Mauna Kea.

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mountain in the central Pacific Ocean basin known to have been glaciated. As such, it provides an important terrestrial control to verify models of global climatic change.

Geologic Setting of Glacial Deposits

Exposed lavas of Mauna Kea form a cap that conceals the underlying tholeiitic basalts erupted during the volcano's shield stage. Recent geologic studies[34] show that the postshield cap consists of basaltic lavas overlain by younger hawaiitic lavas. Basaltic and hawaiitic lavas are not interlayered and are separated by a distinct compositional gap. E. W. Wolfe and colleagues[34] redefined the Hamakua Volcanics to include all of the postshield basaltic lavas and the Laupahoehoe Volcanics to include all of the hawaiitic lavas. They subdivided these formational units into members on the basis of lithologic and stratigraphic relationships (Figure 3).

Tills representing Pohakuloa, Waihu, and Makanaka glacial episodes are intercalated with lavas on the upper flanks of Mauna Kea (Figures 3&4). All three are bouldery diamicts (diamictite and diamicton) composed of clasts of the differing lavas that capped the summit and upper flanks during successive glacial episodes.

The oldest exposed till on Mauna Kea comprises the Pohakuloa Glacial Member of the Hamakua Volcanics. Boulders and cobbles in the till are predominantly porphyritic basalt like the underlying Hopukani Springs Volcanic Member of the Hamakua Volcanics. On the south flank, the Pohakuloa Glacial Member was buried by younger lavas of the Liloe Spring Volcanic Member of the Hamakua Volcanics and is now exposed only in the eroded walls of Pohakuloa and Waikahalulu Gulches. However, weathered till mapped as Pohakuloa glacial deposits that was never buried by younger lavas is exposed along Waipahoehoe Gulch on the volcano's east flank (Figure 1; localities 9&10 on Figure 4)

The second oldest till comprises the Waihu Glacial Member of the Hamakua Volcanics. It is exposed in canyon walls and in discontinuous surface outcrops on the upper southwest flank of Mauna Kea. During the Waihu glacial episode, the volcano was capped by basalt of the Liloe Spring Volcanic Member of the Hamakua Volcanics; this material dominates the boulders and cobbles of Waihu till. In addition, basalt was erupted both during and after the Waihu glacial episode, and flows partly bury the Waihu Glacial Member. In places (e.g., localities 7&8 on Figure 4), Waihu till rests on striated, glacially eroded basalt of the Liloe Spring Volcanic Member. The age of the Waihu Glacial Member is not well constrained by available K–Ar ages (Figure 3), which taken alone indicate an age in the range of 70 to 150 ka (1 ka = 1000 years).

The youngest till comprises the Makanaka Glacial Member of the Hamakua Volcanics. It nearly encircles the summit, and lavas uphill from the till have been extensively eroded by glacial ice. Hawaiitic lavas of the Laupahoehoe Volcanics largely capped the summit during the Makanaka glacial episode; thus, hawaiitic boulders and cobbles predominate in the Makanaka till. In addition, hawaiitic lavas of the Laupahoehoe Volcanics erupted locally both during and after the Makanaka glacial episode.

A topographically distinct morainal crest, within Makanaka till north of the summit, extends 3 km northeastward from the headwaters of Kemole Gulch. Two Laupahoehoe lava flows sampled at localities 11 and 13

Figure 3 (right).
Stratigraphic terminology[34] and chronologic summary of the upper flanks of Mauna Kea.

VOLCANICS	Member	Glacial member	Approximate age, ka based upon only K–Ar and ^{14}C ages (Wolfe et al.[34])	Approximate exposure ages, ka
LAUPAHOEHOE	younger volcanic rocks member		13–4	
LAUPAHOEHOE	older volcanic rocks member	Makanaka Glacial Member	40–13	40–13
LAUPAHOEHOE	older volcanic rocks member		65–14 (possibly as old as 100)	
HAMAKUA	Liloe Spring Volcanic member	Waihu Glacial Member	within interval from 150 to 70	60–70
HAMAKUA	Liloe Spring Volcanic member		within interval from 150 to 70	
HAMAKUA		Pohakuloa Glacial Member	within interval between 200–150 and 150–100	>135–163
HAMAKUA	Hopukani Springs Volcanic Member		within interval from 200 to 150	

Figure 4 (below).
Generalized geologic map of the summit and upper flanks of Mauna Kea.
MODIFIED FROM WOLFE ET AL.[34]

