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Cosmogenic ^{36}Cl ages of Quaternary basalt flows in the Mojave Desert, California, USA

Fred M. Phillips*

Department of Earth and Environmental Science, New Mexico Tech, Socorro, NM 87801, USA

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Abstract

Basalt flows provide excellent opportunities for calibration and intercomparison of Quaternary dating methods, remote sensing methods, and rates of geomorphic processes. The immediate motivation for this study was to provide chronology for a blind test of the utility of rock varnish microstratigraphy as an indicator of the age of flow emplacement. Five basaltic eruptive centers in the Mojave Desert of California were sampled for cosmogenic ^{36}Cl analysis. Multiple samples were taken from most centers and, with one exception, produced good agreement. Assuming a surficial erosion rate of 1 mm/kyr^{-1}, the flows yielded the following ages: Amboy Crater, 79 ± 5 ka; Pisgah Crater, 22.5 ± 1.3 ka; Cima field, I-Cone, 27 ± 1.3 ka; Cima field, A-Cone, 21 ± 1.6 ka and 11.5 ± 1.5 ka; Cima field, flow of unidentified origin, 46 ± 2 ka. The ages from the Cima I and A cones are in good agreement with previous cosmogenic ^{3}He dating. Ages from the three previously undated flows are significantly older than previous estimates based on flow appearance. Tanzhou Liu performed varnish microstratigraphic analysis on samples collected from the same sites. His results were submitted for publication without knowledge of the ^{36}Cl ages. His age estimates agree well with the ^{36}Cl ages for the three previously undated flows, strongly supporting the validity of varnish microstratigraphy as a chronological correlation tool.

Keywords: Mojave Desert; Cl-36; Volcanic rocks; Basalts; Geochronology; Exposure age; Quaternary

1. Introduction

A number of relatively fresh, youthful-appearing basaltic cones and flows in the Mojave Desert have attracted geological attention since the time of the earliest investigators (Darton et al., 1916). In this study, ^{36}Cl surface-exposure dating has been used to obtain ages on two previously dated flows, those from the “A” and “I” cones in the Cima volcanic field, and on three flows not previously quantitatively dated: Amboy Crater, Pisgah Crater, and an unnamed flow in the Cima field (Fig. 1).

There were several motivations for dating these flows. The primary one was as a test of the rock varnish microstratigraphy method for surface dating and paleoenvironmental reconstruction (Liu, 1994; Liu et al., 2000). Rock varnish from arid regions is typically deposited as alternating dark, manganese-rich layers and reddish, iron-rich layers. The manganese-rich layers are thought to be deposited during intervals of relatively humid climate and the iron-rich ones during more arid intervals. If the varnish chem-

* Tel.: +1-505-835-5540; fax: +1-505-835-6436.
E-mail address: phillips@nmt.edu (F.M. Phillips).

