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Late Quaternary caldera-forming eruptions in the eastern Aleutian arc, Alaska

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ABSTRACT

Late Quaternary calderas have been identified at 12 of 40 volcanic centers in the eastern Aleutian arc, and sufficient radiocarbon dates and geologic information have now been obtained to either date or constrain the timing of the climactic caldera-forming eruptions. At least eight major caldera-forming events, each characterized by estimated eruption volumes of more than 10 km^3, occurred at seven different volcanic centers in the Holocene, and as many as six of these had estimated eruption volumes of more than 50 km^3. Eruptions of similar magnitude formed two other calderas in Wisconsin time. The dating of these hitherto little-known events adds significantly to the previously existing chronology of large prehistoric eruptions. This refined chronology is important in understanding eruption-induced climate changes, in assessing volcanic hazards, and in developing a tephrochronology for northwestern North America.

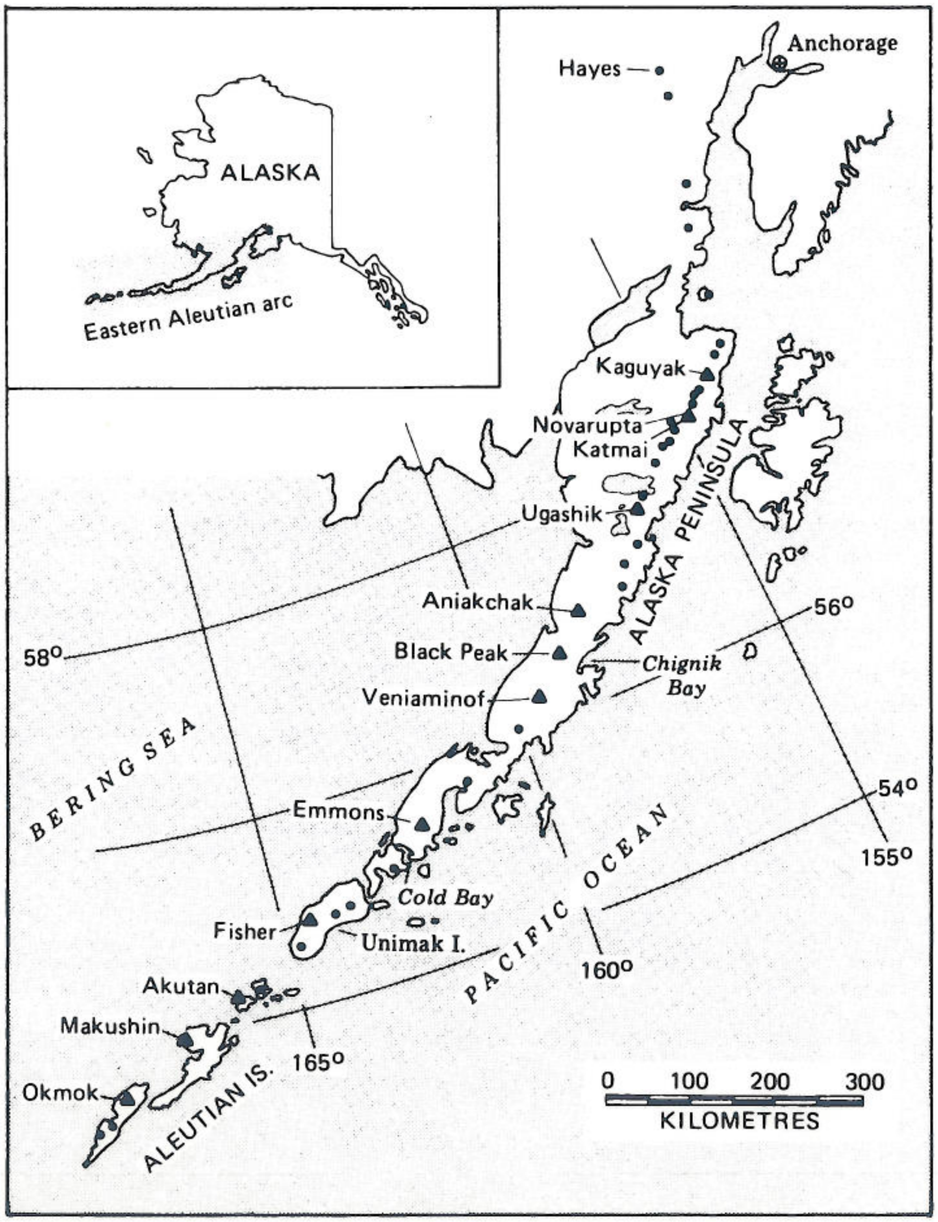

Figure 1. Volcanoes of eastern Aleutian arc; triangles denote calderas, circles are volcanoes.

INTRODUCTION

An accurate chronology of large caldera-forming eruptions is important in considering such topics as the effect of volcanism on climate, volcanic hazards, and stratigraphic correlation. Short-term (1–3 yr) climate changes (Lamb, 1971; Hammer et al., 1981) have been postulated for certain historic eruptions, particularly those that ejected large volumes of sulfur-rich aerosols into the stratosphere (Rampino and Self, 1984). Attempts to identify possible eruption-induced climate effects over a longer time frame, however, have been hampered by inadequate eruption chronologies. At least 12 caldera-forming eruptions of late Quaternary age have now been documented at volcanic centers in the eastern Aleutian