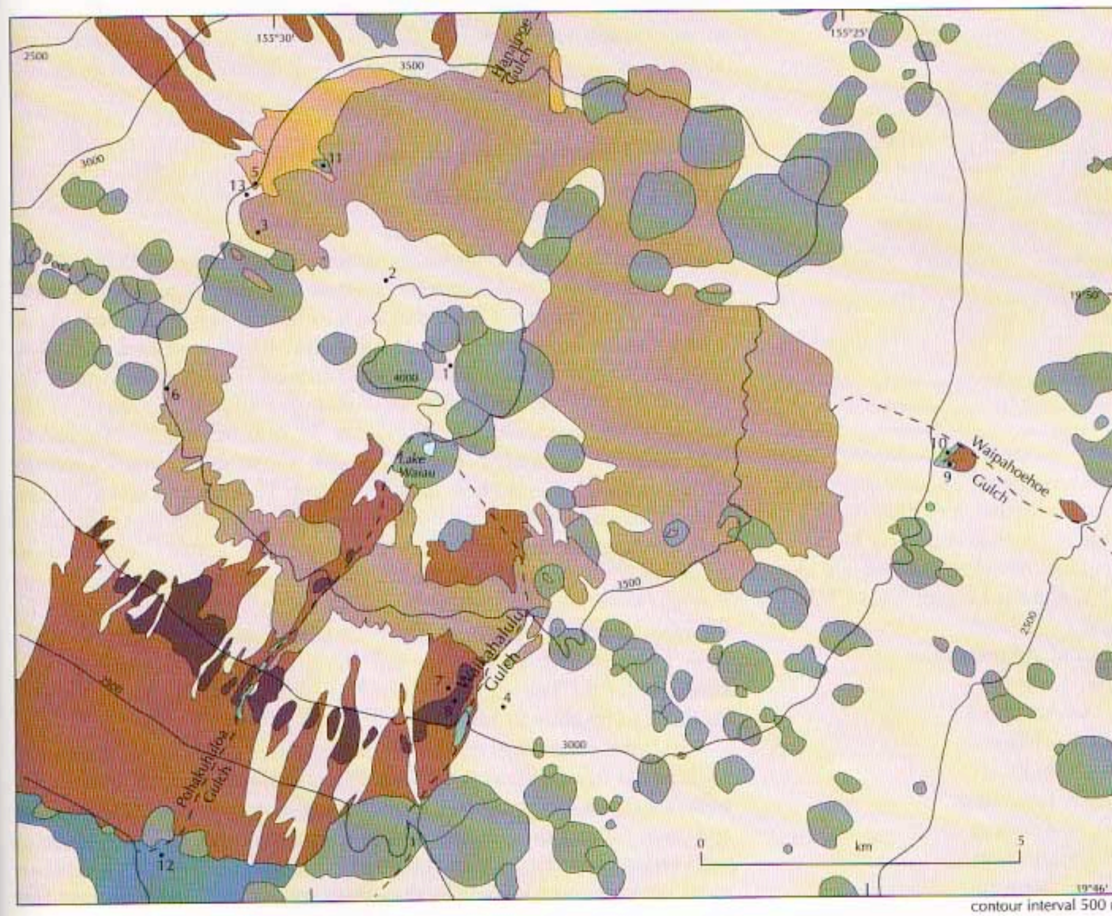
Alluvial Deposits
- Silt, sand, and gravel

Laupahoehoe Volcanics
- Lava flows, undivided
- Cinder cone

Makanaka Glacial Member
- Till
- Older till of north flank

Hamakua Volcanics
- Lava flows and cinder cones, undivided
- Till

Pohakuloa Glacial Member
- Till; mapunit locally includes underlying basalt



contour interval 500 m

Surface-exposure dating is in its infancy, and few people are aware of the method or its potential.

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extend from beneath this inner moraine and overlie till of the outer moraine downslope from it (Figures 5&7). Thus, these flows separate older and younger tills. In addition, a prominent pair of parallel lateral moraines occurs ~0.5 km east of Hanaipoe Gulch. Porter[25] concluded that these two till units represented separate glacial episodes, which he referred to the older and younger drifts of his Makanaka Formation. Distinguishing tills on the basis of weathering and morphologic characteristics, Porter identified and mapped discontinuous outcrops of older (outer) till at many localities at the perimeter of the younger till. However, Wolfe and coworkers[34] found that differences between the two Makanaka till units were so subtle that they distinguished the units only on the north flank, where the tills have distinct morphologic expressions, and intercalation with the two lava flows is unmistakable.

K–Ar dating suggests that the Makanaka glaciation was under way by ~40 ka, and the more easterly of the lava flows (intertill flow 1 on Figure 5) separating deposits of Makanaka till has a K–Ar age of 33 ± 12 ka.[34] Radiocarbon dating of organic material from cores of sediment that accumulated on the floor of Lake Waiau, a small crater lake near the summit of Mauna Kea (Figure 4), indicates that lake deposits began accumulating in the crater between 13 and 14 ka (John W. King, conversation, 19 September 1990). Makanaka glaciation must have terminated at Lake Waiau before this time. Glacial meltwater of the Makanaka glaciation incised Pohakuloa Gulch, and site 12 (Figure 4) is on the surface of the alluvial fan at the base of Pohakuloa Gulch that is derived from this glacially-related sediment release.

