Geochemistry of the Andesitic Admiralty Island Volcanics, An Oligocene Rift-Related Basalt to Rhyolite Volcanic Suite of Southeastern Alaska

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ABSTRACT

The Admiralty Island Volcanics of Oligocene age on southernmost Admiralty Island is an approximately 1,000-km^2 by 3,000-m-thick field of low-MgO, medium- and low-K, dominantly andesitic rocks. Compositions are mostly low-SiO_2 andesite and range from basalt and high-SiO_2 andesite to less abundant dacite and rhyolite of high-K, high-SiO_2 type. Volatile-free SiO_2 content of flow rocks ranges from 47 to 77 weight percent, with a SiO_2 gap at 62–68 weight percent. Numerous comagmatic dikes cut the flow rocks and probably represent fissure feeders for the flows. Most flow and dike rocks contain normative hypersthene and are free of normative olivine. Major-element compositions are generally typical for orogenic, arc-related volcanic suites, but critical incompatible trace elements (Nb, Ta, Hf, Th) show characteristics of a within-plate extensional setting of volcanism that was not related to subduction of a slab of oceanic lithosphere.

The volcanism on Admiralty Island occurred about 10 m.y. after termination of Kula plate convergence at 43 Ma and during right-lateral transform motion of an ancestral Queen Charlotte–Fairweather Fault between the Pacific and North American plates. The transform setting of this volcanic activity contrasts with that of the subduction setting of arc volcanism of the 26- to 0.2-Ma Wrangell volcanic field of southern Alaska and Canada, early phases of which have been correlated with the Admiralty Island Volcanics. The volcanic field of Admiralty Island is part of the 35- to 5-Ma Tkope–Portland Peninsula magmatic belt that approximately parallels the continental margin. The setting inferred for the Admiralty Island Volcanics suggests that this belt is a major, transform-related Cenozoic extensional feature of southeastern Alaska. Extension may be related to weakening of the lithosphere by upwelling of mafic asthenosphere in an area of transform activity.

INTRODUCTION

The Admiralty Island Volcanics (Loney, 1964) forms a volcanic field of about 1,000-km^2 area and 3,000-m thickness on southernmost Admiralty Island (fig. 1). The suite of rocks is largely andesitic, but varies from basalt to rhyolite. Numerous dikes intrude the volcanic sequence. The formation was assigned a late Eocene and Oligocene age by Loney (1964) and has yielded a K-Ar age of 27 Ma (Oligocene). The Admiralty Island Volcanics and the smaller 25- to 16-Ma Icy Strait magmatic field of Brew (1994) near Glacier Bay (fig. 1) are members of the 35- to 5-Ma Tkope-Portland Peninsula magmatic belt of Brew (1994) that extends along most of southeastern Alaska. The northern part of the belt is displaced from central and southern parts by about 150 km of Cenozoic right-lateral separation along the Chatham Strait fault (fig. 1), a segment of the Denali fault (St. Amand, 1957). The fault also has a large component of vertical movement, in which the Baranof Island side is uplifted several kilometers relative to the Admiralty Island side (Loney and others, 1967). Whereas Tertiary rocks of Baranof Island are deeply eroded, those of southern Admiralty Island remain close to the elevations of their formation near or slightly above sea level (Loney and others, 1967).

The volcanism of the Admiralty Island Volcanics and the Icy Strait magmatic field has been suggested to be related to early phases of the extensive 26- to 0.2-Ma age Wrangell volcanic field in southern Alaska and Canada (Richter and others, 1990). The Wrangell volcanic field is characterized by medium-K, calc-alkalic lavas typical of continental volcanic arcs located along convergent plate margins (Richter and others, 1990). Wrangell lavas in southern Alaska, like the Admiralty Island Volcanics, are predominantly andesitic and range from basalt to rhyolite (Richter and others, 1990, 1993). The Wrangell lavas extend southeastward into Canada, where they are similar in character to rocks of the type locality in the Wrangell

Mountains but formed in an arc-transform transition zone (Skulski and others, 1991, 1992).

The field of the Admiralty Island Volcanics lies near the continental margin in a zone of complex Cenozoic interactions between the eastern Pacific and North American plates (Bradley and others, 1993; Plafker and others, 1994). Paleomagnetic data show that volcanism of the field occurred after the accretion of the Wrangellia and other allochthonous terranes of the area (Panuska and Decker, 1985). The Canadian continental margin to the

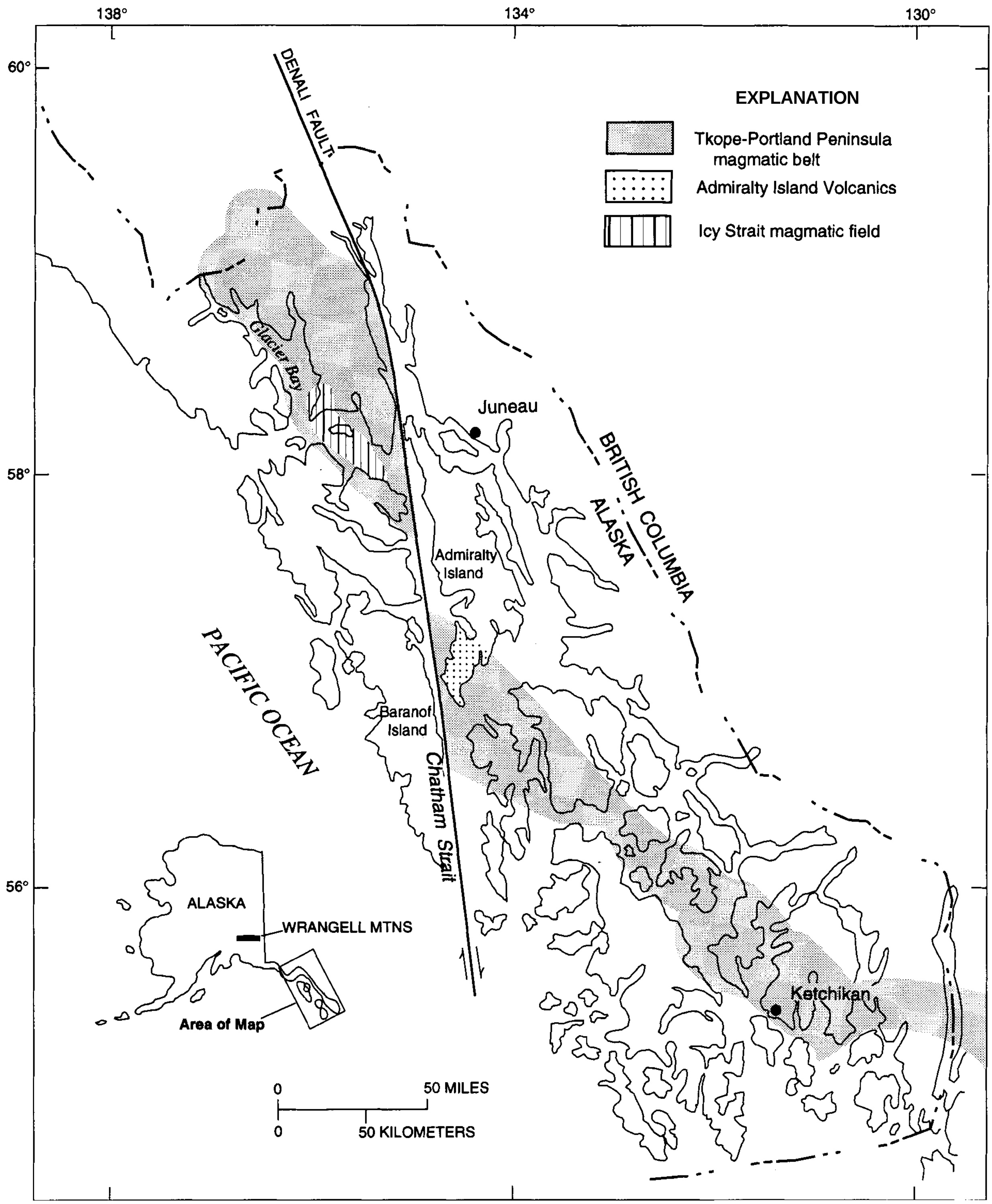

Figure 1. Index map of southeastern Alaska, showing the location of the Admiralty Island Volcanics, the Icy Strait magmatic field, and the Tkope-Portland Peninsula magmatic belt of Brew (1994). Modified from Brew (1994).

south records an abrupt transition from rapid plate convergence and subduction to highly oblique transcurrent motion between North America and the Pacific plate in the middle Eocene (Hamilton and Dostal, 1993). The transition may have been related to a reorientation of Pacific plate motion after cessation of Kula ridge spreading at 43 Ma (Lonsdale, 1988). By about 37 Ma (Irving and Wynne, 1991), relative movements between southeastern Alaska and the Pacific plate were transcurrent along the offshore Transition fault system of Plafker and others (1994), a transform fault ancestral to the later Cenozoic Queen Charlotte–Fairweather fault system. The Admiralty Island Volcanics records a volcanic episode related to plate activity about 10 m.y. after the transition from subduction to transcurrent motion along this part of the North American continent. To the north, eruptive centers of alkalic basalt, trachyte, and rhyolite of the Wrangell field in Canada formed at 18–10 Ma during transition between subduction- and transform-margin-related settings (Skulski and others, 1991, 1992). In southern Alaska, oblique convergence and subduction between the Pacific plate and southern Alaska persisted throughout the 26- to 0.2-Ma arc volcanism of the Wrangell volcanic field (Richter and others, 1990).

Volcanic rocks with the wide compositional range of the Admiralty Island Volcanics are found in settings as varied as subduction-related continental margin arcs (Condie and Hayslip, 1975; Cole, 1981; Gill, 1981; Thorpe and others, 1982), back-arc basins (Rudnick, 1983; Gamble and others, 1995), intraoceanic subduction systems (Gill and Stork, 1979), and intracontinental extensional rift zones (Chapin and Zidek, 1989; Nicholson, 1992; Giese and Biihn, 1993). Interpretation of the tectonic setting of volcanism can be complicated by the presence of rocks of both convergent- and extensional-related tectonic regimes within a single volcanic field (Ewart, 1982; Sawlan, 1991; Wharton and others, 1995). The tectonic setting of magmatism has been shown in many studies to influence the geochemistry of volcanic rocks, particularly in trace elements (Pearce and Cann, 1973; Wood, 1980; Pearce, 1982, 1983). The present study investigates the geochemical signatures of the Admiralty Island Volcanics, with emphasis on trace elements, in an attempt to determine the tectonic setting of this volcanism of Oligocene age. The setting of the Admiralty Island volcanism is used to interpret the origin of the Tkope-Portland Peninsula magmatic belt, which is a major tectonomagmatic feature that parallels the coast of southeastern Alaska (fig. 1).

PREVIOUS AND PRESENT STUDIES

The volcanic rocks of southwestern Admiralty Island investigated in this study were first mapped in Wright's (1906) reconnaissance investigations of southeastern Alaska. The field of volcanic rocks was mapped in more detail by Loney (1964) and Lathram and others (1965). Rocks correlated with the Admiralty Island Volcanics occur on nearby islands to the south of Admiralty Island (Buddington and Chapin, 1929; Muffler, 1967; Brew and others, 1984, 1985; Brew, 1994). Previously published chemical data for the Admiralty Island Volcanics are limited to major-element analyses of six flows of basalt, basaltic andesite, andesite, and "altered lavas," and one dike (Loney, 1964). A plot of rare-earth elements of one sample, for which the locality, lithology, and major-element content were not reported, was shown by Brew (1994).

Thirty-five samples of flows and samples of eight dikes from the field of the Admiralty Island Volcanics were analyzed for this study. The rocks were broken into small pieces on the outcrop in order to exclude as much weathered material, veinlets, and amygdules as possible. Nonetheless, unusually small amygdules and veinlets, which could not be excluded from some samples even with later hand picking, may be reflected in unusually high contents of volatiles (H_2O, CO_2) and anomalous mobile-element variations. Samples were obtained from elevations ranging from sea level to the highest topographic exposures of the field (Bear Pass Mountain, elevation 3,853 ft; fig. 2), so that as much of the stratigraphy of the volcanic field as possible was collected. However, the abundance of steep faults with unknown displacement (Loney, 1964; Lathram and others, 1965) precludes measurement of detailed stratigraphic sections across the entire sequence of flows. Accordingly, the compositional variation of the flows with stratigraphic position in the volcanic sequence has not been determined.

