The Geology of North America
Vol. G-1, The Geology of Alaska
The Geological Society of America, 1994

Chapter 24

Quaternary volcanism in the Alaska Peninsula and Wrangell Mountains, Alaska

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INTRODUCTION

The numerous Quaternary volcanoes of the Alaska Peninsula, Cook Inlet area, and the Wrangell Mountains result from underthrusting of the Pacific Plate, or material coupled to the Pacific Plate, beneath the continental crust of North America. These volcanic centers are among the most prominent physiographic landforms in southern Alaska. They include some of the highest (>5,000 m), largest (>1,000 km^3), and most explosive (five Holocene eruptions with bulk volumes >50 km^3) volcanoes found along the entire circum-Pacific margin.

Edifices of the major Quaternary volcanoes dominate the Alaska Peninsula and Cook Inlet region (Fig. 1); numerous peaks rise 1,800 to 2,500 m above sea level. These volcanic centers, along with those of adjoining Unimak Island, constitute the eastern half of the Aleutian volcanic arc. This classic arc-trench system, equally divided between continental and oceanic segments, extends 2,600 km across the North Pacific. Separated from the northeast end of the Aleutian arc by 400 km is the subduction-related Wrangell volcanic field of Miocene to Holocene age, which underlies >10,000 km^2 of the Wrangell Mountains of south-central Alaska (Fig. 1).

Regional geologic mapping and topical volcanological studies since the early 1970s have resulted in an expanded understanding of the physical volcanology of the eastern Aleutian arc and Wrangell Mountains, including such parameters as size, stratigraphy, eruptive history, spacing, and geologic setting of the volcanic centers. Several volcanoes have now been mapped and studied in sufficient detail to clarify the physical and chemical processes associated with volcanic activity in this part of the circum-Pacific. This report incorporates new and previously unpublished information on the spatial distribution, volume, geologic setting, and major-element composition of the Quaternary volcanoes—information that was not available to authors of previous summary articles (Marsh, 1982; Kienle and Swanson, 1983).

EASTERN ALEUTIAN ARC: ALASKA PENINSULA-COOK INLET

Quaternary volcanism has resulted in a chain of subaerial stratocones on the Alaska Peninsula (including Unimak Island) and west side of Cook Inlet (Fig. 1) that constitutes the eastern Aleutian arc and includes the part of the entire arc built on continental crust. In this region, the Pacific Plate is impinging at close to a 90° angle on the North American Plate at rates of about 7.5 cm/year (Engebretson and others, 1985). The north-dipping Benioff zone lies about 100 km beneath the Cook Inlet portion of the arc and 75 to 100 km beneath the Alaska Peninsula centers (Kienle and Swanson, 1983). The arc-trench gap is about 300 km for much of the Alaska Peninsula but increases eastward to over 500 km in the Cook Inlet area (Jacob and others, 1977).

The recent completion of 1:250,000-scale geologic mapping for much of the region (Detterman and others, 1981, 1987; Riehle and others, 1987a; Wilson and others, 1994) has led to the identification of most major Quaternary volcanic centers. The term "volcanic center" is used in this report to describe a site of more or less continuous volcanism along the volcanic front during late Quaternary time. The actual vent area may have shifted 20 km or more during the life of the center, or there may be a cluster of active vents at an individual center. A center, therefore, may include overlapping lava flows and ejecta from more than one vent.

Using this arbitrary definition, 37 principal volcanic centers (Fig. 1; Table 1) have been identified in the eastern Aleutian arc, including Unimak Island. Centers included in this tabulation are generally aligned along the volcanic front parallel to the arc-trench system. The numerous closely spaced small volcanoes along the volcanic front in Katmai National Park are arbitrarily listed as separate centers. Several closely spaced vents on the lower Alaska Peninsula have been grouped together as the Kupreanof center (No. 28, Fig. 1). Pogromni and Westdahl volcanoes on the west end of Unimak Island have been included as a single

Miller, T. P., and Richter, D. H., 1994, Quaternary volcanism in the Alaska Peninsula and Wrangell Mountains, Alaska, *in* Plafker, G., and Berg, H. C., eds., The Geology of Alaska: Boulder, Colorado, Geological Society of America, The Geology of North America, v. G-1.

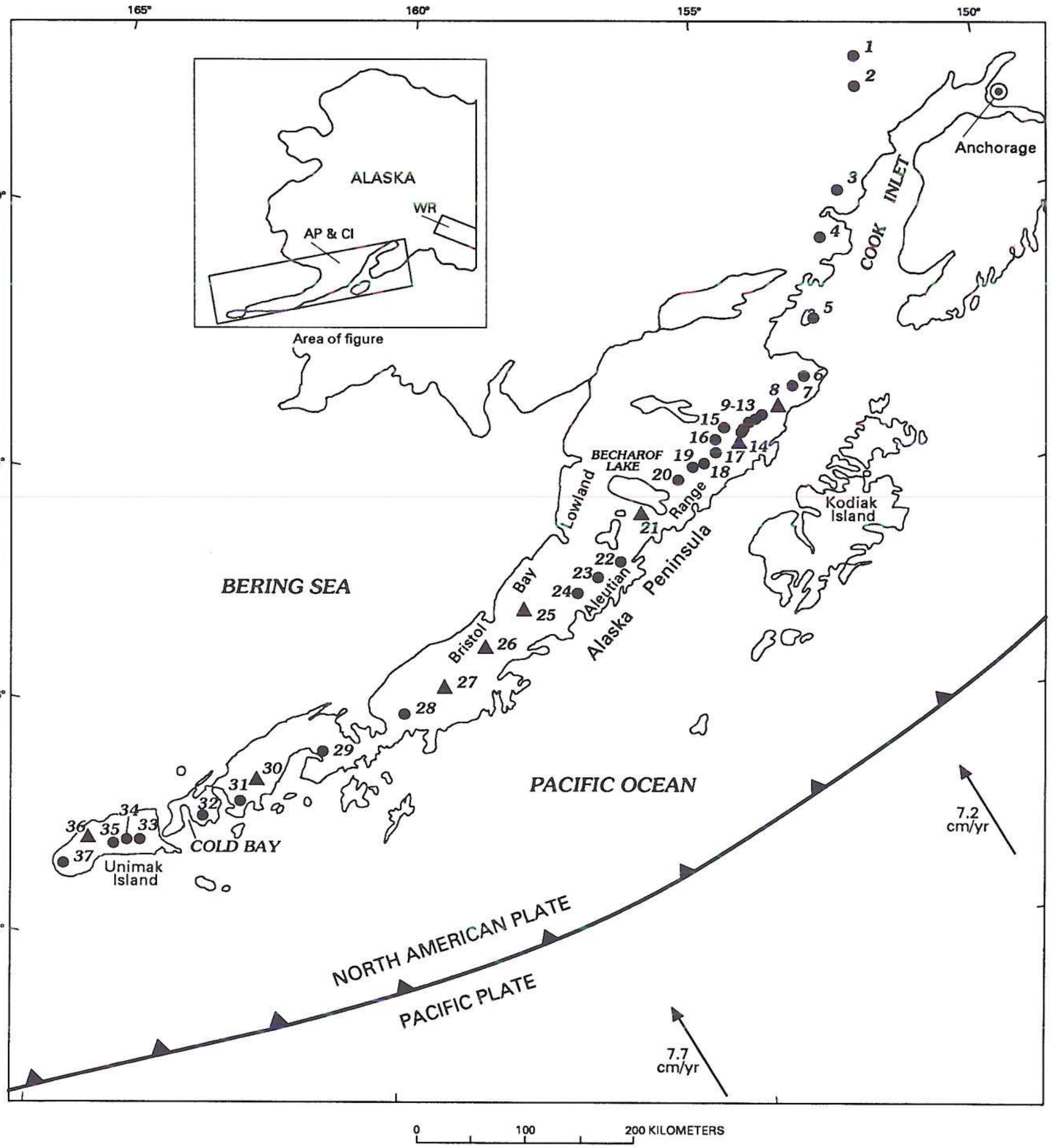

Figure 1. Major volcanic centers of the Alaska Peninsula (AP) and Cook Inlet (CI) region. Volcanic centers in the Wrangell Mountains (WR) are shown in Figure 6. ▲ denotes calderas; ● denotes stratavolcanoes. Numbers refer to centers as follows: 1, Hayes; 2, Spurr; 3, Redoubt; 4, Iliamna; 5, Augustine; 6, Douglas; 7, Fourpeaked; 8, Kaguyak; 9, Devils Desk; 10, Kukak; 11, Stellar; 12, Denison; 13, Snowy; 14, Katmai; 15, Griggs; 16, Novarupta; 17, Trident; 18, Mageik; 19, Martin; 20, Kejulik; 21, Peulik-Ugashik; 22, Kialagvik; 23, Chiginagak; 24, Yantarni; 25, Aniakchak; 26, Black Peak; 27, Veniaminof; 28, Kupreanof; 29, Dana; 30, Emmons Lake; 31, Dutton; 32, Frosty; 33, Round Top; 34, Isanotski; 35, Shishaldin; 36, Fisher; 37, Pogromni-Westdahl. Arrows and numbers adjacent to plate boundary denote direction and velocity of Pacific Plate movement relative to North American Plate (Engebretson and others, 1985). Sawteeth are on upper plate.

center (No. 37, Fig. 1) because the large topographic massif of which they are a part has not been mapped.

Not included in this tabulation is a series of widely separated domes and small monogenetic features such as Amak Island (Marsh and Leitz, 1978), Gas Rocks (Detterman and others, 1987), Ukinrek maars (Kienle and others, 1980), and three unnamed basaltic scoria cones in Katmai National Park (Riehle and others, 1987a); they are north of, and aligned parallel to, the Quaternary volcanic front. Many of these small volcanoes appear to be back-arc features, whose relation to nearby and larger volcanic centers of the Aleutian arc is uncertain.

Some relatively well-known volcanoes are now considered to be part of a much larger center. Pavlof volcano near Cold Bay (Fig. 1), for example, is one of the better known and most consistently active volcanoes in the Aleutian arc. Recent topical studies, however, have shown it to be only the most recently active of several small parasitic cones of Holocene age built on the flanks of the large Emmons Lake center (No. 30, Fig. 1; Table 1).

The Aleutian volcanic arc has been one of the least known volcanic provinces in the world because of its remoteness and the inherent logistical difficulties associated with any attempt to study it. Volcanic centers in the Aleutian Islands began to receive systematic attention from geologists only after World War II (Coats, 1950, 1962). More recently, many of these island volcanoes have been the subject of petrological studies, including trace-element and radiogenic isotope analyses (Kay and others, 1978, 1986; McCulloch and Perfit, 1981; Myers, 1988). Most recent discussions of the composition and petrogenesis of Aleutian arc volcanism are based on studies of the oceanic part of the arc.

The volcanic centers of the eastern Aleutian arc, however, received little attention until the 1960s. Notable exceptions were the studies by Griggs (1922), Fenner (1923, 1926), Allen and Zies (1923), and Zies (1929) of the 1912 eruption in the Valley of Ten Thousand Smokes in Katmai National Park. Regional syntheses of stratigraphy and structure of the basement rocks were lacking prior to the reconnaissance study by Burk (1965). The general structure of even the more noteworthy centers such as Katmai was little understood, and the existence of such large volcanic centers as Emmons Lake caldera (No. 30, Fig. 1) was virtually unknown.