arc. Ten of these eruptions are of sufficient magnitude (10–50 km^3 bulk volume) that they must be considered in hypotheses linking large eruptions and climatic changes in late Quaternary time. In addition, a knowledge of the timing of these events (eruption frequency) is important to assessing volcanic hazards both locally and regionally. Tephra sequences resulting from these dated caldera-forming eruptions are excellent marker beds for geomorphic and archeological studies throughout Alaska and western Canada.

GEOLOGIC SETTING

The Aleutian volcanic arc is defined by over 65 major Quaternary volcanic centers and spans 2500 km of the Alaskan mainland and the Aleutian Islands. At least 21 of these centers have calderas (Miller and Barnes, 1976), perhaps as many as 19 of which formed in the Holocene. Miller and Smith (1983) suggested a correlation between the abundance of Holocene caldera-forming eruptions and postglacial uplift.

Regional studies by the U.S. Geological Survey over the past decade have focused on the 1500-km-long, eastern segment of the arc (Fig. 1), which is built entirely on continental crust, in contrast to the oceanic western arc. Forty volcanic centers have been identified in this part of the arc; they range in size from central-vent volcanoes with edifice volumes as small as 15 km^3 to large stratocones and shield volcanoes with volumes as great as 400 km^3. K-Ar age determinations suggest that most of the larger centers in the present Aleutian arc have been built in the past 1–2 m.y. (Marsh, 1982).

Late Wisconsin glacial ice caps in the western Alaska Peninsula and on large islands in the Aleutians began retreating from sea level about 12,000 B.P., and deglaciation was generally complete by 10,000 B.P. (Black, 1983). Detterman (1986) stated that deglaciation of the Alaska Peninsula occurred about 9000–10,000 B.P. or shortly before. "Postglacial" is therefore used in this report as synonymous with Holocene, unless otherwise stated.