DESCRIPTION OF THE ADMIRALTY ISLAND VOLCANICS

The Admiralty Island Volcanics consists predominantly of andesitic flows that are interlayered with flows of basalt and minor dacite and rhyolite and minor pyroclastic rock. Approximately 23 percent of the rocks of this study are basalt, 43 percent are low-SiO_2 andesite, 23 percent are high-SiO_2 andesite, and 11 percent are dacite and rhyolite, as described below. Loney (1964) described the volcanic field as a "...thick sequence of gently dipping andesitic and basaltic flows and minor rhyolitic breccia and tuff." The volcanic field is probably of terrestrial origin, as suggested by relations with partly coeval terrestrial clastic rocks (Kootznahoo Formation; Lathram and others, 1965) and an absence of pillow lavas. The volcanic rocks are best exposed along shorelines. The total exposed thickness of the field is about 3,050 m, but because the top is erosional the original thickness is unknown (Lathram and others, 1965). The thickness of the volcanic pile is highly variable, owing in part to well-developed topographic relief under the sequence of flows (Buddington and Chapin, 1929). The overall form of the volcanic field appears to be that of a north-trending, block-faulted synclinal structure, the axial trace of which approximately coincides with the trace of the Eliza fault (Loney, 1964). In places, the origin of dark, dense, and structureless rocks is indistinguishable by field characteristics alone. Samples collected from Wilson Cove and Whitewater Bay, for example, were interpreted in the field

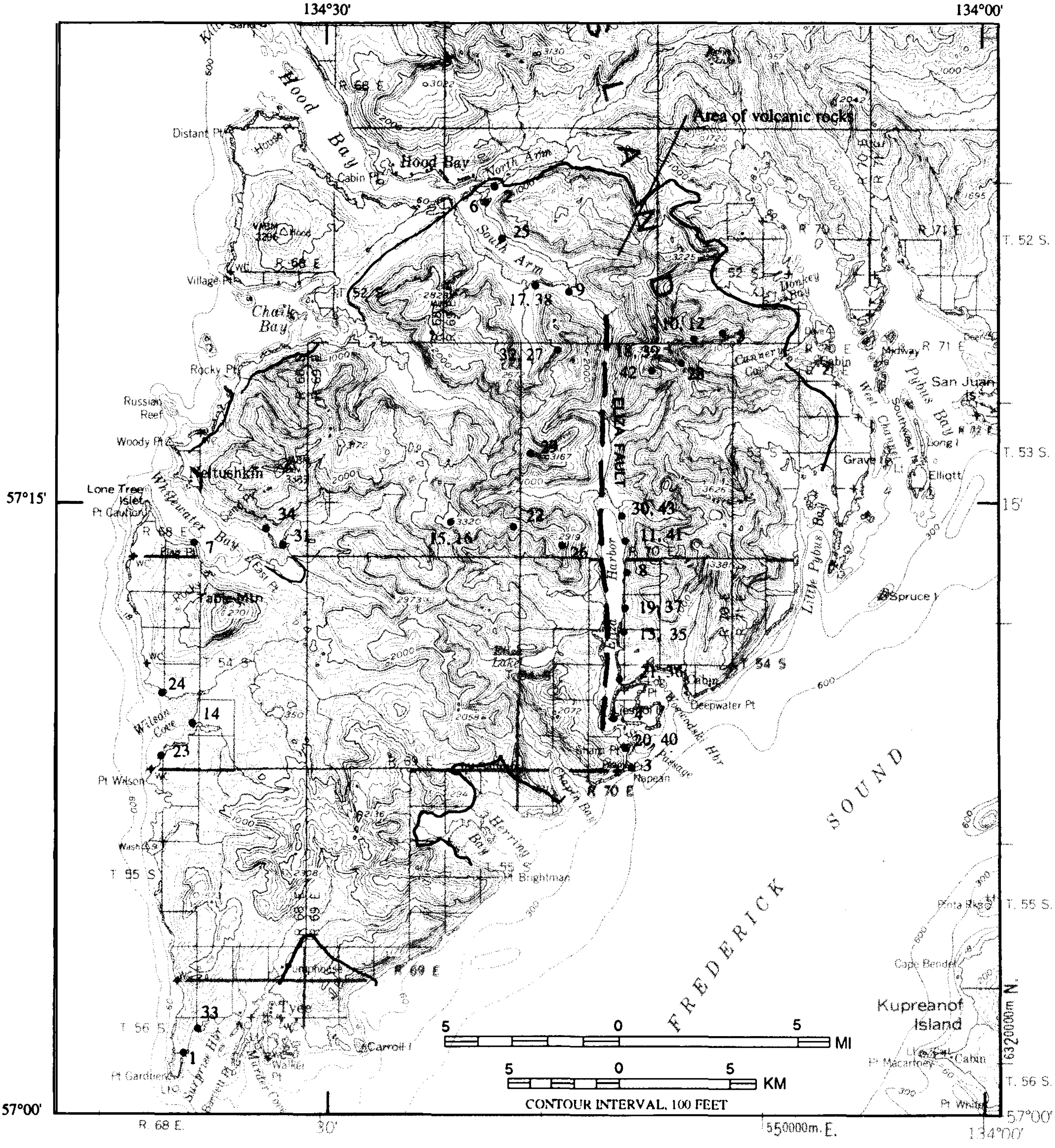

Figure 2. Distribution of the Admiralty Island Volcanics, southern Admiralty Island, showing sample localities (see table 1). Area of volcanic rocks slightly modified from Lathram and others (1965). Base map from U.S. Geological Survey, Sitka quadrangle 1951.

to be hornfelsed metasedimentary rocks, but were later found in thin-section study to be volcanic (localities 23, 34; fig. 2, table 1).

Dikes are present throughout the volcanic field and seem to be especially concentrated as swarms in central areas near Eliza Harbor and Bear Pass Mountain (localities 39, 42; fig. 2). Loney (1964) reported that the dikes are petrographically and compositionally similar to the flows. The dikes range in thickness from 0.6 cm to 6.1 m, and their average attitude (N. 32° E. strike, 75°S. dip) is about normal to axial planes of second-generation folds in pre-Tertiary rocks of the area and approximately parallel with high-angle faults (Loney, 1964). The abundance of dikes within a zone about 2 km wide surrounding the volcanic field and their scarcity beyond that distance suggest that volcanism did not extend far beyond the present area of the field (Loney, 1964). The "numerous vents and craters" that Wright (1906) believed were the source of the lavas were not found in our field work.

The volcanic rocks of this study have varied mineralogy, texture, and structure, and show a wide range in alteration (table 1; Loney, 1964). Fragmental rocks, including breccia and tuff, are present locally but were not collected for this study. Amygdaloidal structure is found in flows of basalt and andesite sampled from near sea level (localities 6, 20, 25; fig. 2, table 1) and higher elevations (localities 28, 29; fig. 2, table l). Xenoliths have not been found in any of the flows. Most rocks are porphyritic and contain phenocrysts principally of plagioclase. In our samples, clinopyroxene (cpx) is common only as a groundmass phase, but Loney (1964) reported clinopyroxene to be a common phenocryst phase, although much lower in abundance than plagioclase. Hornblende is not present as a phenocryst phase in the samples, but green amphibole of apparent secondary origin is locally present in the groundmass. Alteration products from primary minerals include highly variable amounts of clay, chlorite, mica, amphibole, and carbonate minerals, and many rocks contain small amounts of interstitial devitrified material.

The volumetrically minor and poorly exposed dacitic and rhyolitic rocks of the Admiralty Island Volcanics are intercalated with basaltic and andesitic flows at localities from sea level (Eliza Harbor, localities 13, 35; Surprise Harbor, localities 1, 33; fig. 2) to high elevations (west of Bear Pass Mountain, localities 27, 32; fig. 2). In the absence of observed intrusive relations the silicic rocks of the field are interpreted to be extrusive rather than hypabyssal intrusive in origin. However, an origin of some of the silicic bodies by hypabyssal intrusion is possible, as is the case with the silicic intrusive bodies mapped in other basalt to rhyolite suites (Wrangell volcanic field; Chapin and Zidek, 1989; Nicholson, 1992; Richter and others, 1993). The silicic rocks of the Admiralty Island Volcanics commonly show convoluted flow banding. In the absence of shards and pumice fragments typical of silicic volcanic rocks of ash-flow origin (Chapin and Zidek, 1989), the silicic extrusive rocks of the Admiralty Island Volcanics are interpreted to represent lava flows.

AGE

The age of the Admiralty Island Volcanics is not well constrained because paleontologic and isotopic age data are available from few localities and only for rocks of low stratigraphic position. Wright (1906) ascribed a post-Eocene age to the Admiralty Island Volcanics. Loney (1964) considered the formation to be late Eocene to Oligocene, based on the relations between flows of a lower part of the volcanic field at Little Pybus Bay with underlying Eocene(?) conglomerate of the terrestrial Kootznahoo Formation, a unit of Paleocene through Miocene age (Lathram and others, 1965). An Oligocene age of volcanic rocks of a lower part of the sequence is indicated by plant fossils in sedimentary rocks interbedded with the volcanic rocks (J.A. Wolfe, quoted in Lathram and others, 1965). A volcanic rock from near the head of Chaik Bay (locality in Wilson and others, 1994; data from George Plafker, written comm., 1986, quoted in Brew, 1994) yielded a whole-rock K-Ar age of 27 Ma (Oligocene; time scale of Harland and others, 1990). The stratigraphic position of the sample was unreported. The locality, near sea level, is somewhere within the lower part of the volcanic sequence. Ages of intermediate and upper flows of the field have not been determined. Loney (1964) suggested that the oldest volcanic rocks of the field may be Eocene because conglomerate of the Kootznahoo Formation contains volcanic clasts. Although a wider age range is possible, an age of Oligocene is here ascribed to the Admiralty Island Volcanics because the only direct evidence available indicates such an age for the volcanic field.

NOMENCLATURE

The volcanic-rock nomenclature used in this report follows that of Gill (1981). The commonly used classification by CIPW minerals (Irvine and Baragar, 1971) is unsatisfactory owing to the generally poor correspondence between CIPW and modal mineralogy (Le Bas and others, 1986). Moreover, amounts of the normative minerals quartz (Q), orthoclase (or), and olivine (ol) that are critical for classification are dependent on iron-oxidation ratio (Fe_2O_3/FeO; Middlemost, 1989), a ratio that probably has been modified by alteration in rocks of this study. In Gill's (1981) classification, rock names are based primarily on SiO_2 content recalculated to a volatile-free amount

Table 1. Sample locations and petrographic features of the Admiralty Island Volcanics

[Rock groups: BA, basalt; AN-L, low-SiO_2 andesite; AN-H, high-SiO_2 andesite; SIL, dacite and rhyolite; DK, dike. Widths given for dikes. Thin-section textures and structures: Am, amygdaloidal; Pp, porphyritic; Gl, glomeroporphyritic; Fl, flow structure; Ho, holocrystalline; Is, intersertal; Ig, intergranular; Mp, microporphyritic; Op, ophitic; Dv, devitrification features. Minerals: PL, plagioclase (abundant, all samples except dacite and rhyolite); QZ, quartz; CPX, clinopyroxene; AM, amphibole; OX, opaque oxides (minor, all samples); CA, carbonate; EP, epidote; CL, clays, chlorite, secondary mica. *, phenocrysts; #, groundmass; +, abundant; tr, minor. Textures underlined.]