Surface-exposure Dating Methods and Their Limitations

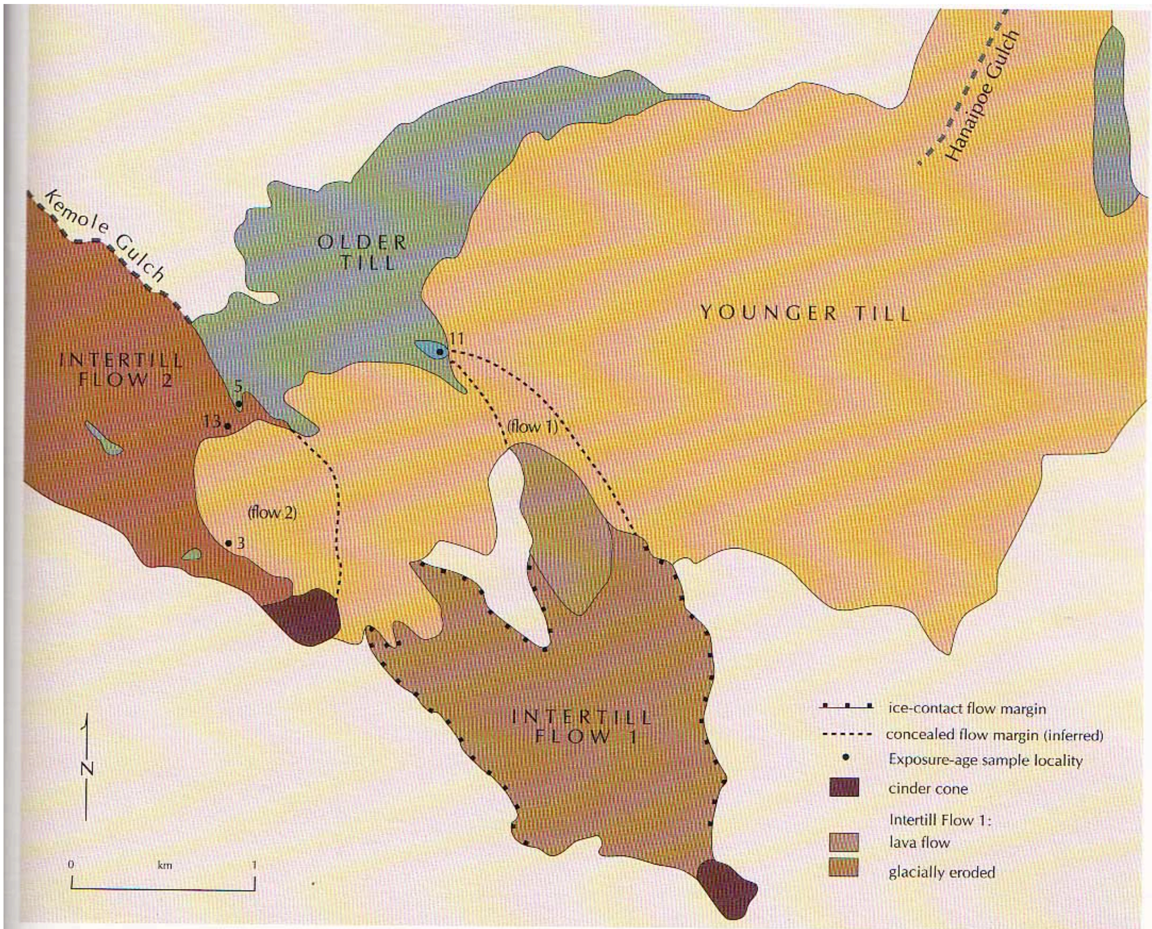
The conventional approach for estimating numerical ages of till is to use stratigraphic deposits that can be dated to infer ages of associated glacial deposits. For example, a K–Ar date on lava flow buried by or overlying till constrains the age of the till. On Mauna Kea, errors associated with K–Ar dates for basalts of the Hamakua Volcanics do not tightly constrain the ages of the intercalated Waihu or Pohakuloa Glacial Members, or the retreat of the Makanaka glacier (Figure 3). Our approach is to directly date glacial retreat and till deposition with a new set of surface-exposure dating methods, divided here into cosmogenic isotopes and rock coatings.

As ^{40}K decays it produces ^{40}Ar. Because newly solidified igneous rock contains very little Ar, the age of igneous rock may be calculated based on the half-life of ^{40}K and the ratio of ^{40}K to ^{40}Ar.

List of abbreviations:
Ar = argon
C = carbon
Cl = chlorine
He = helium
K = potassium
Ti = titanium
Th = thorium
U = uranium

Cosmogenic isotopes build up in minerals of exposed rocks as cosmic rays interact with atoms in rocks.[18] After altitude, latitude, and exposure geometry are accounted for, the buildup of these isotopes reflects exposure age.[35] We discuss three cosmogenic isotopes that are best suited for the mafic lithology of Mauna Kea: ^{36}Cl is appropriate for the time range from 1 ka to ~1000 ka.;[21,22,35] in situ ^{14}C is valuable for measuring exposure ages for the past ~20 ka;[9,15] and ^{3}He builds up in the mineral olivine for <1 ka to possibly >1 Ma.[5,17]

Two types of coatings on the exposed surfaces of rocks on Mauna Kea provide age information. Rock varnish is a dark accretion of mostly clay minerals that is cemented to the underlying rock by oxides of manganese and iron. Silica skin is composed of mostly amorphous silica–alumina with varying amounts of iron and other minor elements.[7,32] Silica skins are more common on Mauna Kea than rock varnish, but both coatings trap



enough organic matter for radiocarbon dating by accelerator mass spectrometry. The method used to extract organic matter from the basal layer of rock varnish has been elaborated elsewhere.[13] Organic matter that looked like root hairs under 30 to 45× magnification was picked out with fine tweezers from under a 1.5-mm-thick silica skin at site 2. After treatment with HCl, the accelerator radiocarbon age was measured at 16 045 ± 130 BP (Lab No. ETH 4811).