Only within the past 20 years, starting with the classic study by Curtis (1968) of the ejecta of the 1912 Valley of Ten Thousand Smokes eruption have studies of eastern Aleutian arc volcanic centers and related phenomena begun (Hildreth, 1983, 1987; Riehle and others, 1987b; Miller and Smith, 1977; Nye, 1987). Previously unknown Quaternary volcanic centers such as those at Kialagvik, Hayes, and Yantarni (all of which exhibit Holocene activity) were identified during this period. Also, the existence of several of the more remote Katmai National Park volcanoes was confirmed by Kienle and Swanson (1983).

Geologic setting

The Alaska Peninsula–Cook Inlet centers are built entirely on continental crust (in contrast to the oceanic western arc) that is part of the Peninsular tectonostratigraphic terrane (Jones and others, 1987; Silberling and others, this volume). This terrane was formed far south of its present position and accreted onto mainland Alaska in Late Cretaceous and early Tertiary time (Stone and Packer, 1977; Vallier and others, this volume).

The eastern Aleutian volcanoes overlie continental and marine sedimentary rocks that range in age from mid-Paleozoic to Holocene (chiefly of Late Jurassic to early Tertiary age), volcanogenic rocks of late Mesozoic and mid- to late Tertiary age, and Jurassic to early Tertiary plutonic rocks of the Alaska-Aleutian Range batholith (Detterman and others, 1981, 1987; Riehle and others, 1987a; Reed and Lanphere, 1972; Wilson and others, 1991; Magoon and others, 1976). The volcanic centers rest on progressively younger basement rocks from east to west.

The regional structural grain is northeast-southwest, parallel to the axis of the Aleutian Range. The terrane is marked by normal, reverse, and thrust faults and numerous open folds. One of the major structural features of the region is the northeast-trending Bruin Bay fault, which has been mapped for 530 km from near Mt. Spurr (No. 2, Fig. 1) to Becharof Lake (Fig. 1) and may extend an additional 140 km to the southwest (Detterman and others, 1987).

Tertiary volcanism is represented by the Meshik and Aleutian volcanic arcs. The Meshik arc is predominantly of Eocene and Oligocene age, yielding K-Ar ages ranging from 48 to 22 Ma (Wilson, 1985), and is oriented subparallel to the Aleutian arc (Fig. 1). Aleutian arc volcanism includes the present-day Quaternary chain of volcanoes. It began in the middle Miocene and continued sporadically to the present. The locus of Aleutian arc magmatism has shifted from its Miocene position about 50 km northwestward to the present Pleistocene-Holocene volcanic front (Wilson, 1985).

Many of the volcanic centers served as sites of ice caps in Quaternary time; glacial deposits recording four major Pleistocene glacial episodes have been mapped in the region (Detterman, 1986). Volcanic edifices have been extensively glaciated, and many still host glaciers and extensive snow and ice fields. The volcanoes also provided much of the debris found in the morainal ridges and drift sheets of Pleistocene age that overlie most of the Bering Sea Lowland north of the Aleutian Range.

Age and eruptive activity

Potassium-argon ages from Veniaminof, Aniakchak, Yantarni, Mt. Spurr, and Redoubt volcanoes (Fig. 1) suggest that most of the Alaska Peninsula and Cook Inlet centers began forming within the last 10^6 years (Luedke and Smith, 1986; Riehle

TABLE 1. PHYSICAL CHARACTERISTICS OF PRINCIPAL QUATERNARY VOLCANIC CENTERS IN THE EASTERN ALEUTIAN ARC*

Volcanic Center	Location	Elevation (m)	Height (m)	Diameter (km)	Estimated Volume* (km^3)	Eruptive Activity: Holocene	Eruptive Activity: Historic	Eruptive Activity: Fumarolic	Remarks
1. Hayes	61.6°N 152.5°W	1,690	300 (?)	5 (?)	<20 (?)	◆			Volcano largely destroyed by catastrophic eruptions about 3,500 ^{14}C B.P. and by subsequent glacial activity. Remnants are snow- and ice-covered pyroclastic deposits adjacent to Hayes Glacier.
2. Spurr	61.3°N 152.3°W	3,374	>1,000	10 +	30–50	◆	◆	◆	Stratocone and summit dome; explosion amphitheater open to the south summit dome, and parasitic cone on south flank (Crater Peak); associated pyroclastic flows. Fumaroles on summit dome and at Crater Peak.
3. Redoubt	60.5°N 152.8°W	3,108	1,500–1,800	11	38	◆	◆	◆	Stratocone with widespread Holocene lahars; fumarolic area in ice-filled summit crater.
4. Iliamna	60.0°N 153.1°W	3,053	1,800	10	45	◆	?	◆	Deeply eroded, strongly altered andesitic stratocone. Slope failure is common with much landslide activity. Large fumarolic area near summit. Widespread Holocene pumice in quadrant northeast of volcano.
5. Augustine	59.4°N 153.4°W	1,259	950	6–8	15	◆	◆	◆	Nested summit domes surrounded by volcaniclastic apron composed of pyroclastic flow deposits, lahars, and debris avalanches; summit area breached to north. Fumaroles on and around summit.
6. Douglas	58.9°N 153.6°W	2,135	1,000	10	25	?	◆		Little studied, small, chiefly ice-covered stratocone; fumaroles and hot crater lake near summit.
7. Fourpeaked	58.8°N 153.7°W	2,104	900	7	10				Poorly exposed, ice-covered, strongly altered stratocone.
8. Kaguyak	58.6°N 154.1°W	901	600	5	4 *	◆			Stratocone with lake-filled caldera of Holocene age. At least one post-caldera dacitic dome. Surrounded by nonwelded pyroclastic flow deposit.
9. Devils Desk	58.5°N 154.3°W	1,955	430–735						
10. Kukak	58.5°N 154.4°W	1,040	500–800					◆	A group of small, closely spaced, largely ice-covered central vent volcanoes composed of andesitic flows, tuffs, and breccias.
11. Stellar	58.4°N 154.4°W	2,272	400		60				
12. Denison	58.4°N 154.5°W	2,318	500						

TABLE 1. PHYSICAL CHARACTERISTICS OF PRINCIPAL QUATERNARY VOLCANIC CENTERS IN THE EASTERN ALEUTIAN ARC* (continued)

Volcanic Center	Location	Elevation (m)	Height (m)	Diameter (km)	Estimated Volume* (km³)	Eruptive Activity: Holocene	Historic	Fumarolic	Remarks
13. Snowy Mountain	58.3°N 154.7°W	2,161	640	5	5	◆		◆	Largely ice-covered central vent volcano; two main vent areas about 3.5 km apart along ridge crest; fumarolic.
14. Katmai	58.3°N 155.0°W	2,047	800	7	10 *	◆	◆	◆	Glacier-clad stratocone with lake-filled caldera formed in 1912. Intracaldera dome activity; sub-lacustrine fumaroles.
15. Griggs	58.4°N 155.1°W	2,265	740	6	7	◆		◆	Stratocone with nested summit craters; fumaroles on south flank near summit.
16. Novarupta	58.3°N 155.2°W	841	?	1	1	◆	◆	◆	Post-caldera plug dome surrounded by 2-km-wide subsidence structure largely covered by caldera-fill tephra. Fumarolic. Source area for 1912 VTTS Pyroclastic flows.
17. Trident	58.2°N 155.1°W	2,070	850	5	5	◆	◆	◆	Deeply eroded multivent andesite-dacite stratocone consisting of three main peaks; fumarolic. Historic activity has been on south flank.
18. Mageik	58.2°N 155.3°W	2,210	1,000	6	10	◆	◆	◆	Multivent andesite-dacite stratocone: fumarolic.
19. Martin	58.2°N 155.4°W	1,844	550	6	5	◆	◆	◆	Stratocone with strongly fumarolic summit crater.
20. Kejulik	58.1°N 155.6°W	1,586	670	5	5				Small basaltic stratocone.
21. Peulik-Ugashik	57.7°N 156.3°W	921	300	8	15 *	◆	?		Ugashik is a deeply eroded stratocone with a small summit caldera containing a group of nested domes. Peulik is a Holocene satellitic andesitic stratocone built high on the north flank of Ugashik. The summit of Peulik contains a dome and is breached to the west; a large area of block-and-ash flows and avalanche deposits mantles the west flank of the volcano.
22. Kialagvik	57.2°N 156.7°W	+1,700	900	5	5–10	◆			Poorly exposed, ice-covered dome and ash-flow complex.
23. Chiginagak	57.1°N 157.0°W	2,135	1,300	6	15	◆	◆	◆	Symmetrical stratocone. Deep breach on south flank extends to summit crater; domes near summit. Fumarolic area high on north flank.
24. Yantami	57.0°N 157.2°W	1,250	430	6	5	◆			Small andesitic stratocone with dacitic summit dome; cone is breached to the north. Extensive Holocene avalanche deposits and block-and-ash flows east and northeast of volcano.

TABLE 1. PHYSICAL CHARACTERISTICS OF PRINCIPAL QUATERNARY VOLCANIC CENTERS IN THE EASTERN ALEUTIAN ARC* (continued)

Volcanic Center	Location	Elevation (m)	Height (m)	Diameter (km)	Estimated Volume* (km^3)	Eruptive Activity: Holocene	Eruptive Activity: Historic	Eruptive Activity: Fumarolic	Remarks
25. Aniakchak	56.9°N 158.2°W	1,341	650	20	8 *	◆	◆	◆	Stratocone with large (10 km) ice-free summit caldera formed about 3,400 ^{14}C B.P. Intra-caldera domes, tuff cones, spatter cones, lava flows, and small lake. Hot (85°C) ground in northwest corner of caldera. Center is surrounded by pyroclastic flow deposits for distances of up to 50 km.
26. Black Peak	56.6°N 158.8°W	955	350	8	10 *	◆	◆		Small stratocone with summit caldera formed 4,100 to 4,700 ^{14}C BP. Intracaldera nested dacitic dome complex. Thick block-and-ash deposits in valleys north and west of caldera.
27. Veniaminof	56.2°N 159.4°W	2,507	1,900	35	400 *	◆	◆	◆	Large stratocone truncated by 10-km-wide summit caldera formed about 3,700 ^{14}C B.P. Caldera is occupied by an ice field that covers the south rim of the caldera. Alpine glaciers fill valleys on the north, east, and west flanks of the volcano. Active intracaldera basaltic cone. Lahars and pyroclastic flow deposits fill many of the valleys on the volcano's flanks. Northwest-trending belt of post-caldera cinder and scoria cones extends across the volcano from the Bering Sea to the Pacific Ocean side.
28. Kupreanof	55.9-56.1°N 159.8-160.1°W	1,320-1,890	400-900		70	◆	◆	◆	Easternmost of at least 5 known Quaternary vents occurring along a 30-km-long belt on the Aleutian Range crest; also called the Stepovak Bay Volcano Group (Wilson, 1989). Volcanic products from these vents are andesitic and commonly overlapping. Fumarolic activity at two localities.
29. Dana	55.6°N 161.2°W	1,354	1,000	5.5	8	◆	◆		Small central vent dome with lake-filled summit crater; surrounded by apron of volcaniclastic debris. Block-and-ash flow erupted 3,840 ^{14}C B.P. fills valleys north and south of volcano (Yount, 1990).