Field No.	Plot symbol	Rock group	Latitude	Longitude	Location	Petrographic features and notes
91AF085A	21	AN-L	57°10'43"	134°16'52"	Eliza Harbor	Fresh. Mp. Fl. Dv(?). PL,*,#; OX,#.
91AF085B	36	DK	57°10'43"	134°16'52"	Eliza Harbor	Dike, 1.4 m. Altered (CA, CL, tr). Ho. Ig. PL, OX, CPX.
91AF086A	35	SIL	57°11'40"	134°16'59"	Eliza Harbor	Altered. Dv. Fl. QZ, CL. Banded.
91AF086B	13	AN-L	57°11'40"	134°16'59"	Eliza Harbor	Altered, minor (CL, CA, tr.). PL; CPX, tr.; QZ, tr.
91AF087A	19	AN-L	57°12'20"	134°16'47"	Eliza Harbor	Altered, minor (CA, CL). Dv. Is. PL; CPX, tr; OX.
91AF087B	37	DK	57°12'20"	134°16'47"	Eliza Harbor	Dike, 2 m. Altered, minor (CA, CL, tr.) Pp. PL,+,*,#.
91AF088A	8	BA	57°13'17"	134°16'47"	Eliza Harbor	Altered (CL, EP, tr). Dv(?). PL; CPX, tr.; OX.
91AF089A	11	AN-L	57°14'03"	134°16'45"	Eliza Harbor	Altered (CL, CA, tr). Dv. Pp. Is. PL; CPX, tr; OX
91AF089B	41	DK	57°14'03"	134°16'45"	Eliza Harbor	Dike, 2 m. Altered (CA, CL, AM, prehnite). Ho. Pp. PL, *,#; CPX, *,#.
91AF090B	30	AN-H	57°14'39"	134°17'01"	Eliza Harbor	Altered (CL, EP). Dv (?). PL.
91AF090C	43	DK	57°14'39"	134°17'01"	Eliza Harbor	Dike, > 30 cm. Altered (CL, EP, AM) Pp. Dv. PL, *,#. AM, #, tr., OX.
91AF091A	4	BA	57°09'48"	134°17'19"	South of Eliza Harbor	Fresh. Pp. Fl. PL,*,#; CPX, #; OX, CA, tr.
91AF092A	20	AN-L	57°09'07"	134°16'29"	South of Eliza Harbor	Altered (CA, CL). Pp. Fl. Am. PL, *,#; OX.
91AF092B	40	DK	57°09'07"	134°16'29"	South of Eliza Harbor	Dike, 3 m. Altered (CA, CL). Mp. Dv. Am. varioles. PL,OX.
91AF093A	3	BA	57°08'34"	134°16'35"	South of Eliza Harbor	Fresh. Ho. Pp. Fl. PL, *,#; CPX, #; OX.
91AF095A	1	BA	57°01'30"	134°36'25"	Surprise Harbor	Fresh. Pp. Op. Fl. PL, *,#; CPX, *,#; OX; CL, tr.
91AF096A	33	SIL	57°02'04"	134°35'48"	Surprise Harbor	Altered(?). Pp. Dv.
91AF097A	14	AN-L	57°09'31"	134°36'08"	Wilson Cove, head	Fresh. Pp. Ho. Fl.. PL, *,#; CPX, #tr; OX,#tr.
91AF098A	24	AN-H	57°10'34"	134°37'30"	Wilson Cove, N. side	Fresh. Mp. Ho. Fl (strong). PL*.
91AF099A	34	SIL	57°14'22"	134°32'10"	Whitewater Bay, head	Altered. Dv. Pp. Flow(?) banded.
91AF100A	31	AN-H	57°13'35"	134°32'20"	Whitewater Bay, head	Altered. Pp. Dv(?). PL, *.
91AF101A	7	BA	57°14'02"	134°36'08"	Whitewater Bay, S. side	(No thin section)
91AF102A	2	BA	57°22'44"	134°22'40"	Hood Bay, North Arm	Fresh. Pp. Op. PL, *,#; CPX, #; OX, #.
91AF103A	6	BA	57°22'17"	134°23'09"	Hood Bay, South Arm	Fresh. Pp. Am. PL, *,#.
91AF104A	25	AN-H	57°21'29"	134°21'59"	Hood Bay, South Arm	Altered(?). Ho. Mp. Fl. Am. PL, *, #.
91AF105A	17	AN-L	57°20'22"	134°20'34"	Hood Bay, South Arm	Fresh. Ho. Fl. PL, #.
91AF105C	38	DK	57°20'22"	134°20'34"	Hood Bay, South Arm	Dike, 2 m. Fresh. Ho. PL, #.
91AF106A	9	AN-L	57°21'19"	134°19'19"	Hood Bay, South Arm	Fresh. Ig. Fl. PL, #.
91DB034A	23	AN-L	57°08'44"	134°37'32"	South of Wilson Cove	Fresh. Ho. Fl. PL, #; CPX, #
92AF023A	10	AN-L	57°03'58"	134°13'17"	East of Bear Pass Mtn	Altered (?). Pp. Ho. Gl. PL, *,#; CPX, #.
92AF023B	12	AN-L	57°03'58"	134°13'17"	East of Bear Pass Mtn	Altered (?). Pp. Ho. Gl. PL, *,#; CPX, #.
92AF024A	5	BA	57°04'13"	134°12'09"	East of Bear Pass Mtn	Altered (?). Ho. Mp. Fl. PL, *,#.
92AF025A	28	AN-H	57°03'18"	134°14'08"	South of Bear Pass Mtn	Altered. Pp. Dv. Am. Is. PL, *, CA, tr. Glass (?) present.
92AF026A	18	AN-L	57°03'10"	134°15'12"	Southwest, Bear Pass Mtn	Altered. Dv. Fl. PL, #, tr, CA, EP.
92AF026B	39	DK	57'03'10"	134°15'12"	Southwest, Bear Pass Mtn	Dike, 2 m. Altered. Pp. PL, *,#; CA, +, #.
92AF026C	42	DK	57°03'10"	134°15'12"	Southwest, Bear Pass Mtn	Dike, 3 m. Altered. Pp. Fl. Dv (?). Quartz (?), *.
92AF027A	32	SIL	57°03'31"	134°18'42"	West of Bear Pass Mtn	Fresh (?). Pp. Dv. Fl. PL, *,#; CPX, *. Glass(?) present.
92AF027B	27	AN-H	57°03'31"	134°18'42"	West of Bear Pass Mtn	Fresh (?). Pp. Dv. Fl. PL, *,#. Glass(?) present
92AF028A	29	AN-H	57°16'26"	134°20'57"	3167' pk, SE. Chaik Bay	Altered. Pp. An. PL, *,#; CA,+. CA in veinlets and vesicles.
92AF029A	26	AN-H	57°14'13"	134°19'55"	2919' pk, W., Eliza Harbor	Fresh. Mp. Fl. Is. PL, *,#.
92AF030A	22	AN-L	57°14'29"	134°21'55"	West of Eliza Harbor	Altered. Pp. Gl.. PL, *,#; CPX, *,#; CA.
92AF031A	16	AN-L	57°14'28"	134°14'25"	3320' pk, W., Eliza Harbor	Fresh. Mp. Fl. PL, *,#; CPX,#; OX, #.
92AF031B	15	AN-L	57°14'28"	134°14'25"	3320' pk, W., Eliza Harbor	Fresh. Mp. Fl. PL, *,#; CPX,#; OX, #.

(basalt, <53 percent; andesite, 53-63 percent; dacite, 63-70 percent; rhyolite, >70 percent). Andesites, typically containing normative hypersthene (hy), are further subdivided into low-silica (or basaltic) andesite (SiO_2, 53-57 percent) and high-silica andesite (SiO_2, 57-63 percent), following Gill (1981). Normative plagioclase composition at An_{50} (Thompson, 1972) distinguishes basalt from andesite in most rocks of this study.

The alterations indicated by secondary minerals in many rocks (table 1) resulted in variable increases in volatile constituents (H_2O, CO_2) that affect the relative amounts of major elements analyzed. Therefore, CIPW norms, ratios, and major-element plots in this report are based on amounts of major elements normalized to volatile-free amounts for comparison of rock compositions within this volcanic field and with rocks of other areas, and for rock classification. CIPW norms were calculated using the PETCAL program of Bingler and others (1976), as modified by R.D. Koch (written commun., 1992), and using FeO/Fe_2O_3 ratios of original analyses (Le Bas and others, 1986).

MAJOR-ELEMENT CHEMISTRY

The SiO_2 content (volatile-free basis) of flow rocks ranges widely from about 47 to 77 weight percent (table 2). Most flow and dike rocks of the volcanic field are Q normative and most contain hy, with minor. ol in a few basalts. The flow rocks show a SiO_2 gap at 62-68 weight percent (fig. 3), separating andesitic from dacitic compositions, which is about the same as that of the Icy Strait magmatic field (61-68 weight percent; Brew, 1994). Other volcanic suites commonly show a lower SiO_2 gap separating basalt from andesite (Thompson, 1972). The average major-element composition of the silicic flow rocks (table 2D) is intermediate between average rhyolite and rhyodacite of Le Maitre (1976). The dike rocks have a narrower SiO_2 range than flow rocks (48-65 weight percent; table 2*E*), with SiO_2 contents that lie within the SiO_2 gap of flow rocks (fig. 3).

The flow and dike rocks of the Admiralty Island field are dominantly andesitic in composition, as indicated in the total alkali and silica (TAS) diagram of figure 4. The rocks have medium- to low-K characteristics (fig. 5), except for rocks of silicic flows that have high-K characteristics (average K_2O/Na_2O, 1.2; table 2D, fig. 5). The weak bimodality in frequency distribution of SiO_2 content in the Admiralty Island Volcanics differs from distributions in typical volcanic bimodal suites (Condie and Hayslip, 1975; Giese and Biihn, 1993) in the abundance of andesitic compositions (figs. 3, 4). The metaluminous character of the basalt and andesite flow and dike rocks is shown by A/CNK $[Al_2O_3/(CaO + Na_2O + K_2O)]$ values less than 1.0 (tables 2*A-C*, E). Rocks of silicic flows, however, have higher, strongly peraluminous A/CNK values (1.08-1.32; table 2D). A/CNK values generally vary inversely with CaO content and increase with SiO_2 content (averages: basalt, 0.73; low-SiO_2 andesite, 0.79; high-SiO_2 andesite, 0.87; dacite and rhyolite, 1.20; tables 2*A-D*). Higher normative-corundum contents also show the more aluminous character of silicic flow rocks compared with intermediate and mafic flow rocks of the field (table 2*A-D*). A moderate- to low-MgO character of the rocks is shown by MgO contents (mostly < 6 weight percent; table 2) and by low values of Mg numbers $[100 \times Mg^{2+}/(Mg^{2+} + Fe^{2+})$, in molecular amounts], which vary inversely with SiO_2 content (averages, basalt: 56; low-SiO_2 andesite, 54; high-SiO_2 andesite, 52; silicic rocks, 37; tables 2*A-D*).

Major-element contents of the Admiralty Island Volcanics show different relations in different diagrams. For example, flow and dike rocks are subalkalic (fig. 4), but the rocks form slightly calcic suites according to their alkali-lime "Peacock" index (62; fig. 6). The flow and dike rocks show mixed calc-alkalic and tholeiitic compositions in a diagram of total alkali ($Na_2O + K_2O$), total iron calculated as FeO ($FeO^* = FeO + 0.9 \times Fe_2O_3$), and MgO relations (AFM; fig. 7). All rocks, however, show tholeiitic characteristics when classified by the variation between SiO_2 and FeO^*/MgO (fig. 8). SiO_2 and TiO_2 contents of the dike and flow rocks are similar and show inverse covariation (fig. 9).

TRACE-ELEMENT CHEMISTRY

Trace-element contents of the volcanic rocks of Admiralty Island (table 3) show many variations related to SiO_2 content. Increases with SiO_2 content, for example, are shown by Zr abundance in flow rocks, which averages 150 pprn in basalt, 200 pprn in low-SiO_2 andesite, 199 pprn in high-SiO_2 andesite, and 378 pprn in silicic rocks. Th content increases with SiO_2 content to a maximum abundance in silicic rocks (11.4 ppm; table 3*D*), and U content also increases with SiO_2 content (table 3). Total abundance of rare-earth elements (REE) generally increases with SiO_2 content, from an average 70.7 pprn in basalt, 93.8 pprn in low-SiO_2 andesite, and 98.1 pprn in high-SiO_2 andesite, to 172 pprn in silicic rocks (CREE; table 3). The ratio between chondrite-normalized light-rare-earth elements (LREE) to heavy-rare-earth elements (HREE) also generally increases with SiO_2 content, as discussed below. Vanadium content (averages: basalt, 233 ppm; low-SiO_2 andesite, 168 ppm; high-SiO_2 andesite, 135 ppm; silicic rocks, 31 ppm; table 3) and K/Rb value (averages: basalt, 494 ppm; low-SiO_2 andesite, 409 ppm; high-SiO_2 andesite, 347 ppm; silicic rocks, 342 ppm; table 3), in contrast, vary inversely with SiO_2 content.