The rock varnish that coats glacial polish and till on Mauna Kea also yields an age signal from the cation ratio of $(K^{+}+Ca^{2+})/Ti^{4+}$. Over time, capillary water leaches more mobile elements (K and Ca), leaving behind the more immobile titanium. The lowering of this cation ratio over time has been duplicated by laboratories in the United States, Canada, South Africa, Soviet Union, and China (see discussions in Dorn,[10,12] Dorn and others[12]).

Figure 5.
Map relations among older and younger tills of the Makanaka Glacial Member of the Laupahoehoe Volcanics and intertill lava flows, upper north flank of Mauna Kea.
MODIFIED FROM WOLFE ET AL.[34]

KEY ASSUMPTIONS AND LIMITATIONS FOR MAUNA KEA

EROSION. To provide an accurate surface-exposure age for a glacial event, surface erosion must be limited. This factor also constrains more conventional surface-exposure dating methods, such as soil development and other post-depositional modifications.[e.g.,2]

Figure 6.
Glacially eroded rocks at site 1; samples collected just to the left of the silver observatory.
RONALD I. DORN

There are over 30 K–Ar dates, many of which contradict each other and are thrown out for various reasons.... It would be unfair to just present the K–Ar dates in a table without the 30-or-so pages of interpretation.[35] *It is best to present the generalized interpretation of the K–Ar dates in Figure 3.*

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Most subject to this problem are rock coatings that are removed by spalling of the underlying rock. Even the slightest bit of erosion will remove rock coatings, resetting the varnish and silica skin "clocks." Cosmogenic isotopes, on the other hand, are much more resilient to millimeter- and centimeter-scale spalling because the half-length of cosmic ray penetration is ~30 to 35 cm into Mauna Kea rocks. However, a similar complication exists if a now exposed boulder was once buried. The varnish "clock" would only record when the boulder surface was first exposed to the atmosphere, but cosmogenic isotopes would start to build up as the rock surface "approached" the surface by progressive erosion of the overlying material. Because of the possibility of complications discussed above, we prefer to analyze multiple boulders for cosmogenic nuclides from each deposit dated. That was not practical in this study, but comparisons between the rock varnish and cosmogenic nuclide methods do provide a check for consistency.

There is also an inherent lag with radiocarbon-dating organics associated with rock coatings. Because most of the organic detritus sampled has been observed to be at the coating/rock interface, the time lag is probably caused by the delay between rock exposure and the time-transgressive onset of varnishing. For example, using ^{14}C-dated charcoal under lava flows,[30] Dorn and coworkers[13] determined that the charcoal ages are ~10% older than the varnish–radiocarbon ages from the same semiarid sites on Hawaii. With these concerns, a conservative interpretation would be to treat surface-exposure dating results as minimum-limiting ages for a glacial event.

With care, however, it is possible for surface-exposure dating methods to yield accurate ages for the timing of glacial events at some sites. Glacial polish at sites 1, 2, and 7 (Figure 4), for example, meet the conditions of no surface erosion. For other sites, samples were collected from the largest (>1 m in diameter) and freshest looking boulders. In particular, we looked for unweathered, rounded, glacially smoothed surfaces that had not experienced obvious spalling.

In order to reduce subjectivity in assessing boulder erosion, we used the development of alternating manganese-rich and manganese-poor layers in rock varnish that are caused by fluctuations in alkalinity.[11,14] If boulder surfaces have spalled and reset the varnish clock, there should be little or no similarity in the sequence of varnish layering. This is the case for varnish on some boulders. Compared with varnishes on other boulders from the same sites, Pohakuloa till boulders with varnish cation ratios >3.15 (sites 9 and 10 in Table 2) and Waihu till boulders with cation ratios >4.68 (site 8A in Table 2) had incomplete sequences of microlaminations. Since boulder weathering is time transgressive, this is the pattern that we would expect for varnishes formed on eroded surfaces. The remainder of the different boulders at each site examined have a consistent development of varnish microlaminations, as would be expected if sampled surfaces were exposed at the same time. The simplest explanation for the same sequence of varnish microlaminations is that the sampled surfaces were exposed by the glacial event, not post-glacial erosion.