TABLE 1. PHYSICAL CHARACTERISTICS OF PRINCIPAL QUATERNARY VOLCANIC CENTERS IN THE EASTERN ALEUTIAN ARC* (continued)

Volcanic Center	Location	Elevation (m)	Height (m)	Diameter (km)	Estimated Volume* (km^3)	Eruptive Activity: Holocene	Historic	Fumarolic	Remarks
30. Emmons Lake	55.4°W 162.0°W	2,519	850–975	30	350 *	◆	◆	◆	Large stratocone with oval-shaped 11 x 18 km caldera. At least two major caldera-forming eruptions in Pleistocene time. Post-caldera basaltic volcanism from Emmons, Hague, Pavlof Sister, and numerous other unnamed parasitic and flank volcanoes. Fumaroles on Pavlof and Hague volcanoes.
31. Dutton	55.2°N 162.3°W	1,506	760	6	5-10	◆			Small stratocone with Holocene domes in summit area and on northeast flank. Flanks are mantled by widespread debris flows and avalanche deposits.
32. Frosty	55.1°N 162.8°W	1,763	1,100	10	25	◆		?	Stratocone with central vent summit dome. Possible fumarolic area in ice-filled summit crater.
33. Round Top	54.8°N 163.6°W	1,871	600	8	10	◆			Ice-covered stratocone with summit and flank domes. Holocene pyroclastic flow deposits, lahars, and debris avalanches on south and southeast flanks.
34. Isanotski	54.8°N 163.7°W	2,446	1,800 (?)	10	45	◆	◆		Deeply eroded stratocone with possible domes.
35. Shishaldin	54.8°N 164.0°W	2,857	1,500 (?:)	10	500	◆	◆	◆	Symmetrical stratocone (upper 2,000 m ice-covered) built on older volcanic rocks (Fournelle and Marsh, 1986). Monogenetic cones and associated lava flows on northwest flanks; pyroclastic flow deposits; fumarolic summit area.
36. Fisher	54.7°N 164.4°W	1,094	960	21	300 *	◆	◆	◆	Large stratocone with oval-shaped (18 x 11 km) Holocene caldera (s); last major caldera-forming activity about 9,100 ^{14}C B.P. Thick intracaldera tephra fill; several post-caldera domes and cones. Fumarolic area near center of caldera.
37. Pogromni-Westdahl	54.5°N 164.7°W	2,000	1,700 (?)	20	200	◆	◆	◆	Large ice-covered volcanic massif with active vents at Pogromni and Westdahl volcanoes. Little information available.

*Pre-caldera volume.

and others, 1987b; Yount, 1984; Turner and Nye, 1986). Six K-Ar ages, ranging from 830 to 109 ka, have been obtained from Veniaminof (No. 27, Fig. 1)—the large volcanic center on the central Alaska Peninsula—and nearby Aniakchak volcano has yielded three K-Ar ages ranging from 661 to 242 ka. Turner and Nye (1986) conducted a detailed geochronologic study of Mt. Spurr volcano and concluded that most of the ancestral stratocone was built from 255 to 58 ka. In contrast, Augustine volcano, the small island center in lower Cook Inlet (No. 5, Fig. 1), is thought to have formed in the last 20,000 years (Johnston, 1978).

Historic eruptive activity has been reported from at least 19 of the 37 Alaska Peninsula–Cook Inlet volcanic centers (Table 1), more than 120 eruptions having taken place since 1760 (Simkin and others, 1981; T. P. Miller, unpublished data); more than half of the centers (21 of 37) show fumarolic activity. The number of historic eruptions is undoubtedly a minimum figure, since many eruptions probably went unreported prior to 1900 because of the remoteness of the region.

Holocene activity has been documented at 30 of the 37 principal volcanic centers (Table 1). Tephrochronologic studies in the region have only recently begun (Riehle, 1985) but they hold much promise for delineating the source and timing of major Holocene eruptions.

At least nine caldera-forming eruptions have occurred at eight of the volcanic centers on the Alaska Peninsula (Miller and Smith, 1987) during late Pleistocene and Holocene time. Five of these major eruptions may have had ejecta bulk volumes of >50 km^3, and all had estimated bulk volumes of >10 km^3; indeed 20 to 30 percent of all known Holocene eruptions of this magnitude worldwide appear to have occurred on the Alaska Peninsula (Miller and Smith, 1987). The 1912 eruption of about 35 km^3 of tephra from the Novarupta vent complex in Katmai National Park (No. 16, Fig. 1)—an event that resulted in the formation of calderas at Katmai and Novarupta—was the most voluminous rhyolitic eruption in the past 1,800 years and has been called the world's most important igneous event of this century (Hildreth, 1987).

Physical volcanology

Most Alaska Peninsula and Cook Inlet volcanoes are typical stratocones consisting of intercalated lava flows and volcaniclastic rocks and marked by summit craters and calderas. These volcanoes commonly have a basal unit that is predominantly volcaniclastic and an upper unit that is composed chiefly of flows. A few small centers (e.g., Augustine, Kialagvik, Dana, Mount Dutton; Nos. 5, 22, 29, 31 on Fig. 1) appear to consist chiefly of dacitic dome clusters surrounded by an apron of pyroclastic flow deposits.

Diameters of collapse calderas range from 3 km (Kaguyak) to 18 km (Emmons Lake; Miller, this volume), although the scalloped oval shape of larger calderas such as Emmons Lake and Fisher suggests more than one collapse event. The largest circular calderas (such as Aniakchak, Veniaminof; Table 1), each of which may represent a single collapse event, are about 10 km in diameter. Ash-flow tuffs, generally nonwelded, surround most calderas and, in the case of some larger calderas such as Aniakchak, originally covered areas of >2,000 km^2 (Miller and Smith, 1977) and extended as far as 80 km from their source volcano. At least six volcanic centers (Spurr, Augustine, Peulik, Kialagvik, Yantarni, Round Top; Nos. 2, 5, 21, 22, 24, 33, Fig. 1) have associated block-and-ash flows and avalanche and blast deposits indicative of smaller-scale explosive activity.

Attempts to correlate the spacing, size, compositional range, and tectonic setting of eastern Aleutian arc volcanic centers have been hampered by the lack of geological knowledge. When Marsh and Carmichael (1974) made a compilation of Aleutian arc volcanoes, for example, at least six Quaternary centers shown in Figure 1 were yet to be discovered, and few volcanoes of the Alaska Peninsula and Cook Inlet had been mapped in any detail. As additional mapping has become available, new volcanic centers have been identified, and some volcanoes previously considered separate entities have been identified as being part of a single eruptive center.

Volume. Obtaining meaningful figures for the volumes of volcanoes is difficult because of the erosion of deposits, the occurrence of calderas, the somewhat arbitrary classification into centers, and the cyclic eruptive character of many of the larger centers. However, approximate volumes have been estimated based on the regional geological mapping now available. Individual centers vary in size (Table 1) from small central-vent volcanoes, such as Yantarni with a volume of 6 km^3 (Riehle and others, 1987b), to large, long-lived, stratocone-caldera complexes such as Veniaminof, Emmons Lake, and Fisher (Table 1) that are probably cyclic in character and have volumes of 300 to 400 km^3. Most other volcanic centers have volumes generally less than 100 km^3. Volumes of individual volcanic centers in Katmai National Park are less meaningful, because the centers in this region are so close (in some cases overlapping) that it is difficult to determine what constitutes an individual center. Although Mount Spurr (3,375 m above sea level) and neighboring Redoubt (3,110 m) and Iliamna (3,075 m) are the highest volcanoes in the region, the actual height of each edifice is much less, since all three are built on a basement approximately 1,500 m high.

Marsh (1982) stated that the volume of the volcanic centers decreases from east to west along the Aleutian arc. He related this decrease to reduction in the rate of convergence between the Pacific and North American Plates. The largest volcanic centers in the arc, however, are actually in the 700-km-long segment between Umnak Island and Veniaminof volcano on the Alaska Peninsula (Fig. 2). Volcanic centers in the 770 km of arc east of Veniaminof and the 1,200 km of arc west of Umnak Island are smaller. The size of individual volcanic centers therefore seems not to be related in any simple way to plate convergence rates; rather, size is more apt to be due to a complex function of convergence angles and rates, crustal thickness and composition, and nature of the subducted material.

Spacing. Marsh and Carmichael (1974) and Marsh (1982) believed the Aleutian arc volcanoes had a rather regular spacing

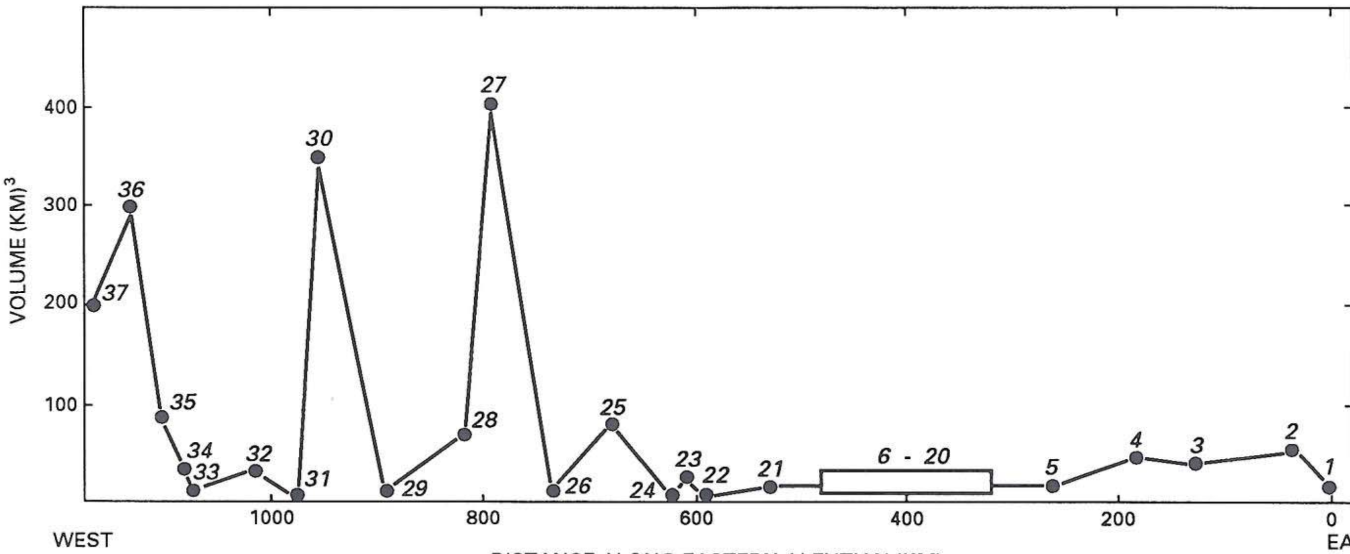

Figure 2. Approximate volumes of Alaska Peninsula–Cook Inlet volcanoes plotted against distance along Aleutian arc. Volcano numbers refer to Figure 1.

of 60 to 70 km, and Marsh (1979) commented on a segmentation of the arc based on the linear distribution of volcanoes. The spacing was thought to represent regularly spaced mantle plumes rising from melt developed at depths of 100 to 150 km along the strike of the subducted plate. Kay and others (1982) related segmentation of the arc to major tectonic breaks at the ends of rupture zones of major earthquakes. Kienle and Swanson (1983) recognized that segments of the easternmost part of the arc had different spacings. They noted a 70 ± 18-km spacing for Spurr-Redoubt-Iliamna volcanoes (excluding Hayes) in the Cook Inlet region, and a 13 ± 7-km spacing for volcanoes in the Katmai area.

Geological mapping in the area shows that spacing between centers varies considerably along this part of the Aleutian arc (Fig. 3). Some short "segments" of the arc indeed have a regular spacing between volcanic centers. The Kialagvik-Chiginagak-Yantarni volcanoes (Nos. 22 to 24, Fig. 1), for example, are almost exactly 18 km apart, and Aniakchak–Black Peak–Veniaminof centers (Nos. 25 to 27, Fig. 1) are almost exactly 54 km apart.