TABLE 1. RADIOCARBON AGE DETERMINATIONS

Sample no.	Lab no.	Volcano Location (lat,long)	Reported age (yr)	Remarks
1	W-3464	Okmok 53°33.8'N 168°04.8'W	2400 ±200	Charcoal in peat from Ashishik Point, Umnak Island
2	W-3424	Fisher 54°55.3'N 164°27'W	9120 ±250	Organic material directly beneath ash-flow tuff in Tugamak Range, Unimak Island
3	W-3125	Aniakchak 56°48.2'N 158°07.1'W	3350 ±200	Charcoal twigs at base of ash-flow tuff in Waterfall Creek
4	I-14,221	56°56.3'N 158°37.2'W	3410 ±90	25-cm-long charcoal log in ash-flow tuff, Port Heiden quarry
5	I-14,226	57°30.1'N 157°31.2'W	3520 ±140	Charcoal in pumice unit at base of distal ash-flow tuff, King Salmon River
6	W-3466	57°06.6'N 158°31.8'W	3610 ±200	Peaty material from 3-5-cm-thick soil horizon at base of ash-flow tuff, Bering Sea cliff
7	W-4052	57°08'N 158°18'W	3490 ±200	Peaty material underlying 5-m-thick ash-flow tuff, Pumice Creek
8	W-4582	57°07.5'N 157°40.5'W	3670 ±60	Peaty material underlying incipiently welded ash-flow tuff, northeast of Cinder River
9	I-14,228	57°02.7'N 158°02'W	3500 ±80	Organic material from soil horizon beneath ash-flow tuff and agglutinate, north flank Aniakchak cone
10	I-14,223	56°27.5'N 158°23.1'W	3370 ±90	Peat horizon underlying Aniakchak air fall, Chignik Bay
11	I-14,236	56°55.7'N 156°48.4'W	3570 ±80	Peat horizon overlying Aniakchak air fall, Pacific Ocean coast
12	W-4572	Black Peak 56°17'N 159°05'W	4470 ±50	Organic material from soil unit underlying Black Peak air fall, Black lake area
13	I-14,225	56°27.5'N 158°23.1'W	4170 ±90	Peat unit underlying Black Peak air fall, Chignik Bay
14	I-14,235	56°55.7'N 156°48.4'W	4700 ±100	Peat unit underlying Black Peak air fall, Pacific Ocean coast
15	W-3123	Veniaminof 56°22.5'N 159°13'W	3640 ±200	Charcoal branches from base of lower ash-flow tuff, Rapid Creek
16	W-3124	56°22.5'N 159°13'W	3750 ±200	Charcoal branches from base of upper ash-flow tuff, Rapid Creek
17	I-14,224	56°27.5'N 158°23.1'W	3660 ±90	Peat unit underlying Veniaminof air fall, Chignik Bay
18	I-14,230	56°19.3'N 159°10.3'W	3620 ±80	Organic material from soil horizon beneath ash-flow tuff
19	W-4569	57°51.6'N 156°34.9'W	31 960 ±1190	Charcoal fragments in beach sands beneath littoral cone
20	W-4580	57°51.6'N 156°34.9'W	42 900 ±3780	Charcoal fragments in beach sands beneath littoral cone

CALDERA-FORMING ERUPTIONS

Late Quaternary calderas have been identified at 12 of the 40 volcanic centers in the eastern Aleutian arc, and enough radiocarbon ages have been obtained to date Holocene caldera-forming eruptions at 10 of these centers. Geologic relations at the remaining two calderas suggest that they were formed in early to late Wisconsin time. The ^{14}C samples (Table 1) used to date these eruptions can be divided into three categories: charcoal within ash-flow tuffs, charcoal and organic material from directly beneath ash-flow tuffs, and organic material associated with air fall assumed (because of thickness and distribution) to be part of the climactic eruption.

Estimates of the eruption volume of the caldera-forming eruptions (Table 2) are derived from considerations of the caldera area (Smith, 1979), the thickness and distribution of the associated pyroclastic flows, and comparison with other better-studied calderas such as Crater Lake (Bacon, 1981) and Novarupta (Hildreth, 1983). These estimates include both pyroclastic flow and tephra volumes and have been arbitrarily grouped into three classes (Table 2): Class I—>50 km^3, Class II—10–50 km^3, and Class III—1–10 km^3. In terms of the Volcanic Explosivity Index (VEI) of Newhall and Self (1982), Class I and II have VEI ⩾6 and Class III has a VIE of 5.

Okmok Caldera

The Okmok volcanic center, Umnak Island (Fig. 1), is a large basaltic composite volcano with a caldera system marking the summit area.