BIOCHEMICAL CONDITIONS. Unlike cosmogenic isotopes, rock coatings are influenced by changes in biogeochemical conditions. Variables other than time influence varnish cation ratios. For example, two boulders site 8A had anomalously low cation ratios (3.11, 3.40); lichens ha increased the rate of cation leaching. Another boulder at site 8A had an anomalously high concentration of calcium that resulted in too high a cation ratio (8.62). In addition to these and other variables known to alter cation ratios,[10,12,16] new influences are likely to be discovered. For this reason we consider the cation-ratio ages to be the least certain data presented here.

ISOTOPIC EXPOSURE SIGNAL. Unlike rock coatings, cosmogenic isotopes can retain a prior exposure signal. An assumption of cosmogenic isotope dating is that the sampled rock has not been exposed to cosmic rays before glaciation excavated the till boulder or eroded bedrock. No exposure to cosmic rays is most reasonable for glacial polish and also reasonable for till.[e.g.,22] However, prior exposure cannot be ruled out because we could not assess whether sampled boulders contain inherited ^{36}Cl.

Because rock coatings are eroded by glacial action, they can provide an independent check on this issue. The samples analyzed by different methods were collected from the same boulders (with the exception of site 5). The sequence of sample analysis was first varnish cation ratios, then varnish radiocarbon, silica skin, ^{36}Cl, and lastly in situ ^{14}C. Age signals from rock varnish and silica skin are similar to the cosmogenic isotope ages, so we have increased confidence that there was no prior exposure history.

ORIENTATION. To provide accurate cosmogenic dates, rock surfaces must retain their orientation after glacial retreat, otherwise the buildup rate of cosmogenic isotopes is changed. This condition is easily met for glacial polish on bedrock. It is also the reason we sampled the largest boulders, since they would be the least likely to move. However, a change in orientation from the side of a boulder toward the top would not significantly influence a rock varnish age.[10] For example, at site 5, the samples on large boulders best suited for ^{36}Cl dating were subject to environmental factors known to give a false cation ratio for rock varnish.[cf.10,12,16] The best boulders for varnish dating were those on a slope (~5 to 15°) with diameters <0.5 m. These smaller boulders were also used for in situ ^{14}C analysis. A reasonable explanation for the lower in situ ^{14}C at site 5 would be change in orientation sometime in the post-glacial period, resulting in more shielding.

When a glacial boulder has eroded, it provides only a minimum age. When a glacial boulder has not eroded, it can provide an accurate age.

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Results and Discussion

Table 1 provides age estimates of rock-varnish radiocarbon, ^{36}Cl, and in situ ^{14}C, and Table 2, of varnish cation ratios. Results reported here are consistent with the sequence of glacial events proposed by Porter[23–28] and Wolfe and coworkers.[34] The numerical and calibrated ages, however, are new. There is good agreement among the surface-exposure methods, especially when analytical uncertainties are considered.

The Pohakuloa glaciation probably belongs in oxygen-isotope stage 6, using the marine oxygen-isotope chronology of D. G. Martinson and colleagues.[19] The >132- to 163-ka age estimates are based on varnish cation-ratios at sites 9 and 10 (Table 2). As noted in the methods section, boulders with cation ratios higher than 3.14 have probably experienced some erosion of the very skin of the boulders (e.g. Figure 1). K–Ar dating[34] also constrains the Pohakuloa Glacial Member to part of marine-oxygen isotope stage 6, which is consistent with these cation-ratio ages.

Table 1. **Surface-exposure Ages of Glacial Landforms of Mauna Kea, Hawaii**

		Data Used to Calculate ^{36}Cl Buildup Ages					In situ ^{14}C Buildup Age	
Site No.	Varnish Radiocarbon Age[a]	^{36}Cl Age	atoms ^{36}Cl / atoms 10^{15} Cl	Cl / K_2O / CaO[b]	Thermal neutron capture[b]	ELD Factor[b]	Age	10^6 atoms/g[d]
1	14.4 ± 0.1	14.7 ± 0.5	1110 ± 36	45 ppm 2.12 % 6.22 %	7.35	9.26		
2	16.6 ± 0.2							
3	18.3 ± 0.2	18.9 ± 0.8	708 ± 30	84 ppm 2.04 % 6.72 %	7.53	7.32	8 to 17	1.0 ± 0.1
4	21.7 ± 0.3						>20	1.1 ± 0.1
5	5a:21.5 ± 0.2 5b:37.2 ± 1.2	20.3 ± 2.3	1121 ± 82	49 ppm 1.99 % 6.82 %	7.10	7.01	3 to 4.3	0.41 ± 0.05
6	6b:32.5 ± 0.3							
7							>20	0.88 ± 0.05
8A	>38	63 ± 2.3	2990 ± 110	45 ppm 0.99 % 9.39 %	9.06	5.67	>18	0.83 ± 0.08
12	11.3 ± 0.1							
13	22.9 ± 0.2	20.5 ± 1.8	532 ± 32	124 ppm 1.56 % 6.56 %				

The Waihu glaciation appears to be a stage 4 (early Wisconsin) event (sites 7, 8A on Figure 4). The ^{36}Cl date of ~63 ± 2.3 ka overlaps with the varnish cation-ratio age-estimate of 68 ± 5 ka for the same site (site 8 in Table 1). Both are consistent with varnish radiocarbon (>38 ka) and in situ ^{14}C (>18 ka) measurements.