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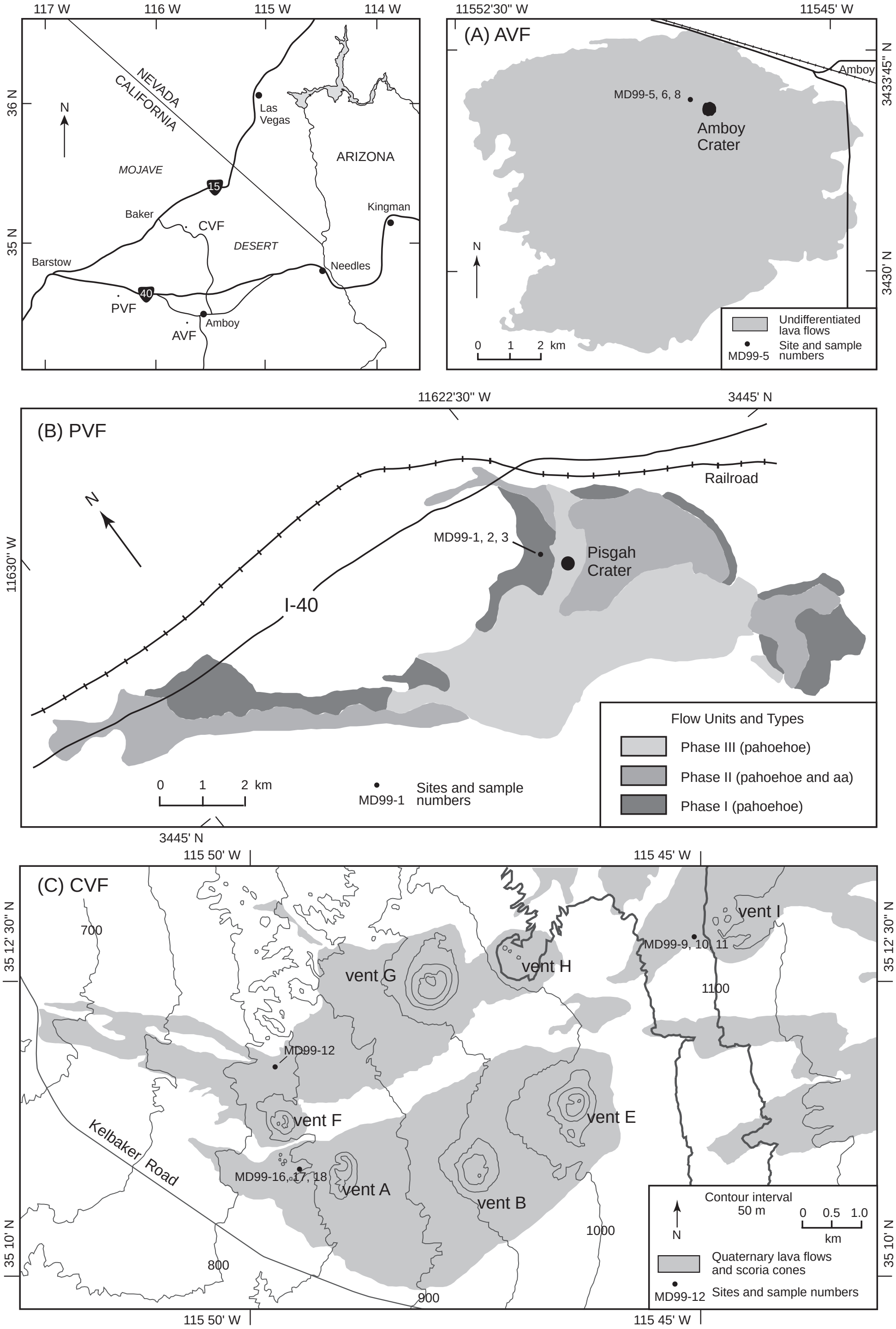

Fig. 1. Location maps of ^{36}Cl samples from late Quaternary lava flows in the Mojave Desert of California, western United States. (A) Amboy volcanic field; (B) Pisgah volcanic field; (C) southern portion of the Cima volcanic field. Geologic map of flows in B by Wise (1966), presented in Greely et al. (1988). Figure modified from Liu (2003-this issue).

istry varies in a regionally coherent fashion and relatively complete microstratigraphic sections are common, then the sequence of layering can potentially provide a record of regional paleoenvironmental conditions (Liu et al., 2000; Broecker and Liu, 2001). The "age" (by correlation) of the basal varnish layer should then yield an estimate of the timing of initial exposure of the rock surface.

In order to provide a rigorous test of the varnish microstratigraphy technique, Tanzhou Liu (Lamont-Doherty Earth Observatory, Columbia University, New York) and I sampled the same outcrops on the basalt flows at the same time. The samples were processed completely independent and have been submitted for publication without knowledge of the other's results. The varnish microstratigraphy results can be found in Liu (2003-this issue).

A second motivation for the study was the intercomparison of Quaternary dating methods. The "A" and "I" cones at the Cima volcanic field have previously been chronologically studied using K–Ar, $^{40}Ar/^{39}Ar$, ^{3}He, and thermoluminescence. The ^{36}Cl results for the flows from this study provide a valuable intercomparison. The ^{36}Cl ages for the Pisgah and Amboy flows will provide opportunity for additional future intercomparisons.

Finally, these Mojave Desert flows have been extensively used for a variety of applied studies. They have been important "calibration" sites for interpretation of remote sensing data (Farr, 1992; Arvidson et al., 1993; Guinness et al., 1997; Greely et al., 1988). Their geochemistry has yielded important information on evolution of basic magma bodies (Smith and Carmichael, 1969; Reid and Ramos, 1994; Farmer et al., 1995). The study of post-eruptive modifications of the flow surfaces have played an important role in the development of theories for geomorphic processes in arid environments (Dohrenwend et al., 1984; McFadden et al., 1987; Wells et al., 1995). All of these, but especially the last, stand to benefit by improved chronology for the flows.