TABLE 2. CHRONOLOGY AND SIZE OF LATE QUATERNARY CALDERA-FORMING ERUPTIONS IN THE EASTERN ALEUTIAN ARC

Eruption	Approximate age (yr)	Size*
Holocene		
Novarupta	38	II
Kaguyak	1000-10 000	II
Okmok II	2400	I
Aniakchak II	3430	I
Veniaminof	3700	I
Black Peak	4170-4700	II
Aniakchak I	4170-10 000	?
Akutan	5200	III
Makushin	7950	III
Okmok I	8250	I
Fisher	9120	I
Late Pleistocene		
Emmons	(?)	I
Ugashik	>42 000	II

*Size category I - >50 km^3, II = 10-50 km^3, III = <10 km^3 bulk volume of erupted material.

This system consists of two large partially overlapping calderas (Byers, 1959), each with an estimated diameter of about 10 km. Postglacial ash-flow tuffs exposed in sea-cliff exposures on the northwest side of the volcano are locally separated by a lava flow 6–9 m thick (Miller and Smith, 1975). A hiatus between extrusion of the lava and deposition of the upper ash-flow sheet is indicated by a well-developed erosional surface on the lava flow; in places, stream channels were cut through the lava flow and later filled by the younger ash flow. The occurrence of two major ash-flow units strongly supports the probability of two major caldera-forming eruptions in Holocene time.

Black (1975) reported ^{14}C dating of a "20- to 30-cm thick" tephra deposited directly on a cultural horizon near the west end of Umnak Island 70 km from Okmok (Fig. 1). The tephra thickens towards Okmok; Black concluded that it represents a catastrophic eruption of the volcano at about 8250 B.P. We suggest that 8250 B.P. is the probable date of the first caldera-forming eruption at Okmok volcano (Table 2).

Charcoal directly beneath the upper ash-flow tuff unit on the north side of the island yielded a ^{14}C age of 2400 ±200 yr (sample 1, Table 1). This is a maximum age for the second ash-flow tuff eruption, presumably the second caldera-forming eruption (Table 2). A minimum of about 5500 yr separates the two caldera-forming eruptions, assuming the correlations are correct.

Makushin and Akutan Calderas

Makushin volcano is an 1830-m-high andesitic stratocone located on the north side of Unalaska Island (Fig. 1). An ice-filled summit caldera about 2.4 × 3.2 km has been the source of andesitic pyroclastic flows that covered glaciated valleys on the north and south sides of the volcano. Reeder (1983) has reported a single ^{14}C age determination of 7950 ±90 yr on organic soil directly beneath the pyroclastic flows. This is a maximum age for the climactic eruption, which had an estimated bulk volume of <10 km^3, based on the small size of the caldera and the limited distribution of pyroclastic flows.

A 2-km-diameter summit caldera on neighboring Akutan Island (Fig. 1) has been the source for small-volume pyroclastic flows of andesitic composition on the north side of the volcano. Reeder (1983), on the basis of 3 dates, reported a ^{14}C age of 5200 ±200 yr on organic material directly beneath the pyroclastic-flow deposits. This is a maximum date for the climactic eruption which, like that of Makushin, is thought to be relatively small.

Fisher Caldera

Fisher caldera, near the west end of Unimak Island (Fig. 1), is one of the largest calderas in the entire Aleutian arc—diameter greater than 11 km. The caldera is surrounded by a thick ash-flow sheet deposited by highly mobile flows (Miller and Smith, 1977).

The ash-flow tuffs fill glaciated valleys and are therefore Holocene in age. An organic layer directly beneath the ash-flow tuff on the north side of the island yielded a ^{14}C age of 9120 ±200 yr (sample 2, Table 1), which would be a maximum age for the caldera-forming eruption. Support for this date as the approximate age of the eruption comes from ^{14}C dates (Funk, 1973) determined for a 10–50-cm-thick pumice-rich tephra unit in the Cold Bay area 120 km east of Fisher (Fig. 1). Organic material directly beneath this tephra unit yielded ^{14}C ages of 9660 ±615 and 10 625 ±550 yr. Granulometric, statistical, and isopach analyses of the tephra deposits by Funk indicate that they were deposited during one pulse of activity from a source on Unimak Island within 180 km of Cold Bay. The climactic eruption of Fisher, the closest caldera west of Cold Bay, is a logical but not unequivocal candidate for the source of the tephra.