The flow and dike rocks of the Admiralty Island Volcanics are characterized by low to moderate REE con-

Table 2. Major-element chemical composition (weight percent) of flow and dike rocks of the Admiralty Island Volcanics in order of increasing SiO_2 content recalculated in volatile-free amount, and CIPW norms based on volatile-free oxide amount

[Major-element analyses, in weight percent, by methods described in Baedecker (1987) and Taggart and others (1987, 1990). Samples prepared by methods in Taylor (1990). FeO, H_2O, and CO_2 by methods in Jackson and others (1987). LOI, Loss on ignition at 925°C. Analysis in U.S. Geological Survey Laboratories. Analysts: J.S. Mee, D.F. Siems, except FeO, H_2O and CO_2 by T.L. Fries, S.T. Pribble. Indexes A/CNK and Mg number defined in text]

A. Basalt flows

Field No.	91AF095A	91AF102A	91AF093A	91AF091A	92AF024A	91AF103A	91AF101A	91AF088A	average
Symbol	1	2	3	4	5	6	7	8	BA
SiO_2 ----------	46.3	45.3	47.4	48.2	49.3	47.2	50.3	48.5	47.8
Al_2O_3 --------	16.1	16.8	16.0	18.0	15.7	17.5	16.9	16.4	16.7
Fe_2O_3 --------	2.94	2.41	3.60	4.10	3.99	2.73	2.37	2.72	3.11
FeO ------------	8.96	8.09	9.27	6.30	7.12	5.68	7.41	5.71	7.32
MgO ----------	7.63	7.14	4.53	5.29	5.71	2.39	5.01	5.44	5.39
CaO -----------	9.40	8.81	9.91	10.30	9.78	10.3	9.25	8.03	9.47
Na_2O ---------	2.84	2.61	2.90	3.07	3.12	3.13	3.47	3.81	3.12
K_2O -----------	.34	.51	.58	.38	.61	.46	.46	.37	.46
H_2O+ ----------	2.04	3.84	.96	1.06	.60	1.73	.65	3.35	1.78
H_2O- ----------	1.01	1.07	.71	.72	.88	.29	.22	.63	.69
TiO_2 ----------	1.99	1.53	2.13	1.58	2.18	1.68	1.48	1.15	1.72
P_2O_5 ----------	.24	.21	.33	.25	.59	.33	.43	.23	.33
MnO ----------	.21	.18	.20	.16	.20	.14	.18	.13	.18
CO_2 -----------	.28	1.31	1.53	.38	.03	6.10	1.50	3.66	1.85
Total	100.3	99.8	100.0	99.8	99.8	99.7	99.6	100.1	99.9
LOI -----------	2.15	5.21	2.05	1.36	.97	7.13	1.58	6.56	3.38
Analyses recalculated in volatile-free amount									
SiO_2 ----------	47.8	48.4	48.9	49.4	50.2	51.6	51.7	52.4	50.1
Al_2O_3 --------	16.6	18.0	16.5	18.4	16.0	19.1	17.4	17.7	17.5
Fe_2O_3 --------	3.03	2.58	3.72	4.20	4.06	2.98	2.44	2.94	3.24
FeO -----------	9.24	8.64	9.57	6.45	7.24	6.21	7.62	6.17	7.64
MgO ----------	7.87	7.63	4.68	5.42	5.81	2.61	5.15	5.88	5.83
CaO -----------	9.70	9.41	10.23	10.55	9.95	11.25	9.51	8.68	9.91
Na_2O ---------	2.93	2.79	2.99	3.15	3.17	3.42	3.57	4.12	3.27
K_2O ----------	.35	.55	.60	.39	.62	.50	.47	.40	.49
TiO_2 ----------	2.05	1.64	2.20	1.62	2.22	1.84	1.52	1.24	1.79
P_2O_5 ----------	.25	.22	.34	.26	.60	.36	.44	.25	.34
MnO ----------	.22	.19	.21	.16	.20	.15	.19	.14	.18
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Indexes									
A/CNK--------	0.73	0.81	0.68	0.74	0.67	0.72	0.73	0.77	0.73
Mg number---	60.3	61.1	46.6	59.9	58.8	42.9	54.7	62.9	55.9
Normative minerals									
Q --------------	0.00	0.00	0.20	0.26	1.87	3.86	.96	0.00	0.89
or --------------	2.07	3.22	3.54	2.30	3.67	2.97	2.80	2.36	2.87
ab -------------	24.79	23.60	25.34	26.61	26.86	28.93	30.19	34.86	27.65
an -------------	31.13	34.85	29.87	35.04	27.50	35.33	30.00	28.71	31.55
di --------------	12.49	8.45	15.43	12.61	14.49	14.98	11.72	10.31	12.56
hy --------------	9.07	12.46	15.27	13.42	14.13	5.28	16.88	16.00	12.81
ol --------------	11.58	10.06	00	00	00	00	00	.56	2.78
mt -------------	4.40	3.73	5.39	6.09	5.89	4.32	3.53	4.26	4.70
il ---------------	3.90	3.11	4.18	3.07	4.21	3.49	2.89	2.36	3.40
ap --------------	.57	.52	.79	.59	1.39	.84	1.02	.58	.79
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Normative plagioclase An percent	55.67	59.63	54.10	56.84	50.59	54.98	49.84	45.17	53.4

Table 2. **Major-element chemical composition (weight percent) of flow and dike rocks of the Admiralty Island Volcanics in order of increasing SiO_2 content recalculated in volatile-free amount, and CIPW norms based on volatile-free oxide amount—Continued**

B. Low-SiO_2 andesite flows

Field No.	91AF106A	92AF023A	91AF089A	92AF023B	91AF086B	91AF097A	92AF031B	92AF031A	91AF105A	92AF026A	91AF087A	91AF092A	91AF085A	92AF030A	91DB034A	averaae
Symbol	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	AN-L
SiO_2 ----------		51.1	51.4	52.5	47.6	53.0	54.3	54.4	53.8	54.5	50.6	52.5	53.3	55.4	55.4	52.7
Al_2O_3 --------	17.4	17.8	18.9	17.8	14.6	15.7	17.1	17.2	17.5	16.8	14.9	14.3	14.9	17.5	15.3	16.5
Fe_2O_3 --------	3.50	3.28	1.35	3.86	2.20	3.74	3.71	3.77	3.89	1.38	2.32	5.31	2.18	3.76	4.28	3.24
FeO ----------	4.67	5.26	5.29	4.91	6.17	6.44	4.40	4.07	3.86	6.64	6.08	6.74	7.94	3.45	5.96	5.46
MgO ----------	4.96	3.15	4.95	3.06	3.33	4.31	4.68	4.49	4.42	4.27	3.22	1.47	2.51	4.68	2.47	3.73
CaO ----------	9.33	9.43	8.38	8.92	6.07	6.30	8.54	8.41	7.23	8.13	7.21	6.14	6.18	7.90	5.68	7.59
Na_2O ---------	3.68	3.26	3.50	3.54	3.33	4.04	3.49	3.60	4.12	3.66	3.24	3.68	4.08	3.47	4.57	3.68
K_2O ----------	.32	.55	.70	.65	2.19	1.20	.93	.98	.87	1.02	.73	1.34	1.08	.80	1.40	.98
H_20+ ----------	.96	1.87	2.73	1.64	1.36	1.11	.62	.72	.85	1.49	3.39	.76	.48	1.14	.43	1.30
H_2O- ----------	1.61	.48	.27	.39	.65	1.55	.83	.53	2.36	.10	.77	.67	.31	1.28	.87	.84
TiO_2 ----------	1.19	1.27	.93	1.27	1.45	1.52	1.30	1.22	1.10	1.36	1.68	1.70	1.76	1.00	1.60	1.36
P_2O_5 ----------	.30	.32	.20	.33	.29	.28	.31	.30	.28	.32	.39	.54	.59	.26	.64	.36
MnO ----------	.14	.14	.12	.14	.12	.13	.13	.13	.17	.15	.15	.22	.20	.11	.20	.15
CO_2 ----------	.11	2.13	.89	1.10	10.9	.01	.03	.05	.05	<.02	5.06	4.36	4.29	.06	.02	2.08
Total	99.6	100.0	99.6	100.1	100.3	99.3	100.4	99.9	100.5	99.8	99.7	99.7	99.8	100.8	98.8	99.9
LOI ---------	1.95	3.83	3.06	2.70	11.7	1.50	1.05	0.81	1.75	0.80	8.0	4.58	4.08	1.96	0.39	3.21
Analyses recalculated in volatile-free amount																
SiO_2 ----------	53.1	53.5	53.7	54.1	54.5	54.8	54.9	55.2	55.3	55.5	55.9	55.9	56.3	56.3	56.8	55.1
Al_2O_3 --------	18.0	18.6	19.7	18.4	16.7	16.2	17.3	17.5	18.0	17.1	16.5	15.2	15.7	17.8	15.7	17.2
Fe_2O_3 --------	3.61	3.43	1.41	3.98	2.52	3.87	3.75	3.83	4.00	1.41	2.56	5.65	2.30	3.82	4.39	3.37
FeO ----------	4.82	5.50	5.53	5.06	7.06	6.66	4.45	4.13	3.97	6.76	6.72	7.18	8.38	3.51	6.11	5.72
MgO ----------	5.12	3.30	5.17	3.16	3.81	4.46	4.73	4.56	4.55	4.35	3.56	1.57	2.65	4.76	2.53	3.89
CaO ----------	9.63	9.87	8.76	9.20	6.95	6.52	8.64	8.53	7.44	8.28	7.97	6.54	6.52	8.03	5.83	7.91
Na_2O ---------	3.80	3.41	3.66	3.65	3.81	4.18	3.53	3.65	4.24	3.73	3.58	3.92	4.31	3.53	4.69	3.85
K_2O ----------	.33	.58	.73	.67	2.51	1.24	.94	.99	.90	1.04	.81	1.43	1.14	.81	1.44	1.04
TiO_2 ----------	1.23	1.33	.97	1.31	1.66	1.57	1.32	1.24	1.13	1.38	1.86	1.81	1.89	1.02	1.64	1.42
P_2O_5 ----------	.31	.34	.21	.34	.33	.29	.31	.30	.29	.33	.43	.58	.62	.26	.66	.37
MnO ----------	.14	.15	.13	.14	.14	.13	.13	.13	.18	.15	.17	.23	.21	.11	.21	.16
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Indexes																
A/CNK--------	0.74	0.77	0.87	0.78	0.77	0.81	0.77	0.77	0.84	0.77	0.77	0.77	0.78	0.84	0.79	0.79
Mg #----------	65.4	51.6	62.5	52.6	49.0	54.4	65.5	66.3	67.1	53.4	48.6	28.0	36.1	70.7	42.5	54.3
Normative minerals																
Q -------------	3.62	6.68	1.75	7.54	1.68	4.77	7.32	7.34	5.88	4.93	9.65	12.14	7.50	10.0	8.78	6.64
or -------------	1.95	3.40	4.32	3.96	14.81	7.34	5.56	5.88	5.29	6.14	4.77	8.43	6.74	4.81	8.49	6.13
ab -------------	32.14	28.87	30.94	30.89	32.26	35.36	29.86	30.90	35.85	31.53	30.29	33.15	36.45	29.86	39.66	32.53
an -------------	30.98	33.81	35.30	31.72	21.09	21.89	28.56	28.28	27.44	26.87	26.46	19.74	20.22	30.32	17.54	26.68
di -------------	11.83	10.57	5.50	9.48	9.24	6.96	9.76	9.59	6.01	9.93	8.42	7.50	6.80	6.18	5.82	8.24
hy -------------	11.20	8.40	17.81	7.38	13.34	14.40	10.28	9.41	10.91	15.19	12.17	6.08	13.99	10.75	8.71	11.33
mt -------------	5.24	4.98	2.05	5.77	3.65	5.61	5.44	5.55	5.80	2.04	3.72	8.20	3.34	5.54	6.37	4.89
il -------------	2.33	2.52	1.85	2.49	3.15	2.99	2.50	2.35	2.15	2.63	3.53	3.44	3.53	1.93	3.12	2.70
ap -------------	.72		.48	.79	.77	.67	.73	.71	.67	.75	1.00	1.33	1.44	.61	1.52	.86
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Normative plagioclase An percent	49.1	53.9	53.3	50.7	39.5	38.2	48.9	47.8	43.4	46.0	46.6	37.3	35.7	50.4	30.7	44.8