Distances between centers elsewhere in the region are much less regular. A 75-km-long arc segment in the Katmai area from Devil's Desk to Martin volcanoes (Nos. 9 and 19, Fig. 1) contains 11 closely spaced centers whose mutual relations are uncertain. S-wave shadowing beneath volcanoes in this region led Matumoto (1971) to infer two 10- to 20-km-wide, shallow (<10 km) magma chambers beneath volcanoes in the Katmai region and a third shallow chamber beneath Snowy volcano (No. 13, Fig. 1) 20 km to the northeast. Hildreth (1987, p. 692) has suggested that these chambers actually consist of dikes and sills that locally inflate into one or more pods of less than a few cubic kilometers of magma each. Some of the nine centers may therefore be hydraulically connected in a manner similar to that of Novarupta and Katmai. A 27-km-long arc segment extending southwest from Kupreanof volcano (No. 20, Fig. 1) includes a recently recognized group of at least five vents within a few kilometers of each other along the arc (Yount and others, 1985; Wilson, 1990); it is uncertain whether all these vents are part of the deeply eroded Kupreanof volcanic center, or represent additional centers. An "average" volcano spacing distance for the eastern Aleutian arc (and by inference the entire arc) would therefore appear to be relatively meaningless. It is more significant that various "segments" of the arc have quite different spacings between individual centers and that throughout the eastern Aleutian arc, the greatest distance between volcanic centers (the largest volcano-free segment) is the 94 km between Spurr and Redoubt (Nos. 2 and 3, Fig. 1).

Structural control. Many authors have suggested structural controls for the spacing of volcanoes. The Alaska Peninsula–Cook Inlet area is certainly a structurally complex and seismically active region characterized by broad open folds and normal, reverse, and thrust faults. Although crustal structure almost certainly influences where a volcanic center forms in a local area, recent 1:250,000-scale geological mapping (Detterman and others, 1981, 1987; Riehle and others, 1987a) indicates no single overriding crustal structural control of volcano spacing. Some individual volcanic centers, or clusters of centers, can be correlated with specific crustal structural features. Examples are the occurrence of Chiginagak and Kialagvik volcanoes on the Wide Bay anticline and Yantarni volcano on the trace of a prominent fault extension of the anticline (Detterman and others, 1987). On the other hand, the 560-km-long Bruin Bay fault is one of the

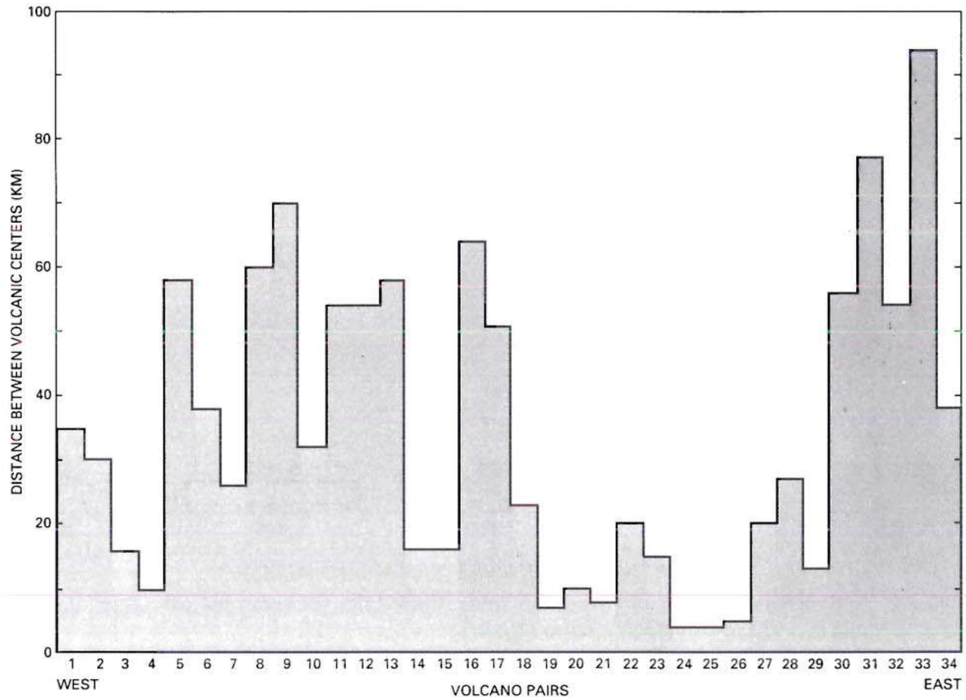

Figure 3. Distances between major volcanic centers in the Alaska Peninsula and Cook Inlet region. Volcano pairs and distance (km) are as follows: 1, Westdahl (Pogromni)-Fisher (35); 2, Fisher-Shishaldin (30); 3, Shishaldin-Isanotski (16); 4, Isanotski-Round Top (10); 5, Round Top–Frosty (58); 6, Frosty-Dutton (38); 7, Dutton–Emmons Lake (26); 8, Emmons Lake–Dana (60); 9, Dana-Kupreanof (70); 10, Kupreanof-Veniaminof (32); 11, Veniaminof–Black Peak (54); 12, Black Peak–Aniakchak (54); 13, Aniakchak-Yantarni (58); 14, Yantarni-Chiginagak (18); 15, Chiginagak-Kialagvik (18); 16, Kialagvik-Ugashik (64); 17, Ugashik-Kejulik (51); 18, Kejulik-Martin (23); 19, Martin-Mageik (7); 20, Mageik-Trident (10); 21, Trident-Katmai (8); 22, Katmai-Snowy (20); 23, Snowy-Denison (15); 24, Denison-Stellar (4); 25, Stellar-Kukak (4); 26, Kukak–Devils Desk (5); 27, Devils Desk–Kaguyak (20); 28, Kaguyak-Fourpeaked (27); 29, Fourpeaked-Douglas (13); 30, Douglas-Augustine (56); 31, Augustine-Iliamna (77); 32, Iliamna-Redoubt (54); 33, Redoubt-Spurr (94); 34, Spurr-Hayes (38). Note: Volcanoes such as Novarupta, Griggs, Ukinrek, and Amak (Simkin and others, 1981) lie north of the axis of the volcanic front and are not included in this pairing. The distance between Dana and Kureanof volcanoes is measured from the western most of the Holocene vents associated with the Kupreanof center.

major structural features of the region, and although a few volcanoes (Redoubt, Iliamna, Nos. 3 and 4, Fig. 1) are on or near the fault and its possible extension, the great majority of volcanic centers show little apparent relation to it.

Nakamura and others (1977) considered the small monogenetic volcanoes on the flank of the Veniaminof center to be aligned along regional stress fractures that developed normal to the trend of the volcanic arc as a result of regional compression in the direction of plate convergence. The volcanic activity marking this trend is chiefly Holocene in age, but a prominent dike swarm developed only in the older cone-building rocks of the center has the same orientation, suggesting that similar stress patterns extended further back in the Quaternary.

Composition

Over 500 major-element chemical analyses of the Quaternary volcanic rocks of the eastern Aleutian arc have recently been obtained. Many volcanic centers, however, have been sampled only in reconnaissance, and we have little detailed knowledge of their stratigraphy or compositional range. For this reason, approximately 330 analyses from ten of the better mapped volcanic centers in the area have been used for the summary presented in this report; at least 15 analyses were available from each of these centers. The following classification of volcanic rocks based on normalized SiO_2 content was used (similar to that adapted by Luedke and Smith, 1986): basalt <54 percent SiO_2, andesite 54

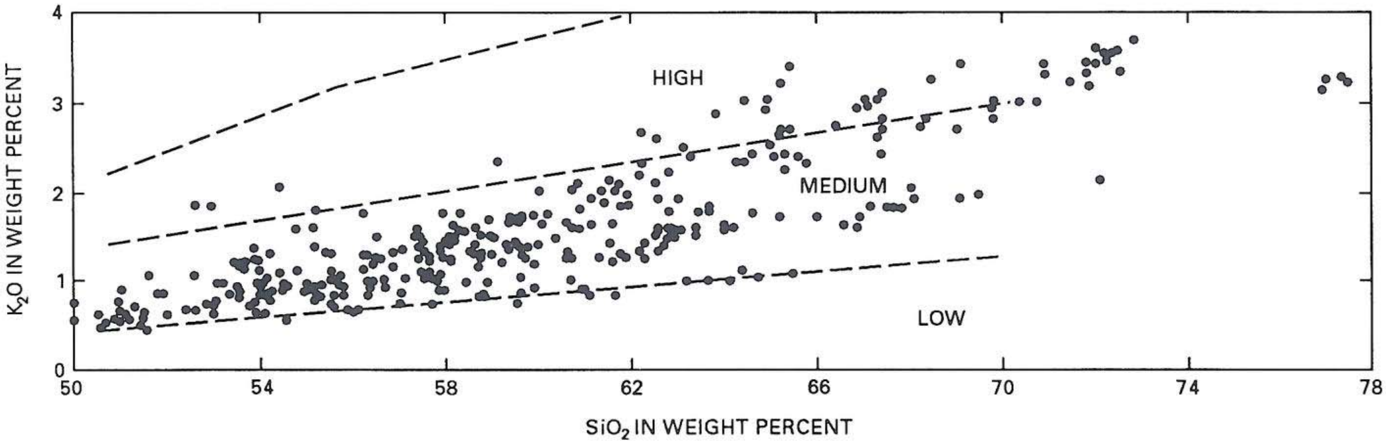

Figure 4. Plot of K_2O versus SiO_2 for 330 analyses from ten Alaska Peninsula and Cook Inlet (AP-CI) volcanoes. Data are from following volcanoes: Spurr, Redoubt, Iliamna, Augustine, Novarupta, Peulik-Ugashik, Yantarni, Aniakchak, Veniaminof, and Emmons Lake. Discriminant lines separating High, Medium, and Low are modified from Pecerrillo and Taylor (1976) and Ewart (1179).

to 62 percent SiO_2, dacite 62 to 70 percent SiO_2, and rhyolite >70 percent SiO_2.

The SiO_2 content ranges from 50 to 78 percent (Fig. 4). Most of the cone-building volcanic rocks, however, consist predominantly of andesite and low-SiO_2 dacite with a SiO_2 range of 55 to 64 percent; basalts (<54 percent SiO_2) are less common in this part of the arc. Rhyolite (>70 percent SiO_2) is known to be present only in ash-flow tuffs and post-caldera domes at the Ugashik-Peulik, Aniakchak, and Emmons Lake centers (Nos. 21, 25, and 30, Fig. 1) and in the Valley of Ten Thousand Smokes. High-SiO_2 (>75 percent) rhyolite is found in ejecta from the 1912 eruption and in the associated Novarupta dome, and nowhere else on the Alaska Peninsula. A composition gap of 72 to 77 percent SiO_2 between the high-silica rhyolite and volcanic rocks from other Alaska Peninsula–Cook Inlet centers is apparent in Figure 4 and attests to the uniqueness of the rhyolite. Hildreth (1983, 1987) has noted a SiO_2 compositional gap of 66 to 77 percent in the 1912 ejecta. Some small stratocones and dome complexes (Augustine, Black Peak, and Dana, Nos. 5, 26, and 29, Fig. 1) are composed almost entirely of andesite and dacite with small SiO_2 ranges of 57 to 63 percent.

Alkaline volcanic rocks appear to be restricted to a back-arc environment consisting of a belt of widely separated small monogenetic centers that subparallels the main andesitic arc for at least 800 km from the Ukinrek maars, near Becharof Lake on the Alaska Peninsula, west to Bogoslof Island in the Bering Sea (Fig. 1).