Emmons Lake Caldera

On the basis of an extensive rimlike physiographic feature, Kennedy and Waldron (1955) postulated the existence of a caldera near the west end of the Alaska Peninsula (Fig. 1). Widespread ash-flow tuffs west, north, and east of the volcano indicate that the rimlike topographic feature does indeed represent the wall of a caldera (Miller and Barnes, 1976), which originally had a diameter of 19 km. The north and east walls of the caldera have been breached by a 20-km-long northeast-trending chain of postcaldera stratocones, including historically active Pavlof volcano.

The absolute age of the caldera-forming eruption is unknown because no ^{14}C or K-Ar^{40} age data are available. Field work in 1986, however, showed that the ash-flow tuffs deposited from the caldera-forming eruption(s) are interbedded with a series of moraines of which most are considered to be late Wisconsin in age (Weber, 1985) but including some of possible early Wisconsin age. The caldera-forming eruption is therefore pre-Holocene in age but probably no older than early Wisconsin.

The pre-Holocene age makes Emmons Lake caldera a possible source volcano for the Old Crow Tephra, an important late Pleistocene stratigraphic marker bed that occurs across much of central and eastern Alaska and northwest Yukon Territory. The tephra has an estimated age of 87 000–105 000 yr and an estimated bulk volume >50 km^3, and its source is now thought to be in the eastern Aleutian volcanic arc (Westgate et al., 1985; Schweger and Matthews, 1985).

Central Alaska Peninsula Calderas: Aniakchak, Black Peak, and Veniaminof

These three calderas are about 55 km apart along the central Alaska Peninsula (Fig. 1). Pyroclastic flows from the caldera-forming eruptions do not overlap, but tephra stratigraphy suggests that the Aniakchak eruption is the youngest, preceded by the Veniaminof and Black Peak eruptions, respectively.

Perhaps the most spectacular caldera in the entire Aleutian arc is Aniakchak, which is ice-free, 10 km in diameter, and more than 1 km deep. Ash-flow tuffs surrounding Aniakchak extend 80 km from the caldera rim onto the Bering Sea lowlands (Miller and Smith, 1977). The ash flows were extremely mobile and surmounted topographic barriers of several hundred metres. Perched basins filled with ash-flow tuff at elevations several hundred metres above the surrounding tuff-filled valleys are common.

Ash flows from the Aniakchak caldera-forming eruption filled deeply glaciated valleys and are Holocene in age. Nine ^{14}C dates from organic material closely associated with either the ash-flow tuffs or the air fall from the climactic eruption closely constrain its timing. Samples 3, 4, and 5 (Table 1) are of charcoal twigs and logs in the ash-flow tuff at three widely separated localities. The weighted-mean age of these samples, which presumably best date the caldera-forming eruption, is 3430 ±10 yr. Four ^{14}C dates are of organic material directly beneath the climactic ash-flow tuff (sample 6–9, Table 1) and represent maximum ages for the caldera-forming eruption; their weighted mean age is 3600 ±130 yr.

Sample 10, dated at 3370 ±90 B.P., is from peat underlying distal air fall and should represent a maximum age for the eruption. Sample 11, dated at 3570 ±80 B.P., is from organic material overlying the same tephra unit at another locality that should represent a minimum age for the climactic eruption; it is, however, somewhat older than the 3430 B.P. date and may not be reliable.

The weighted mean ^{14}C date of 3430 B.P. from charcoal within the ash-flow tuff is consistent with field relations as well as with the ^{14}C ages obtained on organic material beneath the ash-flow tuffs. Thus, we consider 3430 B.P. to be a reasonable date for the climactic eruption (Aniakchak II, Table 2) that formed the present caldera.

An older ash-flow tuff has recently been found in isolated localities on the flanks of the volcano, suggesting the occurrence of an earlier violent eruption (Aniakchak I, Table 2) of unknown volume. This ash-flow tuff unit is postglacial and lies stratigraphically below tephra sections correlated with the caldera-forming eruptions of both Veniaminof and Black Peak, indicating an age between 4400 (see below) and 10000 yr.