2. Methods

Samples were collected from the flow surfaces using hammer and chisel. Care was taken during sample collection to locate sample sites with minimal surface erosion and where the likelihood of cover by scoria or sand was small, inasmuch as removal or addition of material can affect cosmogenic nuclide ages of surfaces (Gosse and Phillips, 2001). All samples were taken from pahoehoe lava flows, with the exception of those from the Cima "A" cone, which was an aa flow. The presence of glassy, frothy, flow-top pahoehoe basalt was used as a primary criterion for minimal erosion on all flows except the "A" cone. Sample thickness and estimated bulk density (affected by vesicularity) were noted for all samples, although Gosse and Phillips (2001) have shown that error in estimating sample thickness or vesicularity have only a small influence on calculated cosmogenic in situ nuclide ages. Sample locations were determined by global positioning system.

The samples were prepared by digestion in mixed HF and HNO_3. A spike of isotopically enriched ^{35}Cl was added during the digestion so that the Cl content of the samples could be determined during the accelerator mass spectrometry (AMS) analysis by means of the isotope dilution mass spectrometry method. The sample preparation methodology is described in Ayarbe (2000). The $^{36}Cl/Cl$ ratio was measured by AMS at PRIME Laboratory (Purdue University) (Elmore et al., 1979). Major oxides and U and Th were measured by X-ray fluorescence at New Mexico Tech (Bureau of Geology) and B and Gd by prompt gamma emission spectrometry.

The ^{36}Cl age calculations were performed using the data-reduction program CHLOE (Phillips and Plummer, 1996). Elevation-latitude scaling was according to Lal (1991). The recently revised production formulation and production rates of Phillips et al. (2001) were employed. This formulation explicitly accounts for muon production. Other aspects of the production calculations were as described in Gosse and Phillips (2001). Calculated ages and sample location data are given in Table 1 and the ^{36}Cl ages for the various volcanoes are compared in Fig. 2. Chemical data are given in Table 2. Apparent cosmogenic ages are affected by erosion, therefore ages in Table 1 are given for three hypothesized erosion rates: zero, 1, and 5 mm/kyr. Based on field observations, the fact that the samples were carefully selected for sites with minimal erosion, and general observations of bare-rock erosion rates in arid environments, the ages calculated based on the assumed 1 mm/kyr erosion

Table 1
^{36}Cl ages and sample data for Mojave Desert basalt flows

Sample no.	Flow	Zero erosion age (ka)	1 mm/kyr age (ka)	5 mm/kyr age (ka)	Longitude (°N)	Latitude (°W)	Elevation (m)	S_T[a]	$\Lambda_{f,e}$[b] (g/cm^2)
MD99-1PC	Pisgah	24.2 ± 2.7	23.3 ± 2.5	21.3 ± 2.2	34.7558	116.3769	685	0.998	166
MD99-2PC	Pisgah	23.0 ± 2.7	23.1 ± 2.5	21.1 ± 2.1	34.7558	116.3769	685	0.998	166
MD99-3PC	Pisgah	21.0 ± 2.1	21.0 ± 1.9	18.9 ± 1.6	34.7558	116.3769	685	0.970	166
MD99-5AC	Amboy	89.2 ± 3.9	78.0 ± 3.1	72.0 ± 3.3	34.5469	115.7964	235	0.997	165
MD99-6AC	Amboy	96.9 ± 5.3	84.8 ± 4.2	80.0 ± 4.7	34.5469	115.7964	235	0.994	162
MD99-8AC	Amboy	84.6 ± 4.5	75.4 ± 3.6	67.2 ± 3.4	34.5469	115.7964	235	1.000	169
MD99-9CV	Cima "I"	29.1 ± 2.8	27.2 ± 2.4	23.9 ± 2.1	35.2167	115.7514	1100	0.999	170
MD99-10CV	Cima "I"	30.5 ± 3.1	28.4 ± 7.0	24.9 ± 5.7	35.2167	115.7514	1100	0.995	169
MD99-11CV	Cima "I"	26.0 ± 1.5	25.8 ± 1.4	23.2 ± 1.1	35.2167	115.7514	1100	0.999	168
MD99-12CV	Cima	52.6 ± 2.5	45.6 ± 1.9	38.8 ± 1.6	35.1950	115.8275	830	0.997	170
MD99-15CV	Cima "A"	22.7 ± 1.8	21.3 ± 1.6	18.9 ± 1.3	35.1819	115.8225	860	0.984	157
MD99-16CV	Cima "A"	11.7 ± 1.1	11.5 ± 1.1	10.8 ± 1.0	35.1819	115.8225	860	0.997	170
MD99-17CV	Cima "A"	12.0 ± 1.7	11.6 ± 1.6	10.6 ± 1.3	35.1819	115.8225	860	0.997	170