Radiogenic isotope data from Alaska Peninsula and Cook Inlet volcanic rocks is relatively sparse. Kay and others (1978) report $^{87}Sr/^{86}Sr$ ratios (SIR) ranging from 0.70305 to 0.70325 and from 0.70309 to 0.70334 from Veniaminof and Aniakchak volcanoes respectively. These ratios are similar to the 0.70368 SIR reported from Katmai volcanoes (Rubenstone and others, 1985; Hildreth, 1987) but lower than the 0.7040 to 0.7046 SIR range reported from Redoubt volcano by Bevier and Wheeler (1983). The SIR from Alaska Peninsula and Cook Inlet volcanic rocks are similar to the 0.70289 to 0.70342 values reported by McCulloch and Perfit (1981) from the western oceanic part of the Aleutian arc. As Hildreth (1987) has pointed out, however, the radiogenic isotopic data presently available are too limited to adequately determine the proportions of mantle, slab, and intracrustal contributions to andesitic magma, and more isotopic studies are needed.

Variations in potassium content of volcanic rocks, particularly andesites, are thought to have tectonic as well as petrogenetic significance (Gill, 1981). Andesites of the Alaska Peninsula–Cook Inlet region are medium-K (Fig. 4) on K_2O vs. SiO_2 plots (Taylor, 1969; Ewart, 1979), typical of many arc suites, and average 1.27 percent K_2O at the 57.5 percent SiO_2 reference level.

Kay and others (1982) recognized both tholeiitic and calc-alkaline differentiation trends in the oceanic part of the Aleutian arc on the basis of the change of FeO*/MgO ratio with SiO_2 (Miyashiro, 1974). This ratio increases with SiO_2 in tholeiitic centers but remains approximately constant in calc-alkaline centers.

Iron-enrichment plots of the Alaska Peninsula and Cook Inlet volcanoes (Fig. 5) exhibit calc-alkaline, tholeiitic, and transitional trends similar to those seen in the western part of the arc by Kay and others (1982). Only the westernmost two of the ten reference centers (Emmons Lake and Veniaminof), however, are tholeiitic; all the reference centers to the east are calc-alkaline, although Aniakchak is somewhat transitional in character (Fig. 5). The calc-alkaline character of eastern Aleutian arc volcanic rocks, first noted by Kienle and Swanson (1983), is thus extended through much of the Alaska Peninsula. The easternmost 30 percent (770 km) of the Aleutian arc therefore appears to be characterized by calc-alkaline magmatism, with few if any tholeiitic suites.

Conflicting views for the origin of calc-alkaline and tholeiitic magmas are discussed by Kay and Kay (this volume) and Myers and others (1985). Kay and Kay argue that these compositional differences result from processes in the Aleutian crust that are controlled by the tectonic setting of the volcano. Magma encountering crust that is under relative extension passes quickly through it and crystallizes at low pressures with little opportunity for intracrustal magma fractionation and mixing, resulting in tholeiitic centers. Magma encountering crust under relative compression, however, passes slowly through it and undergoes crystallization and mixing at greater crustal depths, resulting in calc-alkaline centers. Calc-alkaline centers would therefore form in the middle of tectonically controlled arc segments, and tholeiitic centers would form at segment boundaries, or in areas where segments are not well defined. The tectonic segments themselves are separated by rupture zones defined chiefly by the distribution of aftershocks following great earthquakes.

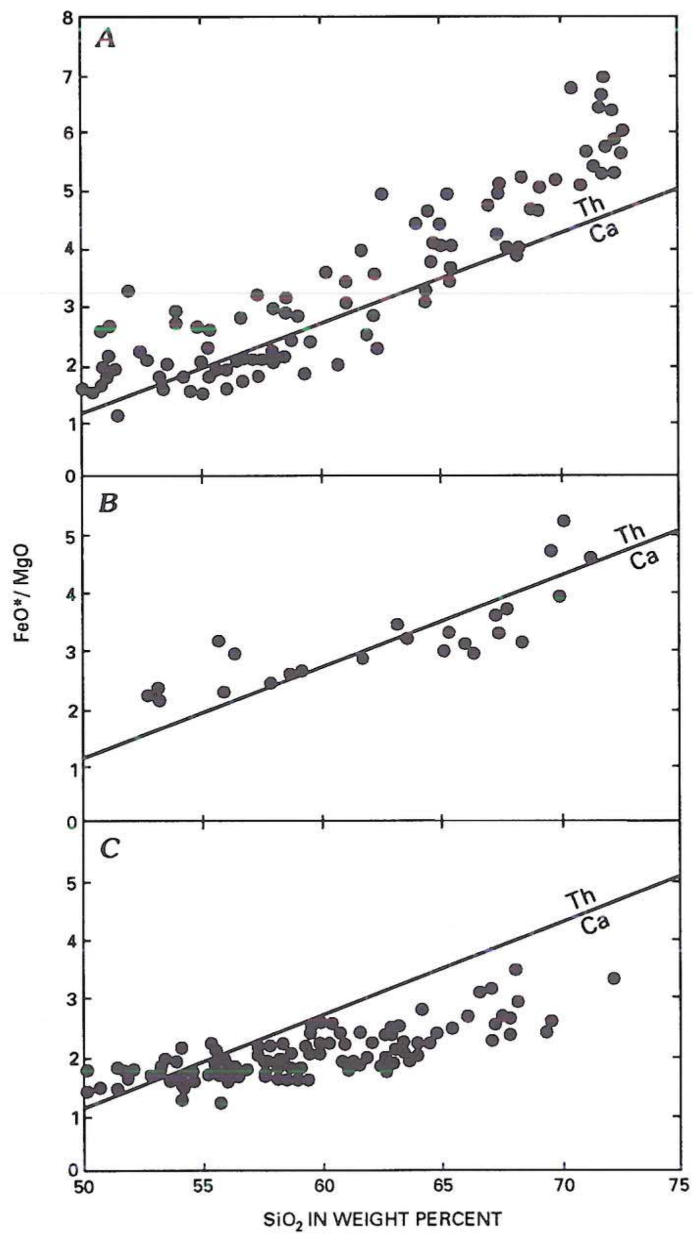

Figure 5. Plot of FeO*/MgO versus SiO_2 for the tholeiitic Veniaminof-Emmons Lake center, the transitional Aniakchak center, and the remaining calc-alkaline centers of the Alaska Peninsula–Cook Inlet (AP-CI). Data base is the same as Figure 2. Line separates tholeiitic/calc-alkaline plots from Miyashiro (1974).

Myers and others argue that calc-alkaline centers form in an early immature stage of conduit development, when mantle is incorporated in the magma during transit through the lithosphere. The volcanic center is transformed into a tholeiitic center over time as the conduit is thermally and chemically preconditioned and no longer contaminates the magmas.

Although the origin of calc-alkaline in contrast to tholeiitic magmatic trends is not the subject of this chapter, it is of interest that the conflicting theories were derived chiefly from studies of the western oceanic part of the Aleutian arc. The present study of the continental half of the arc indicates that the easternmost one-third of the entire Aleutian arc is characterized solely by calc-alkaline volcanic centers. Fisher and others (1981) and Kienle and Swanson (1983), however, consider this part of the arc to be segmented as is the oceanic part of the arc. Both parts show a variation in spacing and alignment of centers and aftershock rupture zones. Tectonic segmentation, therefore, does not appear to have influenced compositional trends (e.g., tholeiitic versus calc-alkaline) of individual centers, and the chemical diversity observed among volcanic centers in the oceanic part of the arc is lacking.

The change in compositional trends does not occur where the Aleutian arc intersects the continent west of Unimak Island but rather is 500 km to the east between Veniaminof and Black Peak volcanoes. This area is the same as the one in which a change in the character of post-caldera volcanism in the eastern Aleutian arc occurs (Miller and Smith, 1983). From Fisher to Veniaminof, post-caldera volcanism is mafic, whereas from Black Peak to Kaguyak, post-caldera volcanism is intermediate to silicic. The abrupt change in two different compositional trends in the same area suggests a common cause, which we believe is related to the nature and extent of continental crust. Kienle and Swanson (1983) suggested that the thickness of continental crust seems to control calc-alkaline versus tholeiitic differentiation trends in the Cook Inlet and Katmai regions—a suggestion we think may hold true for most of the Alaska Peninsula. The continental crust east of Veniaminof volcano may be thick and extensive enough to inhibit the easy passage of magma in spite of tectonic segmentation. Magma fractionation and mixing thus took place and resulted in calc-alkaline magmatic differentiation, similar to that proposed by Kay and Kay. However, crustal thickness figures are not well constrained beneath the Alaska

Peninsula. The thickness of the crust has been estimated to be 38.5 km in the vicinity of the Emmons Lake center on the lower Alaska Peninsula (see McNutt and Jacob, 1986, Fig. 3) and 30 to 35 km in the Katmai region (Kienle and Swanson, 1983). The exact nature of crustal changes (e.g., thickness) northeast of Veniaminof volcanic center remains to be worked out.

WRANGELL VOLCANIC FIELD

The Wrangell volcanic field of Miocene to Holocene age occurs chiefly in south-central Alaska, between 61°15′ and 62°40′N and 141° and 145°W (Fig. 6). Scattered remnants of the field extend into the Yukon Territory, as far south and east as 60°N and 136°W (Campbell and Dodds, 1985). In Alaska the Wrangell volcanic field covers as much as 10,000 km^2, including most of the high country of the Wrangell and St. Elias Mountains and parts of the contiguous eastern Alaska Range. Eight peaks are higher than 4,000 m, including Mt. Bona (5,005 m), the highest peak in the region. The central and western parts of the Wrangell volcanic field have received considerable attention in recent years, but the easternmost part has been mapped only in reconnaissance. Because of this general lack of information, short discussions of individual Quaternary volcanic centers are included in this report.

Wrangell volcanoes differ from those found elsewhere along the circum-Pacific margin because of their extremely large size (Table 2), their shield-like form and apparent nonexplosive summit calderas, and the highest eruptive rate yet reported for convergent plate margins (Nye, 1983).

Geologic setting

Almost all of the Wrangell volcanic field is on the Wrangellia terrane (Jones and others, 1987; Silberling and others, this volume), a major tectonostratigraphic terrane in south-central Alaska consisting of sedimentary and volcanic rocks that range in age from Pennsylvanian to Cretaceous (MacKevett, 1978; Richter, 1975). A small part of the extreme southeast end of the field overlies the Alexander terrane (Silberling and others, this volume), which is composed chiefly of lower to middle Paleozoic sedimentary rocks (MacKevett, 1978). Figure 6 shows the approximate boundary of the Wrangell volcanic field, the extent of perennial snow and ice cover, and the known major eruptive centers. Because of the extensive cover of snow and ice, geological field investigations have been extremely difficult over large parts of the area.

The Wrangell volcanic field and the Aleutian volcanic arc are separated by about 400 km (Fig. 7); the reason for the gap is not clear. Jacob and others (1977) pointed out that this is a region of relatively shallow subduction, and similar regions elsewhere in the circum-Pacific (e.g., the Peru-Chile subduction zone) are marked by gaps in active volcanism (Barazangi and Isacks, 1976). Cross and Pilger (1982) attributed the gap to low-angle subduction of relatively buoyant lithosphere, following subduction of an intraplate island-seamount chain.