Table 2. Major-element chemical composition (weight percent) of flow and dike rocks of the Admiralty Island Volcanics in order of increasing SiO_2 content recalculated in volatile-free amount, and CIPW norms based on volatile-free oxide amount —Continued

C. High-SiO_2 andesite flows

Field No.	91AF098A	91AF104A	92AF029A	92AF027B	92AF025A	92AF028A	91AF090B	91AF100A	average
Symbol	24	25	26	27	28	29	30	31	AN-HI
SiO_2----------	55.9	53.0	57.2	56.8	52.9	55.8	58.1	56.6	55.8
Al_2O_3--------	15.8	15.5	16.2	16.6	15.5	17.1	16.3	14.8	16.0
Fe_2O_3---------	3.98	2.42	3.34	3.12	1.42	4.63	1.49	2.26	2.83
FeO -----------	5.51	4.47	5.14	4.34	6.08	2.19	5.02	6.94	4.96
MgO ----------	2.80	2.50	3.04	3.82	3.06	3.93	4.25	1.27	3.08
CaO -----------	6.08	9.12	6.31	6.91	6.59	5.38	6.65	4.99	6.50
Na_2O---------	4.33	2.90	4.19	3.59	2.80	3.37	3.34	3.46	3.50
K_2O-----------	1.39	.45	1.15	1.12	.31	1.28	.73	.41	.86
H_2O+----------	.41	2.41	.71	.86	4.43	3.15	1.76	3.05	2.10
H_2O------------	.84	.83	.58	.61	1.01	1.40	.29	.52	.76
TiO_2----------	1.54	1.10	1.53	1.11	1.28	.90	1.00	1.38	1.23
P_2O_5----------	.48	.28	.34	.25	.39	.20	.26	.62	.35
MnO ----------	.17	.12	.16	.12	.13	.09	.13	.09	.13
CO_2-----------	<.01	4.32	.48	1.00	4.53	1.65	.02	2.98	2.14
Total	99.2	99.4	100.4	100.2	100.4	101.1	99.3	99.4	99.9
LOI -----------	0.45	6.42	1.07	1.88	8.93	5.24	1.53	5.30	3.85
Analyses recalculated in volatile-free amount									
SiO_2----------	57.1	57.7	58.0	58.1	58.5	58.8	59.7	61.0	58.6
Al_2O_3--------	16.1	16.9	16.4	17.0	17.1	18.0	16.8	15.9	16.8
Fe_2O_3--------	4.06	2.63	3.39	3.19	1.57	4.88	1.53	2.44	2.96
FeO -----------	5.62	4.87	5.21	4.44	6.72	2.31	5.16	7.48	5.23
MgO ----------	2.86	2.72	3.08	3.91	3.38	4.14	4.37	1.37	3.23
CaO -----------	6.21	9.93	6.40	7.07	7.29	5.67	6.84	5.38	6.85
Na_2O---------	4.42	3.16	4.25	3.67	3.10	3.55	3.43	3.73	3.66
K_2O-----------	1.42	.49	1.17	1.15	.34	1.35	.75	.44	.89
TiO_2----------	1.57	1.20	1.55	1.14	1.42	.95	1.03	1.49	1.29
P_2O_5----------	.49	.31	.35	.26	.43	.21	.27	.67	.37
MnO ----------	.17	.13	.16	.12	.14	.10	.13	.10	.13
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.00
Indexes									
A/CNK----	0.80	0.71	0.83	0.84	0.92	1.02	0.89	0.97	0.87
Mg #----	47.5	49.9	51.3	61.1	47.3	76.2	60.1	24.6	52.3
Normative minerals									
Q --------------	9.25	14.34	10.99	11.84	15.96	15.26	14.28	21.63	14.19
C --------------	CO	CO	.00	.00	CO	.91	.00	1.16	.26
or --------------	8.38	2.90	6.89	6.77	2.03	7.97	4.44	2.61	5.25
ab -------------	37.39	26.71	35.96	31.07	26.19	30.06	29.05	31.54	31.00
an -------------	19.97	30.42	22.31	26.46	31.85	26.76	28.09	22.31	26.02
di --------------	6.22	13.80	5.85	5.58	1.23	.00	3.32	CO	4.50
hy -------------	8.78	5.04	9.35	10.91	16.79	10.32	16.02	12.85	11.26
mt -------------	5.89	3.82	4.91	4.63	2.28	5.00	2.22	3.53	4.04
hm-------------	.00	.00	.00	.00	CO	1.43	CO	.00	.18
il ---------------	2.99	2.27	2.95	2.16	2.69	1.80	1.95	2.82	2.45
ap -------------	1.13	.71	SO	.59	1CO	.49	.62	1.55	.86
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Plagioclase normative An percent	34.8	53.3	38.3	46.0	54.9	47.1	49.2	41.4	45.6

Table 2. Major-element chemical composition (weight percent) of flow and dike rocks of the Admiralty Island Volcanics in order of increasing SiO_2 content recalculated in volatile-free amount, and CIPW norms based on volatile-free oxide amount —Continued

D. Silicic flows					
Field No.	92AF027A	91AF096A	91AF099A	91AF086A	average
Symbol	32	33	34	35	SIL
SiO_2	67.1	68.6	71.0	75.8	70.6
Al_2O_3	15.8	14.0	12.9	12.4	13.8
Fe_2O_3	4.80	.88	.88	1.39	1.99
FeO	.18	2.30	2.16	.42	1.27
MgO	.13	.58	.23	.20	.29
CaO	1.61	1.16	1.62	.06	1.11
Na_2O	4.93	1.94	3.43	2.72	3.26
K_2O	2.54	4.91	3.07	4.70	3.81
H_2O+	1.24	2.10	1.44	.81	1.40
H_2O-	.44	1.64	.60	.36	.76
TiO_2	.78	.20	.27	.17	.36
P_2O_5	.26	.03	.03	.03	.09
MnO	.05	.05	.07	.01	.04
CO_2	.04	1.34	1.43	<.01	.94
Total	99.9	99.7	99.1	99.1	99.5
LOI	1.50	3.72	2.90	1.16	2.32
Analyses recalculated in volatile-free amount					
SiO_2	68.34	72.48	74.2	77.43	73.1
Al_2O_3	16.09	14.79	13.5	12.67	14.3
Fe_2O_3	4.89	.93	.92	1.42	2.04
FeO	.18	2.43	2.26	.43	1.33
MgO	.13	.61	.24	.20	.30
CaO	1.64	1.23	1.69	.06	1.16
Na_2O	5.02	2.05	3.59	2.78	3.36
K_2O	2.59	5.19	3.21	4.80	3.95
TiO_2	.79	.21	.28	.17	.36
P_2O_5	.27	.03	.03	.03	.09
MnO	.05	.05	.07	.01	.05
Total	100.00	100.00	100.00	100.00	100.00
Indexes					
A/CNK	1.15	1.32	1.08	1.21	1.20
Mg #	56.3	31.0	15.9	45.8	37.3
Normative minerals					
Q	26.27	35.68	35.79	42.54	35.07
C	2.68	3.65	1.11	2.86	2.58
or	15.29	30.65	18.96	28.37	23.32
ab	42.49	17.34	30.34	23.51	28.42
an	6.41	5.87	8.20	.10	5.15
hy	.33	4.97	3.66	.51	2.37
mt	.00	1.35	1.33	.91	.90
hm	4.89	.00	.00	.79	1.42
ru	.53	.00	.00	.00	.13
il	.00	.40	.54	.33	.44
ap	.61	.07	.07	.07	.21
Total	100.00	100.00	100.00	100.00	100.00
Normative plagioclase An percent	13.1	25.3	21.3	0.4	15.0

tent (CREE for flow rocks, given above; average for dike rocks, 113 ppm; table 3*E*). Basalt and andesite flow and dike rocks of the field have chondrite-normalized HREE values that are much lower than those of silicic rocks (basalt and andesite, ~8 to 20 times chondrite; silicic rocks, ~20 to 40 times chondrite; fig. 10). The flow and dike rocks of the field show moderate enrichment in LREE in chondrite-normalized REE variation (fig. 10). The degree of fractionation in a REE pattern can also be expressed by the ratio between chondrite-normalized contents of a LREE (La or Ce) to a HREE (Yb or Y) (Rollinson, 1993). The volcanic rocks of the Admiralty Island field have moderate chondrite-normalized Ce/Yb $[(Ce/Yb)_N]$ values that generally increase with SiO_2 content (averages: basalt, 2.45; low-SiO_2 andesite, 3.31; silicic rocks, 3.32; high-SiO_2 andesite, 3.65; table 3).

The origin of the small, positive, chondrite-normalized Gd anomaly shown by many rocks of the Admiralty Island Volcanics (fig. 10) and the much larger positive Gd anomaly in rocks of the Icy Strait magmatic field (Brew, 1994) is uncertain. Gd anomalies of this type are not reported for other andesitic suites (for example, Gill, 1981; Sawlan, 1991). Analysis of Gd by instrumental neutron-activation analysis (INAA), such as used in the present study, is difficult (de Baar and others, 1985). de Baar and others (1985) considered the positive Gd anomalies by INAA analysis to be significant in their study. The common, small, negative Eu anomalies $[(Eu/Eu^*)_N < 1$; table 3; fig. 10] in the basalt and andesite flow and dike rocks might be attributed to inaccuracy in analysis of neighboring Gd, and so their significance is uncertain. The silicic rocks of the field, however, have much more pronounced, negative Eu anomalies that are not dependent on uncertanty of Gd analysis (fig. 10).

A variety of geochemical signatures using immobile trace elements have been found to fingerprint magmas that formed in different tectonic settings (for example, Wood, 1980; Pearce, 1982; Rollinson, 1993). The covariation between the immobile elements Ti, Zr, and Y used by Pearce and Cann (1973) to discriminate between a variety of tectonic settings of basaltic volcanism, however, does not indicate well the tectonic setting of the basaltic rocks of the Admiralty Island Volcanics (fig. 11). TiO_2 and Zr covariations in basalts of the Admiralty Island Volcanics plot within the field of ocean-floor basalt in the diagram of figure 12 and show characteristics of within-plate rather than volcanic-arc magmatism according to diagrams of Pearce (1982). The basalt and andesite flow rocks have closely similar MORB-normalized, multi-element variation patterns (fig. 13). Silicic rocks show greater enrichment in incompatible elements and strong depletions in Sr, P, Ti, and Cr compared with the more mafic rocks (fig. 13).