[a] S_T is the topographic shielding factor.
[b] $\Lambda_{f,e}$ is the effective attenuation length for fast neutrons.

rate are preferred. Reported ^{36}Cl age uncertainties reflect only ^{36}Cl analytical uncertainty and are given as ± 1 standard deviation. Empirical evidence indicates that a more complete evaluation of age uncertainty, including factors such as error in chemical analyses and uncertainty in production parameters, yields total age uncertainties in the range of 10% to 15% (Phillips et al., 1996).

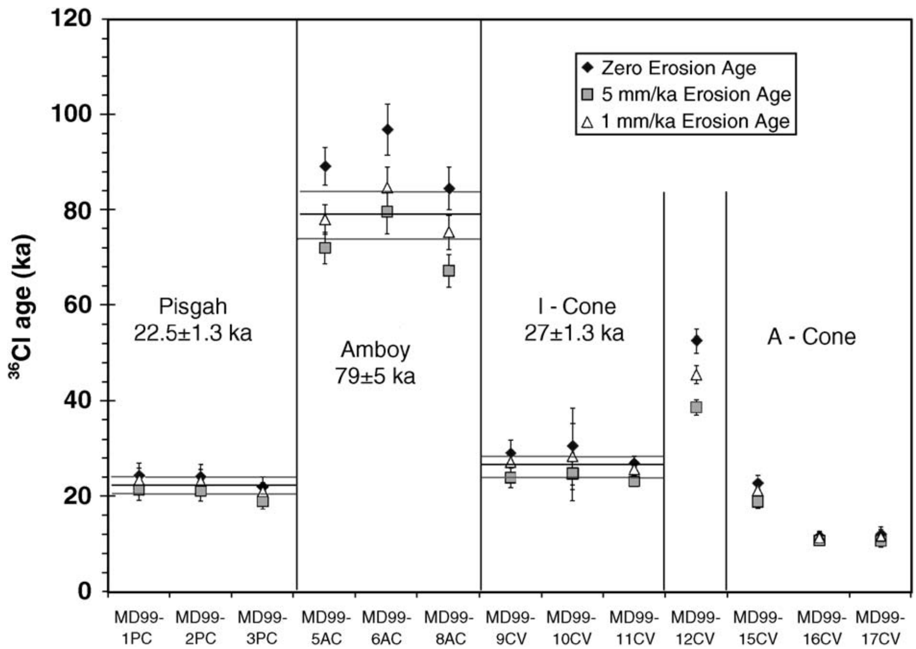

Fig. 2. Summary of cosmogenic ^{36}Cl ages for samples from the Amboy, Pisgah, and Cima volcanic fields. Listed ages are means and single standard deviations of 1 mm/kyr ages for each field. A mean was not calculated for the Cima "A" cone samples because of discrepant results.