Plafker (1969, 1987) has long believed that the Wrangell volcanic field is part of the Aleutian arc because of the seismicity and coseismic deformation associated with the 1964 Alaska earthquake in the area south of the 400-km gap, and because of similarities in composition and age between the Aleutian and Wrangell volcanoes. However, only recently has a Benioff zone associated with the Wrangell volcanic field been confirmed (Stephens and others, 1984). This seismically weak zone is subparallel to the general trend of the Wrangell volcanic field and is nearly normal to the trend of the Benioff zone under the northeasternmost segment of the Aleutian arc (Fig. 7; Stephens and others, 1984; Plafker, 1987). The gap between the Aleutian arc and the Wrangell volcanic field and the apparent misalignment of their Benioff zones may be due to some form of dextral shear along this complex plate boundary.

There is no evidence in marine seismic reflection data of any significant subduction of Pacific oceanic crust under the eastern Gulf of Alaska continental margin since the late Cenozoic (von Huene and others, 1979; Bruns, 1979), although weak seismicity between the Yakutat terrane and the Pacific Plate requires some relative motion along the boundary (Lahr and Plafker, 1980; Plafker, 1987). The Wrangell volcanic field lies north of the Gulf of Alaska on the Wrangellia terrane and inboard of the Yakutat terrane (Silberling and others, this volume), both of which are probably partially coupled to the Pacific Plate (Lahr and Plafker, 1980). In his model of the Cenozoic evolution of the Gulf of Alaska, Plafker (1987) suggests that Wrangell volcanism began about 20 to 25 Ma, following the subduction of about 225 km of the Yakutat terrane beneath the continental margin. Not fully understood, however, has been the continued voluminous outpouring of lava from the Wrangell volcanoes into Quaternary time.

Although the elongate Wrangell volcanic field roughly parallels the structural grain of the underlying basement rocks, no evidence suggests that individual eruptive centers of the field are structurally controlled. The generally older eastern part of the field may be offset 10 to 15 km by the Totschunda fault system (Figs. 6, 7)—a major Quaternary dextral strike-slip structure (Richter and Matson, 1971) related to the Denali fault. However, the fault system does not appear to have affected the location of contemporary volcanic activity. Moreover, there appears to be no pronounced alignment of volcanoes, as in the case of the Alaska Peninsula–Cook Inlet region, nor is there any obvious systematic spacing observed between volcanoes. The presently available data therefore suggest that the volcanic centers are randomly distributed throughout the Wrangell volcanic field.

Age and eruptive activity

Although only a scattering of K-Ar ages are available for the entire Wrangell volcanic field, the data indicate a general progression of eruptive activity from east to west across the field (Fig. 6). In the extreme western part, the known volcanoes are 1 m.y. old or younger (Richter and others, 1979; Nye, 1983); Mt. Wrangell,

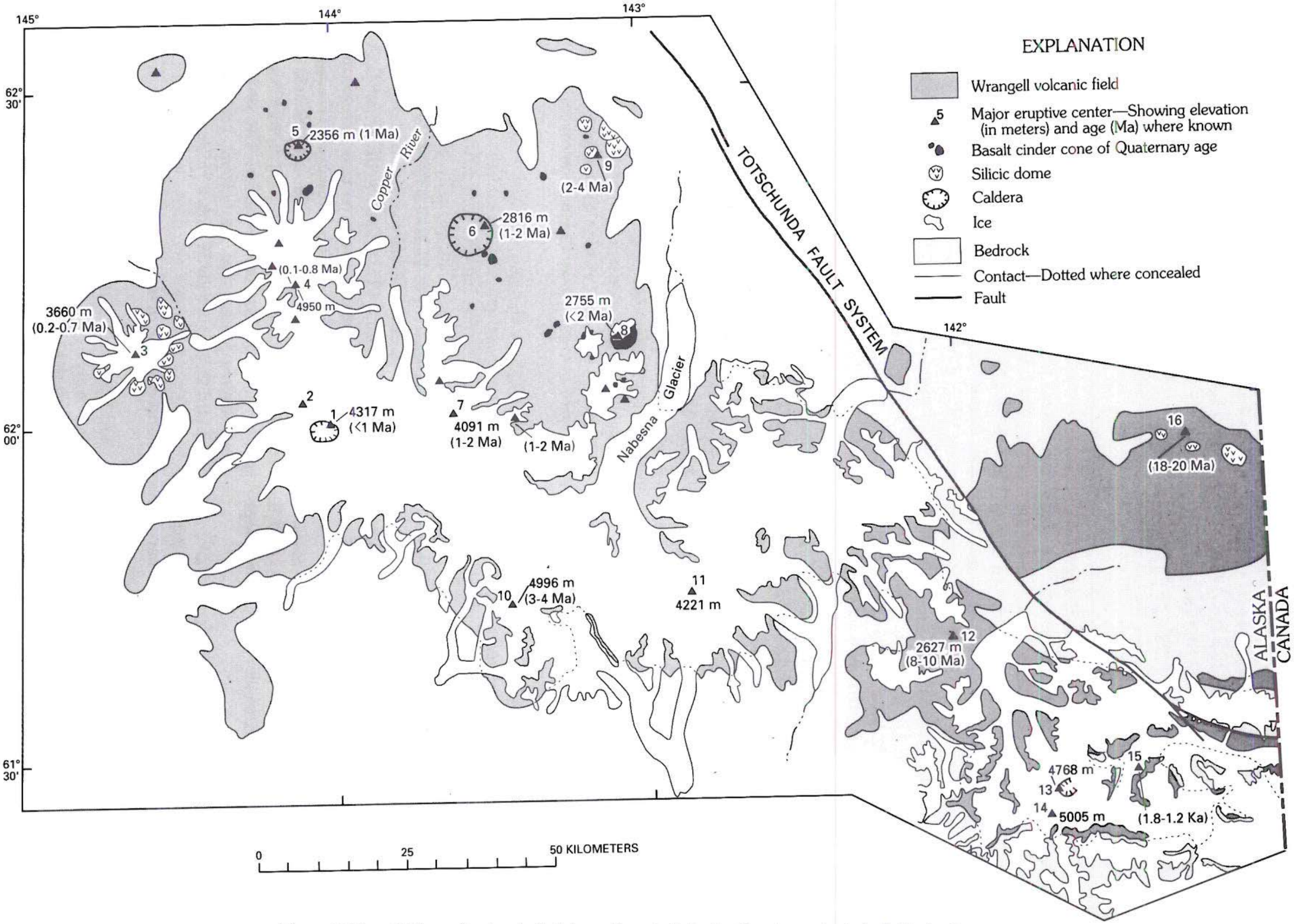

Figure 6. Map of Wrangell volcanic field in south-central Alaska. Numbers refer to individual volcanoes as follows: 1, Wrangell; 2, Zanetti; 3, Drum; 4, Sanford; 5, Capital; 6, Tanada; 7, Jarvis; 8, Gordon; 9, Skookum Creek; 10, Blackburn; 11, Regal; 12, Castle; 13, Churchill; 14, Bona; 15, White River Ash source; 16, Sonya Creek.

TABLE 2. PHYSICAL CHARACTERISTICS OF THE PRINCIPAL QUATERNARY VOLCANOES, WRANGELL VOLCANIC FIELD

Volcano	Location	Elevation (m)	Age (ma)	Height (km)	Diameter (km)	Estimated vol (km^3)*
Wrangell	62.0°N 144.0°W	4,317	0–0.1	2.5	40	1,000
Drum	62.1°N 144.6°W	3,661	0.2–0.6	2.7	27	500
Sanford†	62.2°N 144.1°W	4,949	<1	3.1	34	900
Capital	62.4°N 144.1°W	2,356	1	1.3	18	100
Tanada	62.3°N 143.5°W	2,852	1–2	1.6	22	200
Jarvis	62.0°W 143.6°W	4,091	1.2	--------	Poorly defined	--------
Gordon	62.1°N 143.1°W	2,755	<2	0.6	5	4

*Volume estimated on basis of simple cone.
†Includes the north, west, and south Sanford eruptive centers.

in fact, has a large fumarolic area near its summit and is the only volcano in the field with reported historic activity. Through the central parts of the field, ages range between 1 and 5 Ma (Lowe and others, 1982; Richter and Smith, 1976), and in the east they range from 8 to 20 Ma (J. G. Smith, written communication, 1986). A significant exception to this progression of activity was the eruption of the White River Ash of Lerbekmo and others (1968) from a vent near the Alaska-Yukon border that occurred during two major events about 1,890 and 1,250 B.P. (Lerbekmo and others, 1975). This ash blanketed about 300,000 km^2 of eastern Alaska and western Canada. Other possible exceptions are Mt. Bona and Mt. Churchill near the east end of the Wrangell volcanic field, whose height and shape suggest young primary constructional forms.

Physical volcanology

The volcanic rocks of the Wrangell volcanic field are collectively referred to as the Wrangell Lava (Mendenhall, 1905). They consist predominantly of subaerial, or locally subglacial, lava flows and minor lahars, domes, pyroclastic rocks, dikes, and small subvolcanic intrusions. Thick and extensive piles of flat-lying to gently dipping lava flows, chiefly andesitic, characterize much of the field. Dacite to rhyolite domes are associated with a number of eruptive centers, such as Mt. Drum volcano and the Skookum Creek and Sonya Creek eruptive centers (Fig. 6), but are apparently absent from large areas of the Wrangell volcanic field. Bedded tephra, chiefly andesitic to basaltic, is relatively common and is interlayered with flows throughout the field, but pyroclastic flow deposits are rare. Poorly welded silicic ash-flow tuffs are present west of Mt. Wrangell interlayered with glacial deposits of the Copper River basin, and small volumes of pumiceous pyroclastic flow deposits are present in the Sonya Creek and Skookum Creek centers. With the exception of Mt. Drum—an apparent stratocone—and possibly Mt. Bona and Mt. Churchill—large snow-covered volcanic cones(?) at the east end of the field—the major volcanic structures appear to have been large shield volcanoes similar in form to the present shield of active Mt. Wrangell.

The three known shield volcanoes in the Wrangell volcanic field—Wrangell, Capital, and Tanada—have summit calderas that range in diameter from 4 to 8 km. The apparent absence of associated large-volume pyroclastic flow deposits suggests that these calderas had a nonexplosive origin. In addition to the larger volcanic constructional forms, more than 27 small (generally <2 km in diameter) cinder cones composed of basalt to basaltic andesite are found throughout the northwestern part of the field, especially between Mt. Drum and the Nabesna Glacier-River system (Fig. 6). These cones, many of which retain their original physiographic form, are probably all late Pleistocene and Holocene. They consist mostly of cinder, bombs, and spatter; short small-volume flows are associated with some of the larger cones. Mt. Gordon, largest of these young basaltic cones, is described below in more detail.