The relatively immobile high-field-strength elements (HFSE) afford the best indicators of tectonic setting in

Table 2. Major-element chemical composition (weight percent) of flow and dike rocks of the Admiralty Island Volcanics in order of increasing SiO_2 content recalculated in volatile-free amount, and CIPW norms based on volatile-free oxide amount —Continued

E. Dikes									
Field No.	91AF085B	91AF087B	91AF105C	92AF026B	91AF092B	91AF089B	92AF026C	91AF090C	average
Symbol	36	37	38	39	40	41	42	43	DK
SiO_2 --------	44.4	45.7	50.3	49.1	46.0	55.8	61.2	63.8	52.0
Al_2O_3 -------	15.3	15.9	18.5	16.0	14.2	16.3	16.3	15.3	16.0
Fe_2O_3 -------	3.71	3.45	4.54	1.44	1.24	1.63	.41	1.02	2.18
FeO ---------	5.28	5.23	3.75	6.52	8.51	4.85	3.07	3.67	5.11
MgO --------	5.77	4.29	4.78	5.51	2.98	3.66	1.83	1.90	3.84
CaO ---------	10.9	10.3	7.90	9.07	6.86	5.66	5.10	3.73	7.44
Na_2O -------	3.10	3.16	4.49	2.67	3.53	3.79	3.33	4.49	3.57
K_2O --------	.59	.29	.29	.48	1.40	1.75	1.46	2.48	1.09
H_2O^+ --------	2.46	2.88	.98	3.38	2.03	3.35	2.85	1.33	2.41
H_2O^- --------	.67	.38	3.85	.15	.71	.72	.38	.21	.88
TiO_2 --------	1.87	1.67	1.19	1.46	1.77	.99	1.02	.80	1.35
P_2O_5 --------	.57	.57	.29	.55	.35	.38	.34	.24	.41
MnO --------	.14	.16	.13	.13	.19	.12	.02	.09	.12
CO_2 ---------	4.87	5.87	.08	3.74	10.1	.34	3.06	.01	3.51
Total	99.6	99.8	101.1	100.2	99.9	99.3	100.4	99.1	99.9
LOI ---------	6.58	7.81	3.04	6.05	11.40	3.69	5.59	1.31	5.68
Analyses recalcuated in volatile free amount									
SiO_2 --------	48.5	50.4	52.3	52.8	52.9	58.8	65.1	65.4	55.8
Al_2O_3 -------	16.7	17.5	19.2	17.2	16.3	17.2	17.3	15.7	17.1
Fe_2O_3 -------	4.05	3.80	4.72	1.55	1.43	1.72	.44	1.05	2.35
FeO ---------	5.76	5.77	3.90	7.02	9.78	5.11	3.26	3.76	5.55
MgO --------	6.30	4.73	4.97	5.93	3.42	3.86	1.95	1.95	4.14
CaO ---------	11.90	11.35	8.22	9.76	7.88	5.96	5.42	3.83	8.04
Na_2O -------	3.38	3.48	4.67	2.87	4.06	3.99	3.54	4.60	3.82
K_2O --------	.64	.32	.30	.52	1.61	1.84	1.55	2.54	1.17
TiO_2 --------	2.04	1.84	1.24	1.57	2.03	1.04	1.08	.82	1.46
P_2O_5 --------	.62	.63	.30	.59	.40	.40	.36	.25	.44
MnO --------	.15	.18	.14	.14	.22	.13	.02	.09	.13
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Indexes									
A/CNK----	0.60	0.66	0.89	0.91	0.72	0.84	0.75	1.00	0.80
Mg #----	66.1	59.4	57.4	48.0	38.4	69.4	60.1	51.5	56.3
Normative minerals									
Q ------------	.00	1.66	.92	4.43	.00	8.91	23.26	16.88	7.01
C ------------	.00	.00	.00	.00	.00	.00	.83	.00	.10
or ------------	3.81	1.89	1.78	3.05	9.51	10.89	9.17	15.03	6.89
ab -----------	28.18	29.47	39.51	24.31	34.32	33.78	29.95	38.96	32.31
an -----------	28.47	31.24	30.64	32.56	21.56	23.49	24.53	14.63	25.89
ne ----------	.24	.00	.00	.00	.00	.00	.00	.00	.03
di ------------	21.12	16.89	6.42	9.78	12.56	2.84	.00	2.27	8.99
hy -----------	.00	8.38	10.83	19.27	12.78	14.69	8.73	8.59	10.41
ol ------------	7.00	.00	.00	.00	2.42	.00	.00	.00	1.18
mt -----------	5.87	5.51	6.85	2.25	2.07	2.49	.63	1.52	3.40
il -------------	3.88	3.50	2.35	2.98	3.86	1.98	2.06	1.56	2.77
ap -----------	1.44	1.46	.70	1.37	.93	.93	.84	.57	1.03
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Plagioclase normative An percent	49.9	51.5	43.7	57.3	38.6	41.0	45.0	27.3	44.3

altered volcanic rocks according to many authors (for example, Wood, 1980; Pearce, 1983; Arculus, 1987). Wood's (1980) diagram using the HFSE Th, Hf, and Ta can be applied to basaltic, intermediate, and silicic rocks and is particularly good for discriminating subduction-related volcanic-arc rocks from rocks of other origins (Rollinson, 1993). All rocks of the field of the Admiralty Island Volcanics, including the dikes, plot within Wood's Th-Hf-Ta field for within-plate volcanic rocks and lie in a field distinctly apart from volcanic rocks of either a subduction-related or a MORB origin (fig. 14). The covariation between MgO and TiO_2 contents additionally suggests a nonsubduction setting for the silicic rocks of the field (fig. 15).

DISCUSSION

Plate reconstructions (Plafker and others, 1994) show that northern southeastern Alaska had a transform tectonic setting by the time of formation of the Admiralty Island Volcanics in the Oligocene. The mostly andesitic volcanic rocks show geochemical characteristics of rocks formed in an extensional tectonic setting. Studies of other

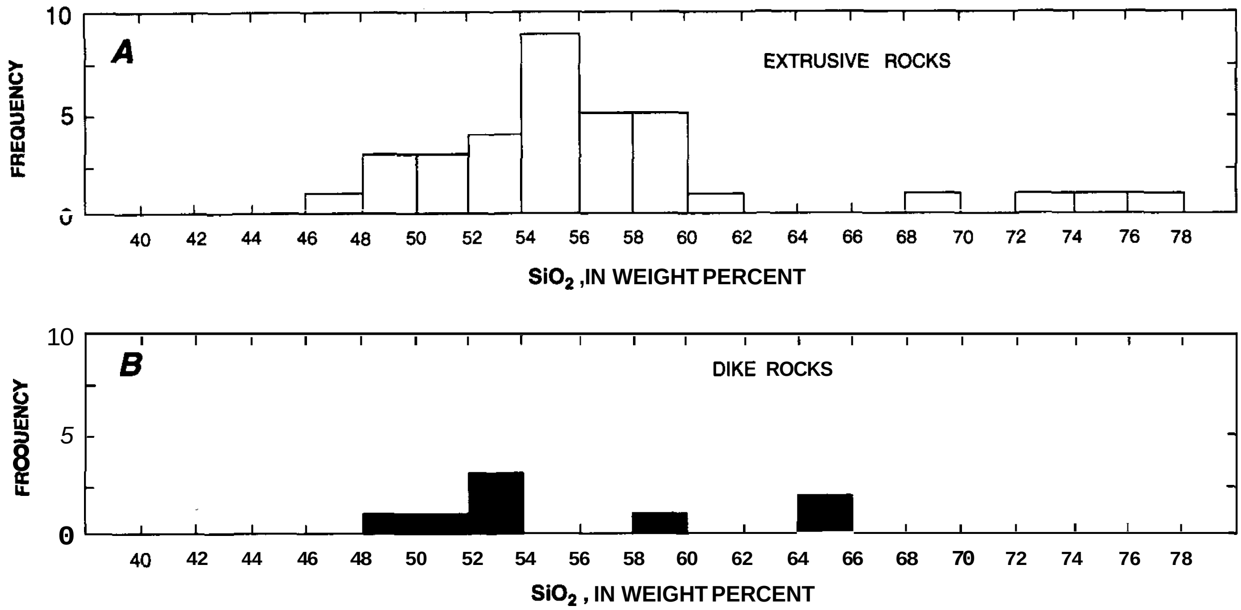

Figure 3. Histogram showing distribution of SiO_2 in flows (A) and dikes (*B*) of the Admiralty Island Volcanics.

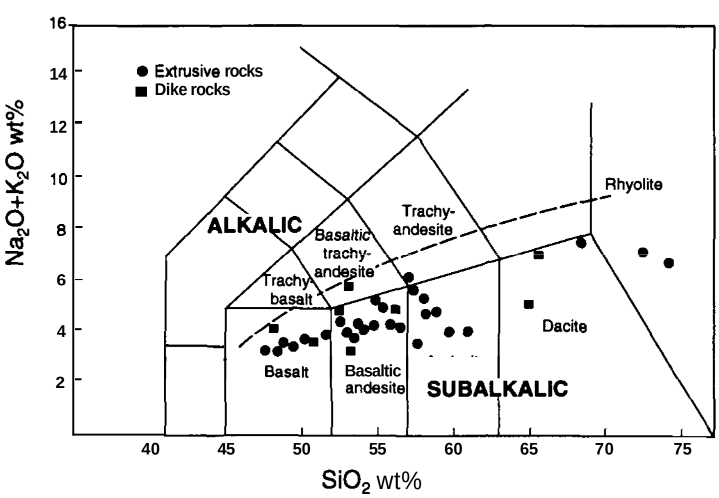

Figure 4. Nomenclature of flow and dike rocks of the Admiralty Island Volcanics based on the classification of Le Bas and others (1986). Heavy dashed line shows division between alkalic and subalkalic rocks of Irvine and Baragar (1971).

extensional zones of transform margins have shown that magmatic activity, which is typically of intermediate composition, was generated from heterogeneous mantle under varied tectonic settings (Pe-Piper and others, 1994). The identification of magmas formed in such a transform-margin setting by geochemical methods, however, is difficult (Pe-Piper and others, 1994). The Admiralty Island rocks show some features of orogenic-arc rocks but others of nonsubduction-related, within-plate extensional magmatism. The rocks of the field lack the alkalic characteristics of rocks typically found in within-plate, intracontinental-rift zones (Hess, 1989; Harangi, 1994), and the abundance of andesitic rocks in the field contrasts with the limited abundance of such rocks of intermediate composition found in transform-related, bimodal basalt-rhyolite volcanic suites of other areas (Lipman and others, 1978).

The volcanism on Admiralty Island followed a long history of magmatic-arc activity in northern southeastern Alaska that was related to Pacific plate slab subduction (62-48 Ma; Plafker and others, 1994). After subduction, the development of a transform plate boundary by Oligocene time led to the formation of a "slab-free" region along this part of southeastern Alaska, analogous to the

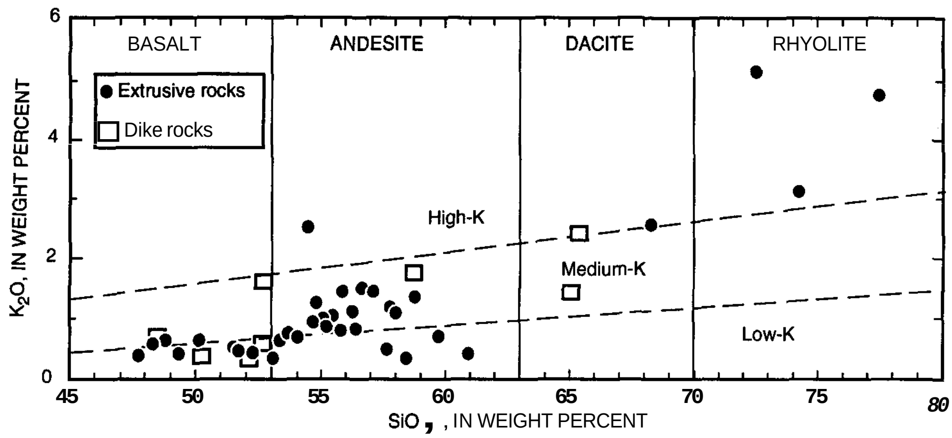

Figure 5. K_2O versus SiO_2 variation in flow and dike rocks of the Admiralty Island Volcanics, based on diagram of Gill (1981).

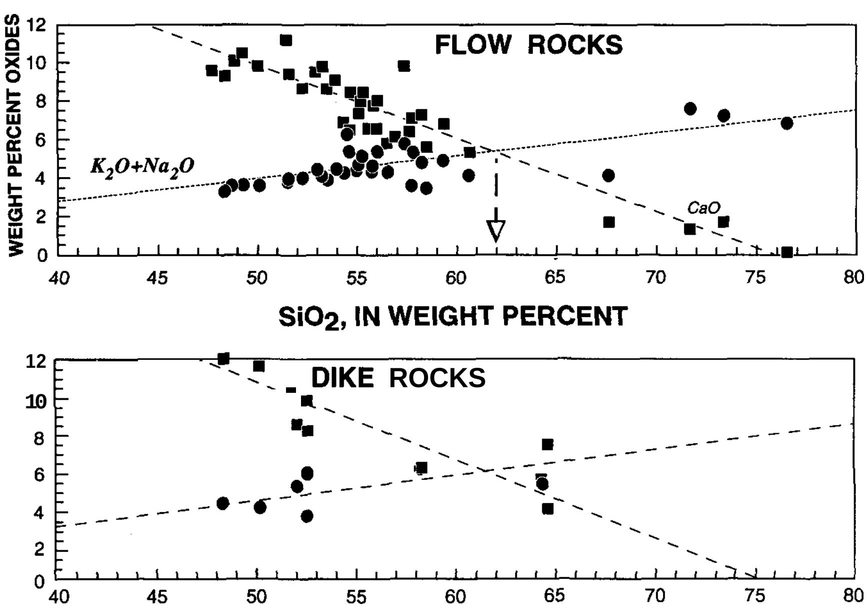

Figure 6. Variation of CaO and Na_2O+K_2O with SiO_2 in flow and dike rocks of the Admiralty Island Volcanics. Lines show best fit of data points by least-squares regression. "Peacock" (alkali-lime) index from intersection (Peacock, 1931), marked by arrow.

situation behind the San **Andreas** transform fault of California following termination of subduction activity (Dickinson and Snyder, 1979). The Admiralty Island volcanism occurred about 300 km east of the transform fault marking the boundary between the Pacific and North American plates.