Table 2
Chlorine-36 ratio and chemical data for Mojave Desert basalt samples

Sample no.	Flow	$^{36}Cl/(10^{15}Cl)$	Cl (ppm)	Na_2O (wt.%)	MgO (wt.%)	Al_2O_3 (wt.%)	SiO_2 (wt.%)	P_2O_5 (wt.%)	K_2O (wt.%)	CaO (wt.%)	TiO_2 (wt.%)	MnO (wt.%)	Fe_2O_3 (wt.%)	B (ppm)	Gd (ppm)	U (ppm)	Th (ppm)
MD99-1PC	Pisgah	115 ± 11	316	3.63	8.52	15.94	47.05	0.58	1.77	8.89	2.51	0.17	11.45	5	5	2	8
MD99-2PC	Pisgah	116 ± 11	315	3.64	8.50	15.88	46.99	0.56	1.76	8.96	2.51	0.17	11.40	< 5	4	2	8
MD99-3PC	Pisgah	102 ± 8	336	3.58	8.76	15.76	47.15	0.60	1.80	8.89	2.50	0.18	11.60	< 5	4	2	7
MD99-5AC	Amboy	290 ± 11	221	3.76	5.53	16.01	49.81	0.54	1.60	8.99	2.46	0.17	11.63	6	6	2	6
MD99-6AC	Amboy	338 ± 16	194	3.85	5.32	16.26	49.94	0.44	1.57	9.01	2.39	0.17	11.12	6	4	2	5
MD99-8AC	Amboy	283 ± 13	218	3.73	5.57	16.12	50.11	0.54	1.61	9.04	2.42	0.17	11.62	6	5	2	6
MD99-9CV	Cima "I"	175 ± 15	337	4.00	6.85	16.48	48.32	0.61	1.88	7.93	2.65	0.17	10.75	5	4	2	7
MD99-10CV	Cima "I"	171 ± 40	381	4.22	6.77	16.55	49.17	0.63	2.01	8.05	2.68	0.17	10.72	6	5	2	6
MD99-11CV	Cima "I"	163 ± 8	317	3.86	7.30	16.41	48.30	0.57	1.76	7.93	2.67	0.17	11.11	< 5	4	2	7
MD99-12CV	Cima	238 ± 10	388	3.74	7.79	15.95	47.50	0.61	1.74	8.59	2.75	0.17	11.21	< 5	5	1	6
MD99-15CV	Cima "A"	105 ± 7	440	4.06	6.78	16.29	48.10	0.55	1.91	8.05	2.81	0.17	11.54	7	5	2	7
MD99-16CV	Cima "A"	75 ± 6	237	3.92	7.12	16.17	48.61	0.46	1.61	8.05	2.76	0.17	11.62	6	5	2	6
MD99-17CV	Cima "A"	72 ± 8	351	4.10	6.63	16.41	47.96	0.45	1.91	7.72	2.79	0.17	11.51	< 5	3	2	6

3. Results

3.1. Amboy Crater

Amboy Crater (Fig. 1) is a basaltic scoria ring that erupted in the bottom of the Bristol Dry Lake basin. The flows from the cone separated what had been a single lake basin into two basins: Bristol Dry Lake and Alkali Dry Lake (Rosen, 2000). Flows from the vent area consist largely of pahoehoe and cover ~ 60 km^2. The crater and associated flows have been described by Parker (1963), Wise (1966), Greely and Iversen (1978) and Greely (1990). Prior age constraints have been weak. Darton et al. (1916) thought the eruption was < 1000 years ago based on surficial characteristics. Parker (1963) estimated an age of < 6000 years based on relation with the Bristol Dry Lake deposits, and Kilbourne and Anderson (1981) estimated < 2000 years from its "fresh appearance." (See Table 3 for a comparison of age estimates by all methods for this flow and for the other basalt flows sampled).

In fact, the surficial characteristics of the pahoehoe flows would seem to indicate a pre-Holocene age. Virtually all of the frothy, glassy, flow-top basalt has been stripped off. Over a large proportion of the flows, several of the thin layers that constitute the next deeper portion of pahoehoe flows have also been removed; and in a few places, the dense flow interior (lacking pahoehoe characteristics) has been exposed. Most depressions in the flows are filled with eolian material. The degree of surface degradation is markedly the greatest of the flows sampled for this study and is much more similar to that observed at the Lathrop Wells volcano than to clearly Holocene basaltic eruptions such as the McCartys (Laughlin et al., 1993) or Carrizozo (Dunbar, 1999) flows in New Mexico.