Volcano description

Some of the physical characteristics of the six principal Quaternary volcanoes and one large cinder cone in the Wrangell volcanic field (WVF) are shown in Table 2. In the following

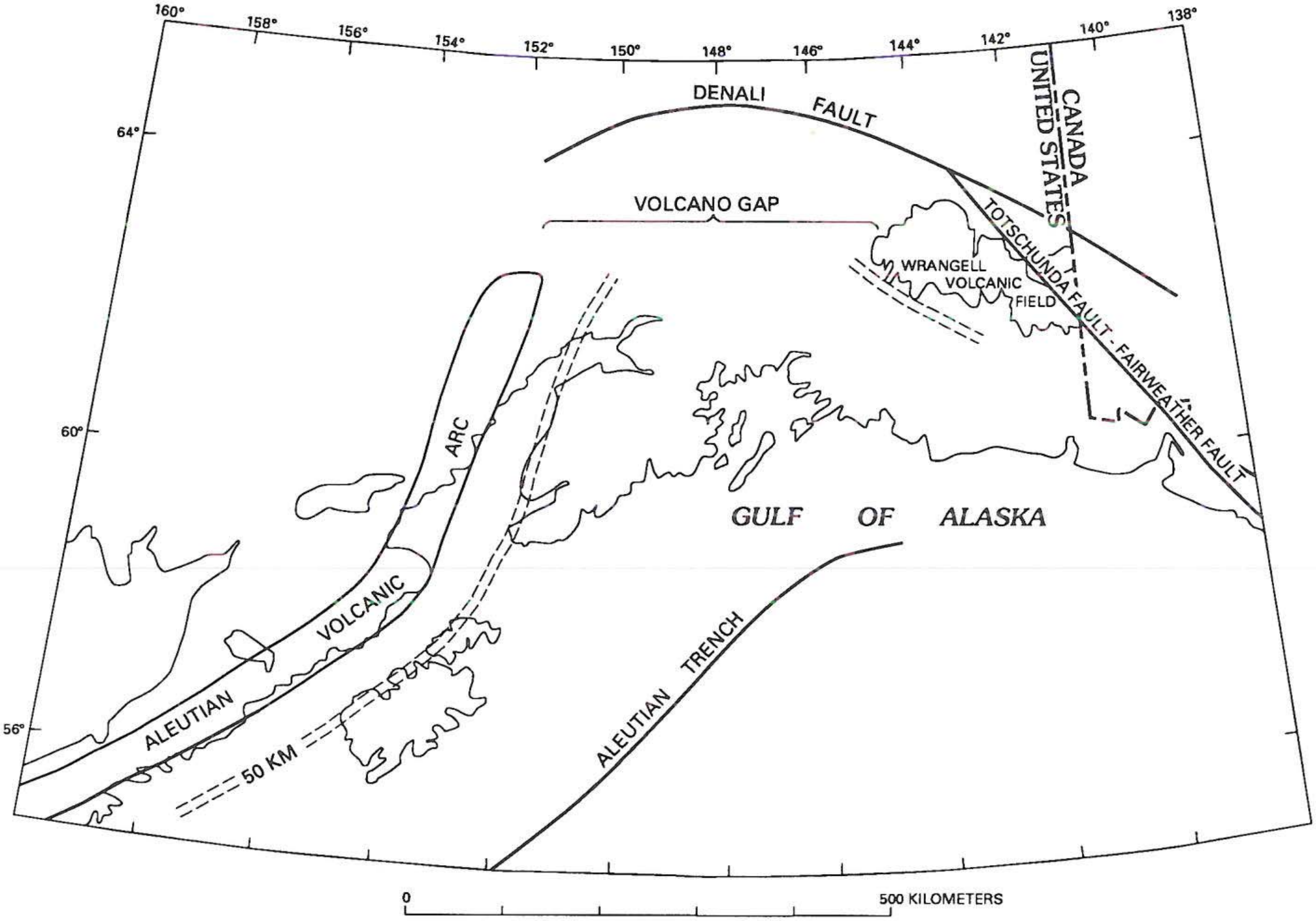

Figure 7. Map of southern Alaska showing location of Aleutian volcanic arc, Wrangell volcanic field, volcano gap, and principal regional tectonic features (modified from Lahr and Plafker, 1980). DF, Denali fault; TF, Totschunda fault; FF, Fairweather fault; AT, Aleutian trench; dashed double line, 50-km isobath of Benioff zone.

section, these volcanoes, together with a few eruptive centers that may be as young as 2 Ma, are described briefly in order of increasing age.

White River Ash. The White River Ash of Lerbekmo and others (1968) and Capps (1915) consists of two large rhyodacitic tephra lobes containing at least 25 km^3 of ejecta and covering more than 300,000 km^2 in eastern Alaska and the Yukon Territory (Lerbekmo and Campbell, 1969). The tephra was deposited during two major volcanic eruptions, 1,890 and 1,250 B.P (Lerbekmo and others, 1975). Source of the ash (Fig. 6) is believed to have been a vent now covered by the Klutlan Glacier about 22 km west of the Alaska–Yukon Territory border (Lerbekmo and Campbell, 1969) and within a few kilometers of a 200-m-high coarse pumice mound adjacent to the glacier. An alternative source may be snow-covered Mt. Churchill, about 10 km farther to the southwest, which has an apparent summit caldera 3 km in diameter that is filled with ice.

Mount Wrangell. This large, active, andesitic shield volcano is indented by a 4- by 6-km ice-filled summit caldera. Three small (<1 km) post-caldera craters, all geothermally active, lie along the west and north rims of the caldera (Benson and Motyka, 1978). Mt. Zanetti—a large (450 m high) undissected parasitic cinder-spatter cone on the northwest flank of the shield, and possible source area for many flank flows—is probably younger than the latest glaciation. The bulk of Wrangell volcano was probably constructed between 0.3 and 0.6 Ma (D. H. Richter, unpublished data; Nye, 1983); however, some of the upper parts may be as young as 0.1 Ma. A lava flow, probably erupted from the summit area, has been dated at 80 ka (Nye, 1983), and the summit caldera may be as young as Holocene (Benson and Motyka, 1978). Nye (1983) believes that the modern Wrangell volcano is built on an older (1 to 2 Ma) dissected center which he refers to as the Chetaslina vent.

Mt. Drum. Mt. Drum is the westernmost volcano in the Wrangell volcanic field. Unlike its neighbors—Sanford, Wrangell, and Capital—it appears to have been more of a composite stratocone than a shield volcano (Richter and others, 1979). It was constructed between about 0.6 and 0.2 Ma (G. B. Dalrymple and M. A. Lanphere, unpublished data) during at least two cycles of cone building and ring dome extrusion (Richter and others, 1979). The first cycle began with the development of an andesitic to dacitic cone and culminated with the emplacement of a series of rhyolite ring domes. The second cycle of activity, followed without an apparent time break and continued to build the cone, but with more silicic lavas, and was accompanied by the emplacement of an early and late series of dacite ring domes. Following the second cycle, but with magma still available, violent explosive activity, apparently from the central vent area, destroyed a large part of the south half of the cone and deposited hot and cold volcanic avalanche debris over an area probably greater than 200 km^2.

Mt. Sanford. Perennial snow and ice almost completely cover Mt. Sanford, a bulbous-topped broad shield(?) volcano. Geological mapping (D. H. Richter, unpublished data) indicates that the upper parts of the volcano are built upon the coalescing flows from at least three main eruptive vents, referred to as the north, west, and south Sanford centers (Fig. 6). Aerial observations of the spectacular 2,500-m-high southwest wall of Mt. Sanford reveal that the bulbous top is composed of a massive 500-m-thick flow or dome that overlies a few hundred meters of flat-lying flows or pyroclastic deposits, which in turn overlie more than 1,500 m of andesitic flows and breccias cut by numerous dikes. Andesitic flows from the base of the west Sanford eruptive center have yielded K-Ar ages of 0.7 and 0.8 Ma (G. B. Dalrymple and M. A. Lanphere, unpublished data).

Capital Mountain. Capital volcano is a relatively small andesitic shield volcano with a roughly circular summit caldera 4 km in diameter. The shield consists of andesitic lava flows and lesser intercalated laharic rocks and pyroclastic deposits that dip gently away from the summit area. The caldera, with walls dipping 50° to 80° inward, is filled with flat-lying massive andesitic flows having an aggregate thickness of more than 450 m. A prominent andesite plug, 100 m high, intrudes the intracaldera lavas and forms the locus of a spectacular radial dike swarm. The hundreds of dikes are chiefly andesitic, but a few dikes are dacitic and rhyolitic. One large rhyolite dike extends westward about 10 km across the shield and caldera from a rhyolite laccolith on the east flank of the shield. K-Ar ages of the shield lavas and dikes are dated at about 1 Ma (Richter and others, 1984, 1989).

Tanada Peak. Tanada volcano, a somewhat larger and older version of neighboring Capital volcano, is an andesitic shield covering an area of more than 400 km^2. Much of the original andesitic shield has been stripped away, leaving the intracaldera flows as the high topographic features of the structure. Remaining shield lavas consist chiefly of andesitic lava flows and lesser laharic and pyroclastic deposits that dip gently away from the summit area. The summit caldera, approximately 8 km long by 6 km wide, is filled with massive flat-lying andesitic flows and dacitic agglutinates at least 900 m thick. The caldera walls consist mostly of pre-Tanada (2 to 3 Ma) flows, are less steep than at Capital volcano, and locally are mantled by thin pyroclastic airfall beds. A few dikes intrude the structure, and a chain of younger andesitic to basaltic andesite cinder cones covers parts of the volcano's north flank. K-Ar ages indicate that the volcano was built between 1 and 2 Ma (Richter and others, 1984).

Mt. Gordon. This is the largest of the young (<1.5 Ma) basalt-basaltic andesite cinder cones that are common in the northwestern part of the Wrangell volcanic field. The cone of Mt. Gordon, about 5 km in diameter and 600 m high above its base of older Wrangell Lava, also erupted a significant volume of basaltic lava flows (Richter and Smith, 1976).

Mt. Jarvis. This mountain is the high point of a slightly curvilinear, north-trending, 10-km-long, 4,000-m-high ridge. The snow- and ice-covered ridge is composed of a thick sequence of dacitic and andesitic lava flows and capped by either a massive dacite flow or by a series of smaller dacite domes. One K-Ar age on basal (?) Jarvis flows suggests an age of about 1.6 Ma (Richter and Smith, 1976).

Skookum Creek. The Skookum Creek eruptive center is an erosionally dissected complex that may, in part, be as young as Quaternary. It consists principally of a series of rhyolite, rhyodacite, and andesite domes and their associated pyroclastic deposits, with an age of about 3.7 Ma, and an extensive sequence of relatively flat-lying andesite flows, some of which have been dated at 2.8 Ma (Lowe and others, 1982). Both the domes and the flows are intruded by a few rhyodacite and andesite dikes that appear to originate from a rhyodacite dome near the center of the complex. Relations between the volcanic units of the complex suggest that the flat-lying flows fill a caldera that is defined by the crude arcuate alignment of the domes.

Mt. Blackburn. The second highest peak in the Wrangell Mountains, Mt. Blackburn may be part of a large exhumed caldera (Winkler and Mackevett, 1981). The mountain is composed of 3- to 4-Ma plutonic rocks (J. G. Smith, unpublished data) that intrude, and possibly are overlain by, Wrangell Lava.

Mt. Bona and Mt. Churchill. Both Mt. Bona and Mt. Churchill are high snow- and ice-covered mountains in the eastern part of the Wrangell volcanic field. They appear to be relatively young constructional forms. Mt. Bona, the highest peak (5,005 m) in the Wrangell Mountains, may be a small stratocone built upon a high platform of Pennsylvanian and Lower Permian rocks (MacKevett, 1978). Mt. Churchill appears to have a 3-km-diameter caldera on its summit and, as mentioned earlier, may be an alternative source of the White River Ash.