Black Peak is the middle and smallest (3 km diameter) of the three neighboring calderas. Ash-flow tuffs as much as 100 m thick are exposed in two large drainages on the west side of the volcano. The tuffs appear to have been more passively emplaced as compared to those from the neighboring calderas, and they have a large air-fall component. In spite of the caldera's small diameter, the apparent widespread distribution of climactic air fall and thickness of the ash-flow tuffs suggest a bulk eruption volume of >10 km^3.

Attempts to find charcoal in, or organic material directly beneath, the ash-flow tuff were unsuccessful. However, organic material from beneath a distinctive coarse air-fall tuff, assumed to represent the climactic caldera-forming eruption of Black Peak, yielded ^{14}C ages of 4470 ±200, 4170 ±90, and 4700 ±100 yr (samples 12–14, Table 1). These are maximum ages; sample 17, dated at 3660 ±90 B.P., is a minimum age from organic material overlying the climactic air fall. These dates are consistent with the tephra stratigraphy and suggest a date somewhere between 3660 and 4170–4700 B.P. for the caldera-forming eruption of Black Peak.

A 10-km-diameter, ice-filled summit caldera marks the top of Veniaminof volcano, a large (>400 km^3) andesitic stratocone (Fig. 1). Postglacial ash-flow sheets extend to 50 km from the caldera rim on the Bering Sea side of the volcano; on the Pacific Ocean side, ash flows apparently entered bays and estuaries.

^{14}C ages of 3640 ±200 yr and 3750 ±200 yr (samples 15, 16, Table 1) were obtained from charcoal in separate phases of an ash-flow tuff west of Veniaminof. These ages compare well with maximum ^{14}C ages of 3620 ±80 yr (samples 17, 18, Table 1) from organic material underlying ash-flow tuff on the west flank of Veniaminof and of 3660 ±90 yr on organic material underlying distal air fall from the caldera-forming eruption. A date of about 3700 B.P., therefore, seems reasonable for the climactic eruption that formed Veniaminof caldera.

Ugashik Caldera

Ugashik is a small (5 km diameter) caldera located south of Becharof Lake on the Alaska Peninsula (Fig. 1). The precaldera cone has been mostly removed by erosion, and the north rim of the caldera has been breached by Peulik volcano, a postglacial andesitic stratocone. Postcaldera nonglaciated silicic domes occupy the interior of the caldera.

The caldera-forming eruption is tentatively assigned a late Pleistocene but pre-Holocene age, on the basis of indirect evidence. Caldera-forming eruptive products are sparse in the vicinity of Ugashik caldera, suggesting that the climactic eruption took place either prior to or during late Wisconsin glaciation. The caldera must be younger than a 171000 ±22000 yr K-Ar age determined on the precaldera cone-building volcanic rocks. Beach sands exposed underneath a littoral cone 15 km west of the caldera on the south side of Becharof Lake (Fig. 1) contain abundant coarse white pumice lapilli and charcoal fragments. These charcoal fragments have yielded ^{14}C ages of 31960 ±1190 and 42900 ±3780 yr (Table 1) which, because of their antiquity and age spread, are almost certainly minimum ages. If both the pumice and the charcoal are related to the caldera-forming eruption (and it is entirely possible that they have no relation to each other or to the caldera-forming eruption), then the eruption would have a minimum date of about 40,000 B.P. The radiometric age information therefore suggests a date of 40,000 to 171,000 B.P. for the caldera-forming eruption, which is compatible with the geologic relations.

Katmai, Novarupta, and Kaguyak Calderas

The only historic caldera-forming eruption in the Aleutian volcanic arc occurred at Novarupta caldera in what is now Katmai National Park, June 6–8, 1912 (Curtis, 1968). Hildreth (1983) has estimated that approximately 20 km^3 of air-fall tephra and 11–15 km^3 of ash-flow tuff were ejected within about 60 h from the Novarupta vent area in what was one of the three most voluminous eruptions in recorded history. The source area was a 6-km^2 depression later obscured by air-fall tephra and by the emplacement of the Novarupta dome. During the course of the eruption, the summit of neighboring Mt. Katmai, 10 km away, collapsed, forming a second caldera 600 m deep and with about the same area as Novarupta (Hildreth, 1983).