The flow was sampled northwest of the crater in the "undifferentiated flow" unit of Greely and Iversen (1978) on three different push-up ridges within a 100-m radius. These sites still retained small remnants of the glassy flow top. The three samples yielded ^{36}Cl ages in good agreement, giving a mean age (assuming 1 mm/kyr surface erosion) of 79 ± 5 ka (Fig. 2). This age appears to be reasonable, given the similarity of the surficial modification at Amboy and at the Lathrop Wells volcano, which has a well-established $^{40}Ar/^{39}Ar$ age of 77 ± 5 ka (Heizler et al., 1999). A total of 14

Table 3
Comparison of age estimates for Mojave Desert basalt flows

Flow	^{36}Cl (this study)	Varnish microstratigraphy Liu (2003-this issue)	^{3}He	$^{40}Ar/^{39}Ar$	K–Ar	Geomorphic comparison and other methods
Pisgah	22.5 ± 1.3	30–24				< 2 (Kilbourne and Anderson, 1981)
Amboy	79 ± 5	85–74				< 1 (Darton et al., 1916), < 6 (Parker, 1963), < 2 (Kilbourne and Anderson, 1981)
Cima "I"	27 ± 3	39	37 ± 6, 31 ± 7 (Wells et al., 1995)		140 ± 20 (Dohrenwend et al., 1984), 110 ± 5, (Turrin and Champion, 1991)	
Cima "uk"	46 ± 2	60–46				
Cima "A"	21 ± 6, 11.5 ± 1.5	24–16.5	19 ± 11, 13 ± 3 (Wells et al., 1995)	119 ± 14 (Turrin and Champion, 1991)	~ 300 (Turrin, 1989[a])	29–16 [paleomagnetism] (Champion, 1990[b]), 9 ± 0.8 [thermoluminescence] (Forman, 1992[a]), < 0.5 [geomorphic] (Katz and Boettcher, 1990)

All ages are in ka.
[a] Quoted in Wells et al., 1994.
[b] Quoted in Wells et al., 1990.

^{36}Cl samples have been measured at the Lathrop Wells volcano, yielding a best-estimate age of 73 ± 6 ka. Based on the mutual similarity of paleomagnetic orientation measurements from several locations within the Amboy lava flows, D. Champion (quoted in Glazner et al., 1991) estimated that all of the flows were erupted within a short time, probably < 20 years; thus the ^{36}Cl age estimate of ~ 80 ka probably applies to the entire eruptive sequence.

3.2. Pisgah Crater

Pisgah Crater (Fig. 1) is an ~ 100-m-high cinder cone in the eastern Mojave Desert. It is surrounded by an elongate field of east–west oriented, mostly pahoehoe, basalt flows, covering ~ 100 km^2 (Wise, 1966; Greely et al., 1988; Theilig, 1990). Attempts to determine the age of the Pisgah eruption have been minimal. Dibblee (1966) mapped the flow as "very late Pleistocene or Holocene." Kilbourne and Anderson (1981) gave an estimate of < 2000 years on the same grounds as for Amboy Crater.

Again, these estimates appear to underestimate the age of the eruption. Surface preservation at Pisgah is significantly better than at Amboy Crater. Glassy, highly vesicular flow top is preserved in many areas. Surficial stripping is usually limited to a few pahoehoe layers. Deep depressions are usually filled, but shallower ones are not. However, much less glassy flow top is preserved, and the extent of eolian fill is significantly greater, than for the Holocene flows in New Mexico cited above.

Three samples were collected at Pisgah ~ 1 km NW of the central vent. They were collected from ridge tops and push-up ridges within about 100 m of each other. The three samples gave ages in very good agreement, averaging 22.5 ± 1.3 ka for an assumed 1 mm/kyr erosion rate (Fig. 2). This age appears to apply to all of the Pisgah flows, based on D. Champion's paleomagnetic orientation data, from the same source cited above.

3.3. "I" cone, cima volcanic field

The "I" cone and associated basalt flow is 1 of ~ 30 vents in the Cima volcanic field (Dohrenwend et al., 1984). It is located near the center of the field and is one of the fresher appearing features in the field. The cinder cone is ~ 1 km in diameter and an elongate flow of ~ 10 km^2 extends 11 km west of the vent. Most of the flow surface is aa lava, but some areas close to the vent consist of pahoehoe. Several isotopic age estimates are available for the "I" cone. K–Ar dating reported in Dohrenwend et al. (1984) gave an age of 140 ± 20 ka (1σ uncertainty). Based on averaging additional K–Ar measurements, Turrin and Champion (1991) gave a revised age of 110 ± 5 ka (1σ). However, Wells et al. (1995) reported much younger results. Two cosmogenic ^{3}He measurements from the flow close to the vent gave ages of 37 ± 6 and 31 ± 7 ka.