The flows and dikes of the Admiralty Island volcanic field represent derivative melts, as shown by Mg numbers that are much lower than those of primary melts of mantle origin (>67; Gill, 1981) and by Ni contents of the most mafic rocks (20-86 ppm, table 3A) that are much below values in rocks of primary mantle origin (300-400

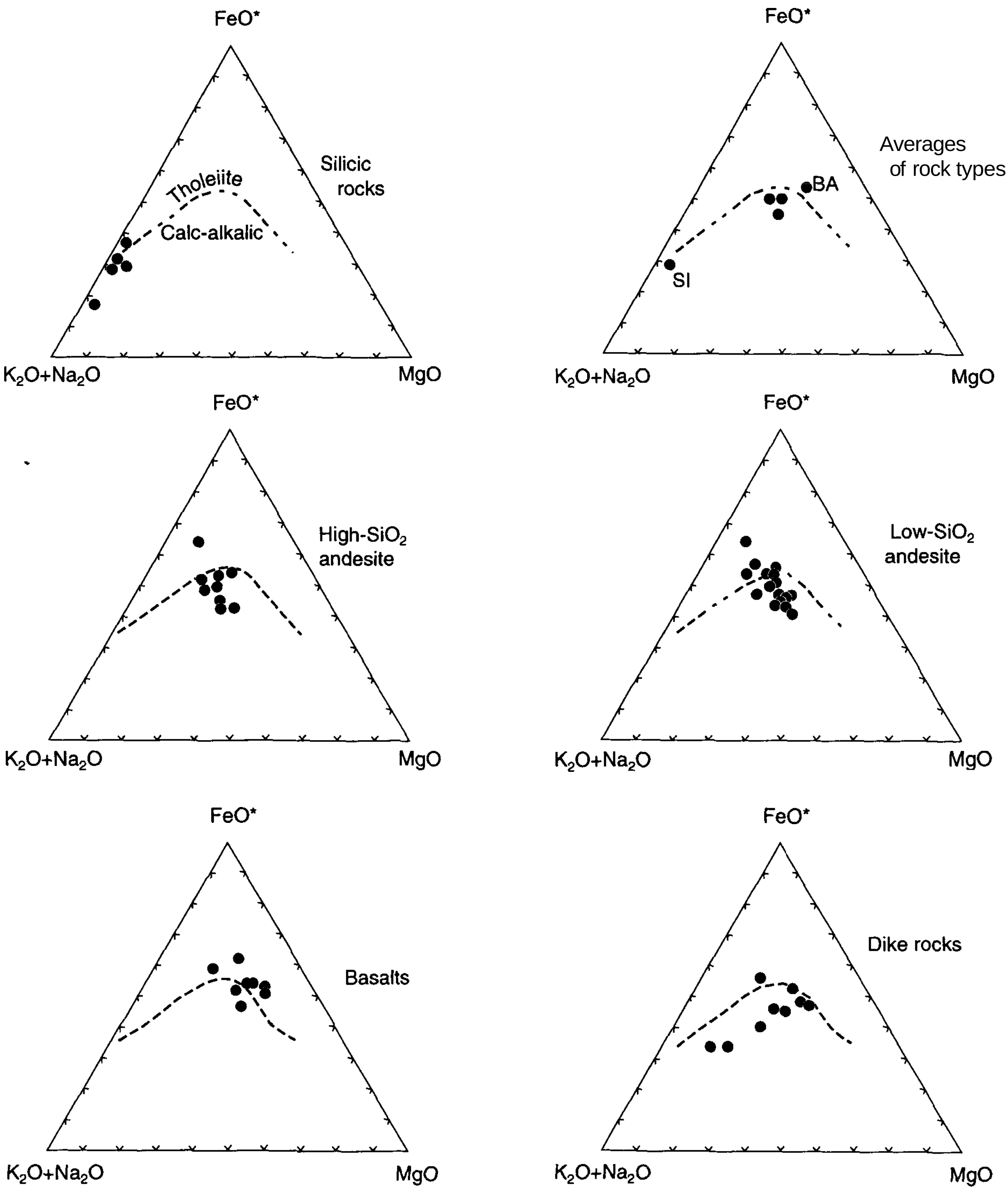

Figure 7 Ternary (AFM) diagrams, showing variation of (A) $Na_2O + K_2O$, (F) FeO* ($FeO + 0.9 \times Fe_2O_3$), and (M) MgO for the Admiralty Island Volcanics. Tholeiitic and calc-alkalic fields from Irvine and Baragar (1971).

ppm; Harangi, 1994). The lack of isotopic data limits conjecture on the nature of the source. Many compositional variations of the rocks can be attributed to fractionation. An absence of hornblende phenocrysts in flow rocks is possibly explained by removal of hornblende from the melt, as is suggested by the inverse variation between A/CNK value and CaO content (Liggett, 1990) in the rocks of this volcanic field. The origin of the pronounced negative Eu anomaly of the silicic rocks (fig. 10) can be explained by fractionation of plagioclase (Rollinson, 1993).

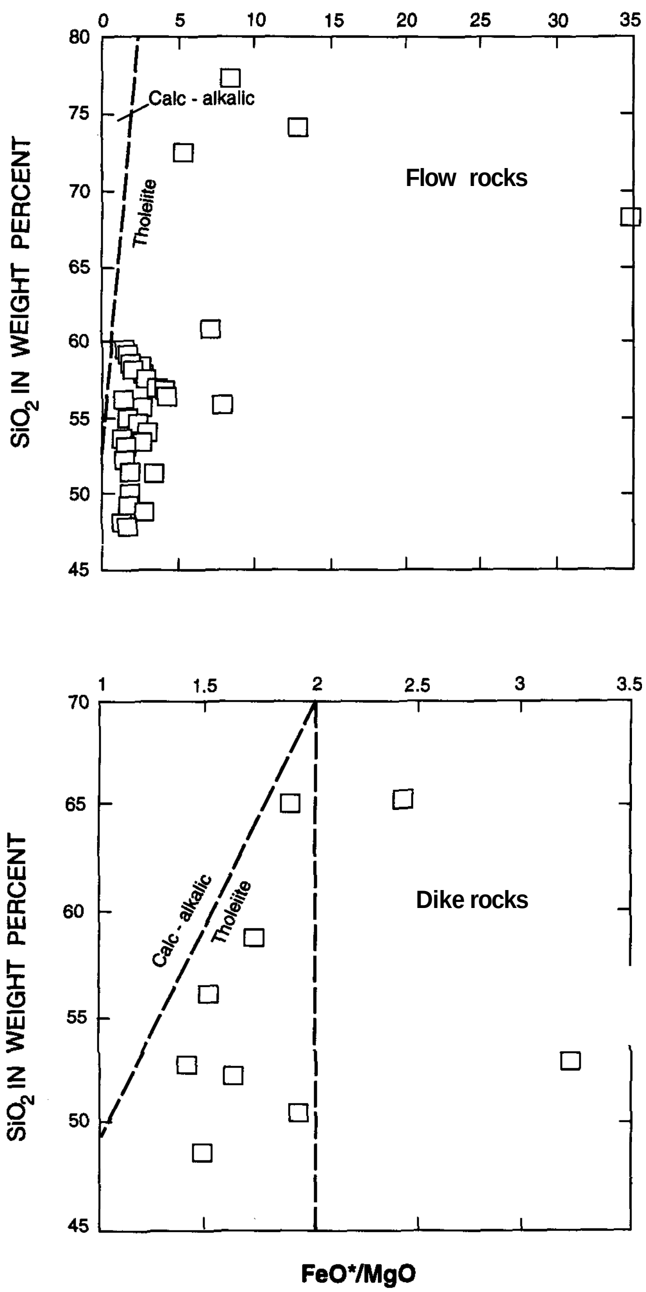

Figure 8. Variation between SiO_2 and FeO*/MgO in rocks of the Admiralty Island Volcanics, showing dividing line of calc-alkalic and tholeiitic compositions of Miyashiro (1974).

The petrologic nature and tectonic setting of the Admiralty Island Volcanics inferred from geochemical characteristics show differences according to different major and minor elements. Major-element compositions of the rocks, for example, are generally typical for orogenic, arc-related volcanic suites, but the suite lacks the high-K, shoshonitic basalt and andesite compositions that characterize some subduction-related orogenic andesitic suites (Ewart, 1982). The rocks of the field have tholeiitic composition rather than the alkalic characteristics of subduction-related volcanic rocks of Baja California (Sawlan, 1991). The tholeiitic nature of the Admiralty Island Volcanics does not exclude a subduction-related origin, however, because rocks of tholeiitic composition are found in arc and back-arc rift settings (Sawlan, 1991; Tamura, 1994; Wharton and others, 1995).

The trace-element characteristics show the principal differences between the Admiralty Island Volcanics and volcanic-arc (orogenic) rocks formed by subduction processes. Although Th contents of the Admiralty Island Volcanics are generally within the range found in orogenic andesite (1-5 ppm; Gill, 1981), Zr abundances are much higher than typical for such rocks (50-150 ppm; Gill, 1981). Average K/Rb values of rocks of the Admiralty Island field are similar to those of calc-alkalic suites and much lower than those of island-arc tholeiitic suites (respectively, 400-500, 1000; Jakes and Gill, 1970). The average TiO_2 content of the basalt flows (1.8 weight percent, table 2*A*) is generally higher than typical for arc-related volcanic rocks (<1.3 weight percent; Gill, 1981) and about the same as for rift-related tholeiite of the Gulf of California (1.1-2.6 weight percent; Sawlan, 1991). The Admiralty Island volcanic rocks have more fractionated chondrite-normalized REE patterns and much higher HREE contents (10-20 times chondrite values) than is typical for island-arc tholeiite (Jakes and Gill, 1970) and for MORB. Chondrite-normalized REE patterns for all rocks of the field are closely similar to those of a (Proterozoic) bimodal, calc-alkalic, continental-margin volcanic arc reported by Condie and Shadel (1984).

The Admiralty Island rocks generally show the enrichments in incompatible elements (fig. 13) that characterize volcanic rocks of a within-plate setting and that differ from the typical depletion of these elements in subduction-related volcanic rocks (Pearce, 1983). Rocks of the Admiralty Island field lack the Ta and Nb depletions, relative to Th and Ce (fig. 13), that typify subduction-related rocks of volcanic arcs (Pearce, 1983; Sawlan, 1991; Wharton and others, 1995) and back-arc basins (Gamble and others, 1995). Multielement variation diagrams of the Admiralty Island rocks (fig. 13) are also more like those of nonsubduction-related rift-zone volcanic rocks than subduction-related rocks of the Gulf of California (Sawlan, 1991). The tectonic setting of the Admiralty Island volcanism is therefore interpreted to be that of within-plate extension (fig. 14). The rifting in this area did not progress to the stage of development of new oceanic crust as in the Gulf of California (Sawlan, 1991; Sawlan and Smith, 1984).