Novarupta and Katmai are not the only calderas in Katmai National Park. Kaguyak crater is a small (2.6 km diameter), little-known, lake-filled, circular caldera in the northeast corner of the park (Fig. 1). Nonwelded ash-flow tuffs are confined to within 7 km of the caldera and do not appear to have been particularly mobile. The ash flows filled previously glaciated valleys and are therefore postglacial in age. Swanson et al. (1981) reported a ^{14}C date of 1000 B.P. on soil stratigraphically above the pyroclastic deposits; this is a minimum date for the eruption. The date of the caldera-forming eruption is therefore poorly constrained between 1000 and about 10,000 B.P.

DISCUSSION

Caldera-forming eruptions of large magnitude have occurred in late Quaternary time at 12 of 40 recognized volcanic centers in the eastern Aleutian arc. At least 10 eruptions had bulk volumes estimated at more than 10 km^3, and as many as 6 of the 10 eruptions may have had volumes in excess of 50 km^3. Eight of these eruptions were Holocene in age, as were two smaller caldera-forming eruptions with ejecta volumes in the range 1–10 km^3. Eruptions with ejecta volumes of 1–10 km^3 have undoubtedly occurred elsewhere in the arc at volcanic centers not characterized by calderas. For example, Riehle (1985) has suggested that as many as 8 eruptions, each similar in size to the May 18, 1980 Mount St. Helens eruption (approximately 1 km^3), occurred at about 3650 ±150 B.P. at Hayes volcano (Fig. 1) at the eastern end of the arc.

The dating of at least 8 large caldera-forming Holocene eruptions in the eastern Aleutian arc adds significantly to the existing eruption chronology. Rampino et al. (1979), for example, compiled a time-distribution list of the largest known eruptions (i.e., those with a bulk volume >10 km^3) of the past 100000 yr. They listed 14 such eruptions as occurring in the Holocene, but only the 1912 Novarupta eruption was known from the Aleutian arc at the time of their compilation. Simkin et al. (1981), in their tabulation of Holocene volcanic activity, listed 17 eruptions with VEI 6 or greater (Classes I and II in this study), again including only the then-known Novarupta eruption from this arc. Dating of the caldera-forming eruptions in the western Aleutian arc (whose absolute ages are unknown) will refine still further the chronology of large volcanic eruptions by adding perhaps as many as 10–12 more events.

The effects of large volcanic eruptions on the climate are not completely understood, and recent studies have shown that factors such as the sulfur content of the eruption and its location may also be involved in eruption-induced climatic changes (Jakosky, 1986). At least one large eruption in the Aleutian arc appears to have had an effect on climate. The 1912 eruption at Novarupta, although not the largest of the caldera-forming eruptions in the arc, is probably representative of the genre in terms of the amount of material erupted in a single event. High acidity levels attributed to this eruption have been detected in cores from the Greenland ice cap (Hammer et al., 1981), and Rampino and Self (1984) estimated that a world-wide temperature drop of 0.2 °C was related to the eruption. Other large Aleutian eruptions may have had similar climatic effects. If a valid assessment is to be made of the effects that these and other large volcanic eruptions have on climate, an accurate eruption chronology is a necessity.

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Reviewer's comment

We've seen too many idea-rich, data-poor papers on volcanism-climate relations, particularly with interest rekindled by extinction and nuclear winter ideas, but here is a paper that forces rethinking of many such papers by the simple marshalling of hard-won field *data*. It is a major contribution to volcanology and the volcano-climate relationship. Furthermore, it is a useful reminder, in the post-Ruiz concern for volcano hazards, that the recent geologic record is loaded with events dwarfing the volcano tragedies of recent decades.

Thomas Simkin