I sampled the flow on the west side of the tuff-ring cone where the flow surface had pahoehoe characteristics. The samples were collected within 100 m of each other and were from the flow levees and channel in the immediate vicinity of the vent. The flow surface was very similar to the Pisgah flow described above. The three samples yielded ages in excellent agreement, averaging 27 ± 1.3 ka. This age is in good agreement with the younger of the ^{3}He ages reported by Wells et al. (1995) and marginal agreement with the older one.

3.4. "A" cone, Cima volcanic field

The "A" cone (also known as the Black Tank cone) is generally thought to be the youngest feature in the Cima volcanic field. The eruptives consist of a complex, fairly substantial cinder cone with a small but thick and blocky aa flow extending ~ 2 km to the east and occupying ~ 1.3 km^2. The age of the "A" cone has been quite controversial and the range of ages estimated has been very wide. At the upper end of the range, Turrin (1989) (quoted in Wells et al., 1994) obtained a K–Ar age of ~ 300 ka. Turrin and Champion (1991) averaged 12 ^{40}Ar/^{39}Ar values to yield an age of 119 ± 14 ka (1σ). Wells et al. (1995) reported three cosmogenic ^{3}He ages: 20 ± 10 and 18 ± 12 ka on volcanic bombs on the scoria cone and 13 ± 3 ka on a sample from the flow. D. Champion (quoted in Wells et al., 1990) estimated an eruption age range of 29 to ~ 16 ka based on paleomagnetic orientation measurements. S. Forman (1992, quoted in Wells et al., 1994) performed thermoluminescence measurements on a soil sample baked by one of the "A" cone flows, yielding an age of 9 ± 0.8 ka. Finally, based on appearance, Katz and Boettcher (1990) suggested that the "A" cone may be as young as a few hundred years.

Wells et al. (1994) considered the "A" cone to be a type example of a polycyclic basaltic cinder cone. They distinguished by field mapping three episodes of eruption, one probably mid-Quaternary and the other two latest Pleistocene. They found the variation in the cosmogenic ^{3}He ages to be consistent with their proposed chronology of eruption. However, Turrin and Champion (1991) contested this interpretation, considering the cone and flows to be the result of a single eruption at ~ 100 ka.

I sampled the apparently youngest flow (mapped as unit Qv3lb by Wells et al., 1994) about 500 m west of the breach in the cone from which the flow originated. Sample 15 was flow-top lava from the surface of an ~ 4-m-high mound toward the north edge of the flow. Samples 16 and 17 were collected 50 m south of sample 15, within 30 cm of each other. Sample 16 was a volcanic bomb lying on a raised surface, and 17 was from the surface itself. Sample 15 gave a ^{36}Cl age of 21 ± 1.6 ka, while 16 and 17 gave nearly identical ages of 11.5 ± 1.1 and 11.6 ± 1.6 ka, respectively. This was the only case in this study where discrepant ages were obtained from what was thought to be a single flow.

One possible explanation is that the discrepancy results from the difficulty of selecting suitable surface-exposure dating sampling sites on unstable aa flows. In this case, the oldest age should be preferred, since erosion of substantial thickness of loose aa rubble will result in an anomalously young age, and the possibility of cosmogenic nuclide inheritance in a lava flow is remote. However, the very close agreement of the ages from the volcanic bomb (sample 17) and the surface it was resting on (sample 16) represents a somewhat improbable coincidence if this is the explanation.

An alternative explanation is that the "A" cone is in fact polycyclic and that different flow units were sampled. The similarity to the bimodal ^{3}He age distribution reported by Wells et al. (1995) is intriguing. In the field, all of the samples appeared to be from the Qv3lb unit of Wells et al. (1994), but sample 15 in fact may have been from the southern margin of the Qv3la unit and 16 and 17 from Qv3lb. This would be consistent with the ^{3}He age determination of Wells et al. (1995), whose 13 ± 3 ka age was from the distal end of the Qv3lb flow. However, the two 18 and 20 ka ^{3}He ages were from bombs on the Qv2s subcone, not the Qv3s vent. While the suggestion of polycyclic eruptive activity is interesting, further sampling and analysis would clearly be necessary to adequately test it. The ~ 10 ka difference in the ages of the possible eruptive events would render such a test relatively straightforward.