Composition

Available major-element chemistry for the volcanic rocks of the Wrangell volcanic field indicates a range of 50 to 74 percent

SiO_2 (Fig. 8)—a compositional spread similar to that exhibited by the volcanic rocks in the Alaska Peninsula and Cook Inlet part of the Aleutian arc but lacking the high-silica rhyolites of the Valley of Ten Thousand Smokes. The volcanic rocks from both the Quaternary and older volcanoes in the Wrangell volcanic field have medium-K, calc-alkaline affinities (Fig. 8) typical of volcanoes associated with lithospheric plate interactions around the circum-Pacific tectonic belt. Unlike the volcanoes on the oceanic segment of the Aleutian arc and western Alaska Peninsula–Cook Inlet, no pronounced tholeiitic affinities are shown by the Wrangell volcanic rocks, although a few flows from Mt. Sanford appear to have tholeiitic tendencies (Fig. 9). At 57.5 percent SiO_2, the andesites contain an average of 1.44 percent K_2O (Fig. 8), which is somewhat, but probably not significantly, higher than the andesites of the Alaska Peninsula–Cook Inlet. Figure 9 also shows that, in general, Mt. Drum rocks have a low FeO*/MgO ratio, in contrast to other volcanic rocks in the Wrangell volcanic field—a feature that undoubtedly resul;ts from the abundance of olivine-rich (and hence MgO-rich) andesites and dacites from this volcano.

SUMMARY

The Aleutian arc and the Wrangell volcanic field, although separated by about 400 km, are both related to the underthrusting of the Pacific Plate beneath a collage of tectonostratigraphic terranes that make up the continental margin of southern Alaska. Volcanoes of both volcanic provinces are similar in composition and age but vary greatly in eruptive behavior and physical form. Quaternary volcanism in the region has resulted in some of the largest, most active, and most explosive volcanoes found along the entire circum-Pacific margin. The 1912 eruption of about 35 km^3 of tephra from the Novarupta vent complex in Katmai National Park, for example, was the most voluminous rhyolitic eruption in the past 1,800 years and has been called the most important igneous event of this century.

Aleutian arc Quaternary volcanism in the Alaska Peninsula–Cook Inlet region is defined by 37 major volcanic centers spread along 1,200 km of a seismically active arc-trench system. Over 100 eruptions have been reported from 19 centers since 1760, and more than half of the centers still show fumarolic activity. Eastern Aleutian centers were formed entirely on continental crust. Potassium-argon ages indicate that the centers were formed within the past million years.

Most Alaska Peninsula–Cook Inlet volcanoes are typical stratocones consisting of intercalated lava flows and volcaniclastic rocks, and are marked by summit craters and calderas. Caldera-forming eruptions with bulk ejecta volumes as large as 50 km^3 have occurred at eight of the volcanic centers on the Alaska Peninsula in late Pleistocene and Holocene time; 20 to 30 percent of known Holocene eruptions of this magnitude worldwide are located on the Alaska Peninsula and adjoining Unimak Island.

The centers generally have volumes of <100 km^3, although some large, long-lived stratocone-caldera complexes are as large as 300 to 400 km^3. The largest and most active volcanic centers in the eastern Aleutian arc (and the entire Aleutian arc) are found in the 700-km-long segment west of Veniaminof volcano on the Alaska Peninsula. The spacing between individual centers varies so much along the eastern Aleutian arc that an "average" volcano spacing figure is relatively meaningless. It is probably more significant for modeling purposes that various "segments" of the arc have quite different spacings between individual centers and that the longest volcano-free segment of the eastern Aleutian arc is less than 100 km.

The cone-building volcanic rocks consist predominantly of medium-K andesite and low-SiO_2 dacite; basalt is less common. Rhyolite is present in some ash-flow tuffs and intracaldera dome complexes. High-SiO_2 (>75 percent) rhyolite is restricted to the

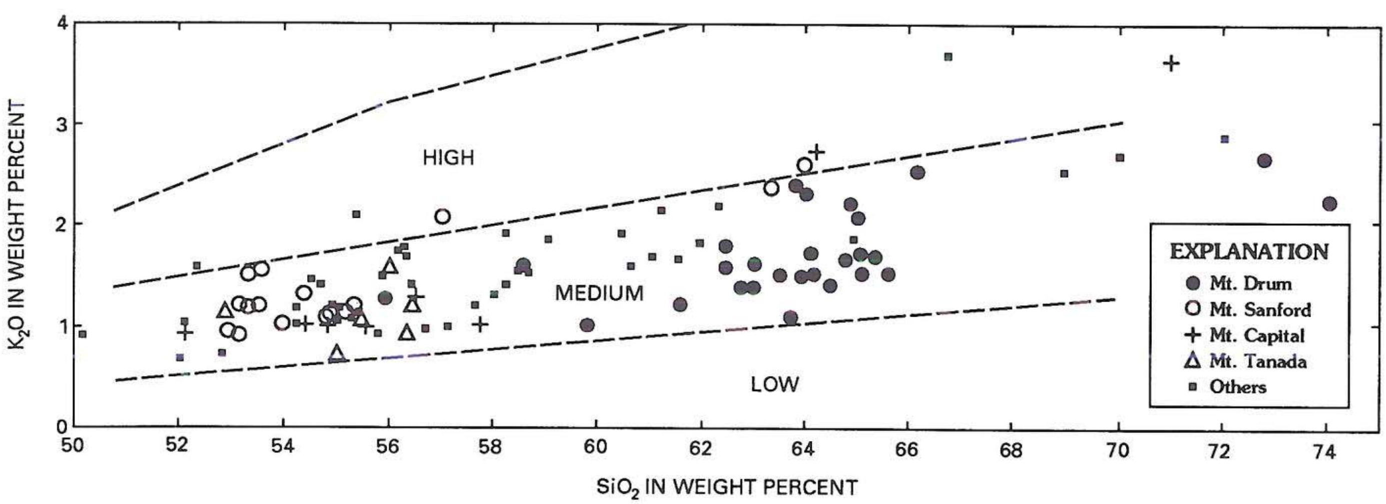

Figure 8. K_2O versus SiO_2 for volcanic rocks of the Wrangell volcanic field (WVF). Discriminant lines separating High, Medium, and Low are modified from Pecerrillo and Taylor (1976) and Ewart (1979).

ash-flow tuff of the Valley of Ten Thousand Smokes and the associated Novarupta dome.

Although the largest centers in the Alaska Peninsula–Cook Inlet region are tholeiitic, the easternmost 770 km of the Aleutian arc (one-third of the entire arc length) is characterized solely by calc-alkaline volcanic centers. Compositional trends of Quaternary volcanoes in the eastern Aleutian arc do not appear to have been influenced by tectonic segmentation such as has been proposed for the western oceanic part of the arc. Instead, continental crust east of Veniaminof volcano may be thick and extensive enough so as to inhibit the easy passage of magma. Magma fractionation and mixing could then lead to a calc-alkaline differentiation trend.

The Wrangell volcanic field, which covers more than 10,000 km^2 in south-central Alaska, contains at least six major volcanoes of Quaternary age. These volcanoes, located in the western part of the Wrangell volcanic field, as well as older volcanoes (5 to 20 Ma in the central and eastern parts of the field), are mostly large andesitic shield volcanoes with volumes as much as 1,000 km^3. Three of the Quaternary volcanoes contain recognizable near-circular summit calderas whose diameters range from 4 to 8 km. The absence of any known extensive pyroclastic flow deposits in the Wrangell volcanic field suggests that most of the calderas were of a nonexplosive origin. Neither the Quaternary volcanoes nor the older centers show any pronounced alignment or clustering that might be attributable to some form of structural control. The Wrangell volcanic field itself, however, does exhibit an east-west trend subparallel to the structural grain of southern Alaska.

The volcanic rocks of the Wrangell volcanic field are medium-K calc-alkaline rocks consisting predominantly of thick and extensive piles of flat-lying to gently dipping andesitic flows. Dacite to rhyolite domes, flows, and pyroclastic flow deposits are associated with some of the volcanoes. Bedded tephra is common, interlayered with flows throughout the field; small, young basalt to basaltic andesite cinder cones are scattered throughout the northwestern part of the field.

Regional mapping and topical studies of the Alaska Peninsula–Cook Inlet and Wrangell volcanic field regions, beginning in the early 1970s, have provided much new information on these previously little-understood volcanic provinces. The distribution, geologic setting, spacing, volume, and compositional trends of volcanic centers are now known in at least a general way. Future and more detailed topical studies including isotopic and trace-element analyses, geochronology, and large-scale geologic mapping of individual volcanic centers will undoubtedly contribute greatly to the understanding of these volcanic arcs in particular, and also to such arcs worldwide.

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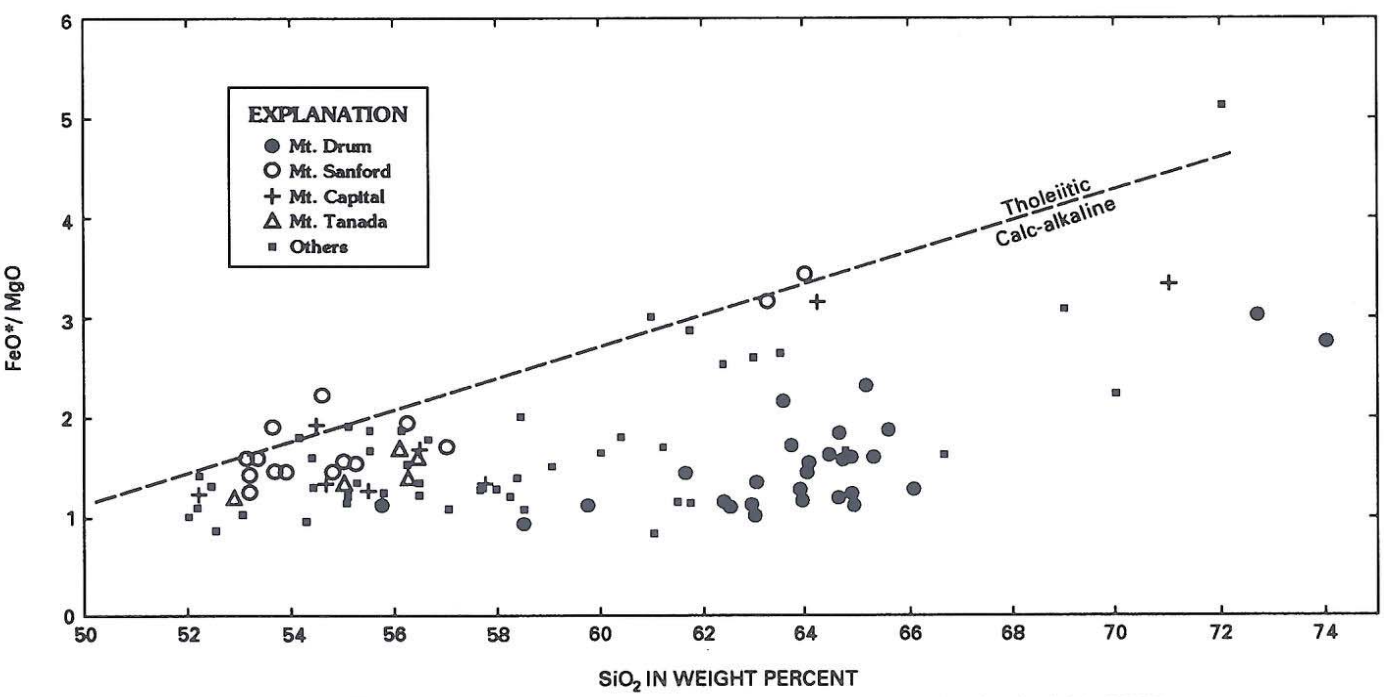

Figure 9. FeO*/MgO versus SiO_2 for volcanic rocks of the Wrangell volcanic field (WVF). Tholeiite–calc-alkaline line after Miyashiro (1974).

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MANUSCRIPT ACCEPTED BY THE SOCIETY MAY 23, 1990

Printed in U.S.A.