K–Ar and ^{14}C dating of lava flows and sedimentary deposits, bracketing and intercalated with glacial deposits,[34] constrain the Makanaka glaciation to be from ~40 ka to 13 ka, coincident with marine oxygen-isotope stage 2 and part of stage 3. Our surface-exposure ages verify this conclusion, but also indicate timing for specific Makanaka events.

The age of the younger Makanaka end moraine (Figure 7) on the no flank of Mauna Kea is ~20 to 21 ka at ~3500 m elevation (site 3 in Figure 5 The ice cap had receded on the north side to ~3900 m by ~18.3 ka (site 2 Figure 4), and to ~4054 m (site 1 in Figure 4; Figure 6) by ~15 to 16 ka. Cerling (conversation, 16 October 1990) has obtained a similar ^{3}He surfa exposure age for glacially abraded bedrock at ~3750 m on the south side Mauna Kea, which suggests that the site was deglaciated by ~15 ka.

Boulders on the alluvial fan near the mouth of Pohakuloa Gulch been exposed since 12 to 13 ka (site 12 in Figure 4). While there have been a time lag between the cessation of glaciation and the f transport of glacially prepared material down Pohakuloa Gulch, this sult is in close agreement with the ^{14}C dating of sediment from co collected from Lake Waiau (3968 m), showing that lake deposits be

Table 2. Varnish Cation-ratio Dating at Mauna Kea, Hawaii

Site No.	Varnish Cation-ratio Dating (K+Ca)/Ti[e]	Age
6	Ave. Set 6a:	40 ± 2
	5.21	42
	5.26	41
	5.30	40
	5.40	38
	Ave. Set 6c:	20.5 ± 1
	6.43	21
	6.48	21
	6.49	21
	6.53	20
	6.60	19
7	Average:	63 ± 6
	4.23	72
	4.38	67
	4.40	66
	4.57	60
	4.62	58
	4.65	57
8A	Ave. Top 7:	68 ± 5
	4.19	74
	4.22	73
	4.30	70
	4.36	67
	4.40	66
	4.48	63
	4.57	60
	4.68, 4.77, 4.80[c]	
8B	Average:	22 ± 2
	6.20	24
	6.31	23
	6.32	23
	6.35	22
	6.46	21
	6.55	20
9	Ave. Top 6:	149 ± 8
	2.77	163
	2.88	153
	2.90	151
	3.00	143
	3.00	143
	3.02	142
	3.26, 3.33, 3.42, 3.50[c]	
	3.53, 3.70, 3.82[c]	
	3.92, 3.94[c]	
10	Ave. Top 6:	137 ± 4
	2.99	144
	3.08	137
	3.08	137
	3.10	135
	3.11	135
	3.14	132
	3.20, 3.24, 3.51, 3.52[c]	
	3.90, 4.20, 4.25, 5.05[c]	
11	Average:	22 ± 3
	6.11	25
	6.20	24
	6.29	23
	6.37	22
	6.53	20
	6.59	19

Mauna Kea contains the only clear record of Pleistocene glaciation in the central Pacific Ocean. Dating these glacial deposits would be of importance to Quaternary studies in the region. These age determinations would provide important data in the modeling of global and tropical climatic changes in the Pleistocene.

NGS GRANT PROPOSAL

Key (Tables 1&2)

All ages are in thousands of years BP (ka).

[a] *Reported analytical precision does not reflect the true accuracy. These are minimum-limiting ages on organic matter collected from multiple boulders. Lab numbers are, in order: ETH 4808; ETH 4298; ETH 4295; ETH 4476; TO 1630; ETH 4484; TO 1633; ETH 5262; ETH 5269; and ETH 6576.*

[b] *These data are used for calculating ^{36}Cl buildup ages. Cl, K, and Ca are measured since they are the parent atoms for ^{36}Cl. ELD is a dimensionless elevation, latitude, and altitude correction factor elaborated by Zreda and coworkers.[35] Total thermal neutron capture cross section is reported in cm^2/kg.*

[c] *These varnishes have an incomplete sequence of microlaminations. The scatter of cation ratios for these boulders also indicates that these particular boulder surfaces have eroded, and the assignment of age would be misleading.*

[d] *A more detailed explanation of these in situ ^{14}C measurements can be found in Donahue and coworkers.[9]*

[e] *Each cation ratio is a single measurement by inductively coupled plasma atomic emission spectrometry or wavelength dispersive electron microprobe, collected from individual boulders.[12] Cation-ratio ages are not reported for sites radiocarbon dated, because these dites are used to calivrate the cation ratios.*