3.5. Unidentified flow, Cima volcanic field

A flow whose origin could not be clearly identified was sampled between the "F" and "G" cones at Cima. The main motivation for this sampling was to provide a test for the varnish microstratigraphy technique. The flow was mainly pahoehoe texture where sampled but was covered to the north by a younger flow with aa surface. The origin of the sampled flow section could not be determined due to coverage to the east by younger flows and alluvium, but the most likely sources are the "H" or "I" cones. The flow sampled was probably the same as that mapped as "uk2a" by Royek (1985) ("uk" indicates flow of unknown origin). The degree of surface degradation was similar to, or somewhat greater than, that of the area sampled on the "I" cone flow.

Only one sample was processed from this unidentified flow, and it gave a ^{36}Cl age (assuming 1 mm/kyr erosion) of 46 ± 2 ka. This is consistent with a previous K–Ar age from the same vicinity by Dohrenwend et al. (1984) of 60 ± 15 ka (1σ), but it is older than either the ^{3}He age reported by Wells et al. (1995) for the "I" cone or the ^{36}Cl age for the "I" cone determined in this study. However, it is younger than the ~ 70 ka ^{3}He age that Wells et al. (1995) gave for the "H" cone. The age appears reasonably consistent with the surface weathering characteristics of the flow, but it cannot be traced to a source vent by chronology.

4. Summary

The cosmogenic ^{36}Cl ages for the two Cima flows that have previously been dated form a pattern consistent with previous work. They are broadly in agreement with previous cosmogenic ^{3}He ages and appear to confirm that the "I" and "A" cones are a few tens of thousands of years old, rather than ~ 10^5 years as the K–Ar and ^{39}Ar/^{40}Ar results would suggest. The ^{36}Cl ages for different samples from the "A" cone are not consistent. Given that major erosion will produce anomalously young ages but that there is no plausible mechanism for producing anomalously old ages on basalt flows, both the ^{36}Cl and ^{3}He data show that the "A" cone erupted at about 20 ka. Both cosmogenic nuclides suggest that the cone may have erupted again at about 11 ka, but the evidence is not entirely consistent and additional measurements would be required to adequately test this hypothesis.

The ^{36}Cl ages from the unidentified Cima flow, Pisgah Crater, and Amboy Crater cannot be compared with independent quantitative results, but they are consistent with the relative sequence of surficial modification of these flows. In all cases, these flows are much older than previously published estimates based on the degree of surficial degradation of the flows. Basalt flows clearly erode at a rate much slower than even the trained geological eye would suggest. Although erosion rates remain uncertain, the ^{36}Cl ages are relatively insensitive to a reasonable range of assumed erosion rate, with the partial exception of Amboy Crater. I hope that the availability of these ages will encourage use of these flows for additional geomorphic and remote sensing studies and for additional intercomparison of Quaternary dating methods.

Note Added After Review: after this paper and Liu (2003-this issue) had been returned from review, the manuscripts were exchanged. Age estimates based on rock varnish microstratigraphy from Liu (2003-this issue) are compared with the ^{36}Cl ages and other age estimates in Table 3. The varnish microstratigraphic ages overlap for all sampled flows with the exception of the Cima "I" flow. There, according to Table 3 of Liu (2003-this issue), the varnish stratigraphy was highly variable for the three varnish samples collected close to the ^{36}Cl samples (estimates of 30, 39, and 16.5–12.5 ka). Two other samples more distant from the ^{36}Cl sampling point both yielded varnish stratigraphy age estimates of 39 ka. According to Royek (1985), the "I" cone is polycyclic, with flows of three ages in the vicinity of the ^{36}Cl and varnish sampling points. Although all three ^{36}Cl samples were certainly from the same flow, some of the varnish samples may possibly have been collected from an older flow. Although the varnish stratigraphic results were somewhat inconsistent for the "I" flow, I hope that this will not distract attention from the impressive agreement for the three previously undated flows (Amboy, Pisgah, and Cima unidentified) in this completely blind test. After participating in this test, I feel that it has confirmed the utility of carefully conducted varnish microstratigraphic analysis as a correlative geochronological tool.

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