SITE NO. 1: *Glacially eroded lava flow, near summit of Mauna Kea. 4054 m.*

SITE NO. 2: *Glacially eroded lava flow, on NW side of summit. 3962 m.*

SITE NO. 3: *End moraine of Younger Makanaka till. 3584 m.*

SITE NO. 4: *Makanaka outwash boulders on eroded lava flow. 3158 m.*

SITE NO. 5: *Older Makanaka till. 3500 m. Varnish radiocarbon samples 5a and 5b were collected from different sets of boulders.*

SITE NO. 6: *Makanaka till, mapped by Porter[23] as older. 3505 m. Samples 6a, 6b, 6c were collected from different sets of boulders.*

SITE NO. 7: *Glacially eroded bedrock between Waihu and Makanaka end moraines, 3169 m.*

SITE NO. 8A: *Waihu end moraine, 3109 m.*

SITE NO. 8B: *Ventifact boulders on Waihu end moraine. Varnishes reflect only time since aeolian abrasion ceased.*

SITE NO. 9: *Pokahuloa till, 2926 m.*

SITE NO. 10: *Pokahuloa till, 2926 m.*

SITE NO. 11: *Lava flow no. 1 (Figure 5) separating older and younger Makanaka tills, eroded by periglacial processes, 3658 m.*

SITE NO. 12: *Alluvial fan at base of Waikahalu Gulch, 2036 m.*

SITE NO. 13: *Lava flow no.2 (Figure 5) between sites 3 and 5, eroded by periglacial processes, 3505 m.*

accumulating between 13 and 14 ka after the lake was free of Makanaka ice (John W. King, conversation, 19 September 1990).

The surface-exposure record of the early part of the Makanaka glaciation is less clear. A varnish-radiocarbon sample on a combination of eight boulders from site 5 (Figure 5) yielded an age for the combined basal layers of 37.2 ± 1.2 ka (Table 1). It is likely that the true exposure age is beyond the limit of the radiocarbon method—contamination with <1% of ^{14}C from upper layers in radiocarbon (no measurable radiocarbon left) varnish would give the sample a finite age. However, seven other boulders collected from the same site yielded a varnish-radiocarbon age of 21.5 ± 0.2 ka, consistent with the ^{36}Cl age of 20.3 ± 1.5 ka (Table 1). A similar phenomenon of clustered cation-ratio and varnish-radiocarbon ages occurs at site 6 (Figure 4) at ~20.5 ka (cation-ratio age), 32.5 ka (^{14}C age), and 40 ka (cation-ratio age). Porter[24] mapped site 6 as older Makanaka drift, but Wolfe and coworkers[34] mapped it as undifferentiated Makanaka till.

We have no fully satisfying explanation for the distribution of surface-exposure ages in localities 5 and 6. The most likely possibilities are that a nearby ice front delivered boulders over an extended interval (~40 to 23 ka at locality 5, and ~40 to 20 ka at locality 6), or that cryoturbation of the till reoriented surface boulders or delivered fresh boulders upward to the surface after their initial deposition. The bimodality of exposure ages (modes at 40 and 23 ka) at locality 5 suggests that retreat and readvance of the ice front may have been involved, but we have not found supporting field evidence. Additional dating of older Makanaka tills near locality 5, but more distant from the younger Makanaka margin, might help resolve this question.

The older till east of Kemole Gulch (Figure 5) clearly predates both of the intertill lava flows. Ages of these lava flows therefore provide younger limits for the age of the older till. Surface-exposure age of flow 1 (locality 11) is ~22 ka and of flow 2 (locality 13) is ~20 to 23 ka. Because some

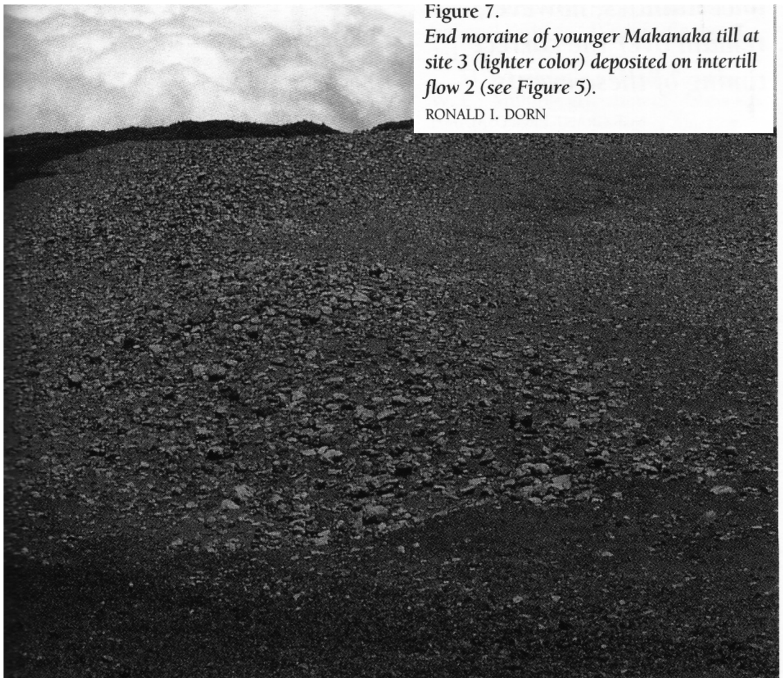

Figure 7.
End moraine of younger Makanaka till at site 3 (lighter color) deposited on intertill flow 2 (see Figure 5).
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degradation of the flow surfaces did occur, probably under periglacial conditions, these exposure ages are younger limits for the actual ages of the lava flows. The K–Ar is 33 ± 12 ka for flow 1,[34] consistent with these data.

Intertill lava flows do not document a hiatus in glaciation. The ice-contact margin on part of the perimeter of flow 1 (Figure 5) indicates that it was erupted within glacial ice, at a time when the ice front had retreated from the maximum position represented by the margin of the older till. After the emplacement of flow 1, ice movement eroded much of the flow surface except for the northern part of its more easterly lobe, including the small lava-flow tip (locality 11) exposed between outcrops of older and younger Makanaka till. No field evidence indicates the presence or absence of glacial ice on Mauna Kea when flow 2 erupted.

The Makanaka glaciation produced substantial aeolian abrasion in proglacial areas. At site 8, for example, several Waihu till boulders show evidence of aeolian abrasion. Rock varnishes that have formed on ventifacted boulders since the aeolian abrasion ceased yield cation-ratio ages ranging from ~20 to 24 ka (site 8B in Table 1).

The rock varnish, silica skin, and to a lesser extent ^{36}Cl and in situ ^{14}C ages for the Makanaka glaciation are all based on radiocarbon years. E. Bard and colleagues[1] used uranium–thorium ages from corals to compare with radiocarbon ages for the past 30 000 years. Their data suggest substantial offsets between ^{14}C and U–Th years. When the U–Th calibration is well established, it may be possible to correct our data.

Conclusions

We used five new dating methods to provide the first surface-exposure ages on the subaerially exposed glacial deposits of Mauna Kea volcano, Hawaii. Cation-ratio dating and accelerator radiocarbon dating of rock varnish, the buildup of in situ cosmogenic ^{36}Cl, the buildup of in situ cosmogenic ^{14}C, and radiocarbon dating of organic matter incorporated in silica skins are used in combination on the same glacial landforms.

Exposure ages of >132 to 162 ka suggest that the earliest recorded glaciation, represented by the Pohakuloa Glacial Member of the Hamakua Volcanics, occurred during marine oxygen-isotope stage 6. The next glaciation probably occurred during marine oxygen-isotope stage 4 as suggested by exposure ages of ~63 to 68 ka for till of the Waihu Glacial Member of the Hamakua Volcanics and for a lava-flow surface striated by the Waihu ice. The third recorded glaciation, which was the most recent and is represented by deposits of the Makanaka Glacial Member of the Laupahoehoe Volcanics, occurred from ~40 to 13 ka, coincident with marine oxygen-isotope stage 2 and part of stage 3. Two topographically and stratigraphically distinct tills are recognized within the Makanaka Glacial Member on the upper north flank of Mauna Kea. Surface-exposure results suggest that the older (outer till) was in place by 23 ka. Boulders near the outer margin of the younger (inner) till give exposure ages of ~20 ka. Nearly all of the ice cap had disappeared by ~15 to 16 ka, although small remnants may have lasted until ~12 to 13 ka.

Mauna Kea provides the only opportunity to study a record of actual glacial deposits in the tropical Pacific Ocean. This research, therefore, is of broad significance in understanding the nature of global climatic change. Several general observations regarding the correlation between the Mauna Kea glacial chronology and other glacial records are of interest.

The Northern Hemisphere tropical latitudes appear to have experienced glaciation that was penecontemporaneous with glacial maxima at higher-latitude locations in the Northern Hemisphere during marine oxygen-isotope stages 6, 4, and 2. For example, the Sierra Nevada experienced glacial maxima at ~145 ka, 65 ka, and 19 to 22 ka,[12,22] at approximately the same time as Mauna Kea. However, Mauna Kea was apparently capped with ice during stage 3. Perhaps preservation of older till was enhanced because subsidence of Hawaii[20] lowered the elevation of the older moraine sufficiently to prevent its having been overriden by the ice that deposited the younger Makanaka till.

A glacial advance in the Sierra Nevada of California at ~115 ka[22] has not yet been found on Mauna Kea. This is consistent with R. S. Cerveny's[6] diurnal radiation model that shows a decrease in July midday insolation at the latitude of the Sierra Nevada (~37°50' N) in oxygen-isotope stage 5d, but not at the latitude of Mauna Kea (~19°50' N).

A "Younger Dryas" cold period ~11 ka[cf.3] did not produce a glacial record on Mauna Kea.

The most recent deglaciation of Mauna Kea started ~18 ka and was almost complete by ~15 to 16 ka, when site 1 near the summit was exposed (Figure 6). Like many other places in the Northern Hemisphere, this preceded the Milankovitch insolation maximum at ~10 ka by >6000 years. However, Cerveny's diurnal radiation model does suggest the onset of deglaciation ~18 to 20 ka at the latitude of Mauna Kea, as we have found.

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