RELATION TO TKOPE-PORTLAND PENINSULA MAGMATIC BELT

The Admiralty Island Volcanics is the largest volcanic field of the Tkope-Portland Peninsula magmatic belt, which extends along almost all of southeastern Alaska. This report on the Admiralty Island Volcanics provides the first critical trace-element data for rocks of this belt. The approximate parallelism of the belt with the continental margin and its proximity to the margin (fig. 1) are suggestive of a back-arc rift setting, but the geochemical characteristics of the rocks and the cessation of subduction before the volcanism indicate that back-arc processes were not involved in the magma generation. The Tkope-Portland Peninsula magmatic belt differs from typical intracontinental-rift belts in that it apparently lacks alkalic rocks typical of such belts (Hess, 1989; Harangi, 1994). The origin of the magmatic belt does not appear to be related to the Chatham Strait segment of the Denali fault system, which crosses the belt at a low angle and in which right-lateral transcurrent movement began by about 62 Ma according to Plafker and others (1994) and continued until after the time of the Admiralty Island volcanism (fig. 1). The spacial relation of the fault to the Admiralty Island volcanic field, however, suggests that fault activity may have played a role in the development of a conduit system for eruption of the volcanic rocks.

The origin of the Admiralty Island Volcanics and the Tkope-Portland Peninsula magmatic belt may be related to processes of extension and crustal thinning developed in an area thermally weakened by asthenosphere upwelling and crustal underplating by intrusion of mafic magmas (Liu and Furlong, 1994; Keen and others, 1994), as proposed for the origin of magmas in the "slab-window" of the San Andreas transform fault (Dickinson and Snyder, 1979). The linear zone of coast-parallel extension and volcanism of the belt may have resulted from lithospheric instability following the Eocene and older subduction activity. The long duration of magmatism in the Tkope-Portland magmatic Peninsula belt (35-5 Ma; Brew, 1994) is similar to that of other transform-related regions (Dickinson and Snyder, 1979). To the north, the late Cenozoic parts of the Wrangell volcanic field in Canada record a transition from a subduction margin to a transform margin (Skulski and others, 1991), while the Wrangell field in Alaska continued to record arc volcanism associated with subduction of the north-moving Pacific plate (Richter and others, 1990).

SUMMARY AND CONCLUSIONS

The Admiralty Island Volcanics consists of a 3,000-m-thick field of low-MgO, medium- and low-K, mostly andesitic flows and dikes that covers an area of about 1,000 km^2 on southernmost Admiralty Island. The volcanic field is composed dominantly of low-SiO_2 andesite flows that are interlayered with flows of high-SiO_2 andesite, basalt, and much less abundant dacite and rhyolite. Volatile-free SiO_2 content of flow rocks ranges from 47 to 77 weight percent and shows a SiO_2 gap at 62-68

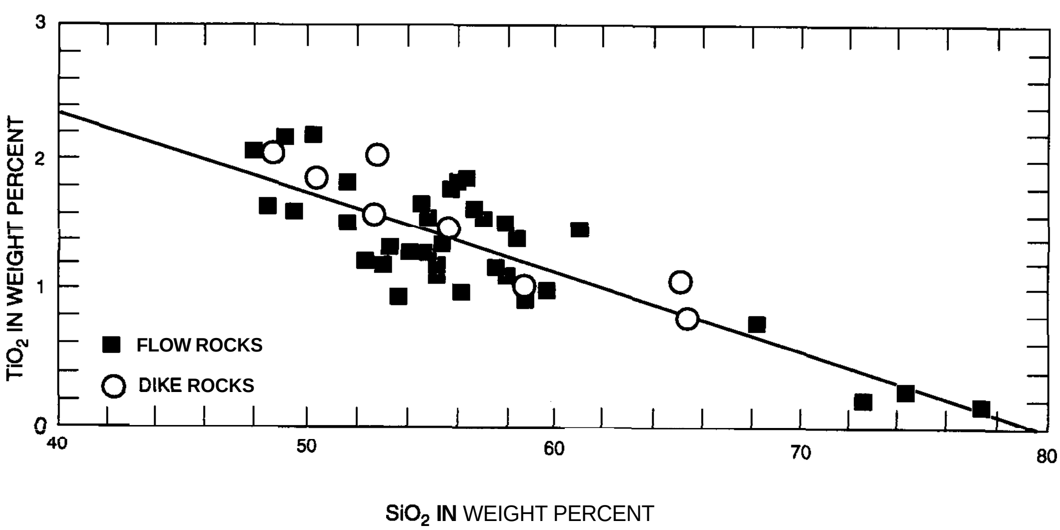

Figure 9. Variation between TiO_2 and SiO_2 in rocks of the Admiralty Island Volcanics. Line shows best fit of data points by least-squares regression.

Table 3. Average trace-element content (parts per million) and ratios for flow and dike rocks of the Admiralty Island Volcanics

[Samples analyzed in laboratories of the U.S. Geological Survey by methods described in Baedecker (1987); X-ray fluorescence (XRF) methods described in Johnson and King (1987) and King and Lindsay (1990); V, by method in Golightly and others (1987); instrumental neutron-activation analysis (INAA) methods in Baedecker and McKown (1987); nd, not determined. Analysts: energy-dispersive XRF methods (#), Judith Kent, B.W. King; INAA (Δ), C.A. Palmer; direct-current arc emission spectrographic analysis (@), P.J. Lamothe]

A. Basalt flows									
Field No.	91AF095A	91AF102A	91AF093A	91AF091A	92AF024A	91AF103A	91AF101A	91AF088A	average
Plot symbol	1	2	3	4	5	6	7	8	BA
K-group elements									
Ba#	64	770	240	168	270	345	250	150	282
CsΔ	.23	.45	.27	<.16	<.17	.27	.74	.19	.38
RbΔ	16	4.8	15	4.5	10	7.3	11	<6	10
Sr#	250	385	275	315	450	360	395	300	341
REE group elements									
LaΔ	7.96	7.13	12.5	8.46	16.8	16.1	15.2	11.1	11.9
CeΔ	20	17	28.6	19	37	34.1	33.7	24	27
NdΔ	14	10	18	14	24	18	19	13	16
SmΔ	4.46	3.73	5.34	3.58	6.14	5.09	5.24	3.79	4.67
EuΔ	1.6	1.3	1.7	1.3	2.1	1.6	1.7	1.3	1.6
GdΔ	6.3	4.4	7.0	4.6	8.0	6.8	6.7	4.5	6.0
TbΔ	.86	.71	.993	.68	.98	.87	.861	.67	.83
TmΔ	nd	nd	nd	nd	nd	nd	nd	nd	nd
YbΔ	2.8	2.6	3.2	2.3	2.9	3.1	3.06	2.3	2.8
LuΔ	.414	.403	.458	.330	.428	.435	.428	.340	.405
Sum REE	58.0	46.9	77.3	53.9	97.9	85.7	85.5	60.7	70.7
Y#	40	32	38	33	34	27	34	20	32
Th group									
ThΔ	0.70	0.52	1.56	0.71	1.40	2.52	1.40	1.40	1.28
UΔ	.24	<.20	.56	2.00	.43	.87	.68	.52	.76
Ti group									
Zr#	140	122	176	120	168	174	168	134	150
HfΔ	3.24	2.61	3.85	2.60	3.50	3.72	3.50	2.93	3.24
Nb#	16	13	17	14	20	16	18	<10	16
TaΔ	.63	.45	.838	.55	.95	.88	.77	.52	.70
Compatible group									
CoΔ	46.9	44.9	39.9	37.4	34.0	25.0	29.5	31.1	36.1
CrΔ	87.2	77.8	60.1	117	92	34.6	96	132	87
Ni#	51	86	44	32	43	20	29	35	43
ScΔ	32.5	31.9	30.7	31.2	33.0	25.2	28.9	25.8	29.9
V@	240	220	270	260	264	230	190	190	233
Chalcophile group									
Cu#	31	31	39	42	22	27	23	19	29
ZnΔ	87	72	95	67	84	85	86	68	80
Ratios									
K/Rb	176	882	321	701	506	523	347.2	nd	494
Rb/Sr	.06	.01	.05	.01	.02	.02	.03	nd	.03
$(Eu/Eu^*)_N$	.93	.98	.84	.98	.92	.84	.89	.97	.92
$(Ce/Yb)_N$	1.82	1.66	2.27	2.10	3.24	2.80	2.80,	2.65	2.45

Table 3. Average trace-element content (parts per million) and ratios for flow and dike rocks of the Admiralty Island Volcanics--Continued

B. Low-SiO_2 andesite flows																
Field No.	91AF106A	92AF023A	91AF089A	92AF023B	91AF086B	91AF097A	92AF031B	92AF031A	92AF105A	92AF026A	91AF087A	91AF092A	91AF085A	92AF030A	91DB034A	average
Plot symbol	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	AN-L
K-group elements																
Ba#----------	196	255	300	295	250	580	370	375	310	405	850	750	465	285	560	416
CsΔ----------	<.14	.20	.54	<.24	3.	.41	.21	.30	.16	.38	.81	.34	.23	.36	.51	.57
RbΔ----------	<11	9.4	14	11	81	26	16	20	18	22	13	27	20	18	32	23
Sr#----------	395	390	435	385	194	290	480	460	345	415	330	290	365	385	305	364
REE group elements																
LaΔ----------	17.5	16.4	12.1	16.9	14.7	19.8	18.2	17.9	18.1	18.5	19.0	23.4	23.2	17.3	28.6	18.8
CeΔ----------	35.6	33.4	25.0	34.6	31.0	42.0	35.0	35.0	35.6	36.0	39.2	50.0	48.0	33.0	58.7	38.1
NdΔ----------	18	18	12	18	16	23	17	18	17	18	19	29	25	17	31	20
SmΔ----------	4.73	4.61	3.16	4.78	4.34	6.90	4.42	4.40	4.42	4.43	4.99	8.55	7.19	4.18	8.82	5.33
EuΔ----------	1.41	1.60	1.10	1.70	1.40	1.90	1.40	1.40	1.32	1.40	1.50	2.44	2.09	1.30	2.46	1.63
GdΔ----------	5.9	5.5	4.5	6.0	5.4	7.8	5.5	4.9	5.1	5.4	6.0	10	7.7	5.9	10	6.4
TbΔ----------	.777	.750	.530	.790	.700	1.21	.680	.670	.714	.710	.760	1.48	1.18	.680	1.40	.87
TmΔ----------	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	-
YbΔ----------	2.71	2.56	1.90	2.63	2.40	4.50	2.24	2.20	2.39	2.20	2.30	5.27	3.90	2.20	4.60	2.93
LuΔ----------	.387	.387	.250	.402	.345	.659	.300	.300	.360	.330	.337	.749	.541	.340	.659	.420
Sum REE---	86.63	82.82	60.29	85.40	75.94	107.11	84.44	84.47	84.64	86.64	92.75	130.14	118.66	81.56	145.58	93.80
Y#----------		25	23	30	30		25	26	27	30	30	51	49	26	52	34
Th group																
ThΔ----------	2.19	1.99	1.90	2.10	2.20	3.17	2.50	2.60	2.71	2.80	3.00	3.33	3.30	2.50	4.10	2.69
UΔ----------	.77	.72	.62	.82	.83	1.6	.99	.99	.99	1.10	.98	1.50	1.10	.91	1.50	1.03
Compatible group																
Zr#----------	184	174	126	182	154	405	150	154	198	160	184	265	245	152	265	200
HfΔ----------	3.91	3.60	2.60	3.68	3.30	7.75	3.33	3.40	3.99	3.44	3.90	5.97	5.13	3.40	5.72	4.21
Nb#----------	17	16	<10	16	14	20	13	14	18	14	20	21	27	14	24	18
TaΔ----------	.88	.82	.612	.86	.78	.91	.816	.809	.878	.746	.95	1.20	1.24	.79	1.30	.91
CoΔ----------	30.4	25.5	27.6	25.8	22.8	31.0	27.2	27.0	26.4	22.0	23.9	18.3	16.2	29.0	14.1	24.5
CrΔ----------	101	26.0	108	26.0	28.1	24.6	75.1	74.6	50.6	65.3	5.90	3.10	2.60	140	<4	52.2
Ni#----------	57	15	60	11	10	36	24	26	46	15	11	<10	<10	63	<10	31
ScΔ----------	22.8	27.1	19.3	27.5	23.9	21.6	23.8	23.8	18.7	24.7	21.8	24.6	25.0	20.0	22.1	23.1
V@----------	180	179	140	164	205	180	196	172	150	188	240	150	150	132	95	168
Chalcophile group																
Cu#	45	45	39	43	25	26	42	36	28	15	27	22	<10	47	17	33
ZnΔ----------	78	80	59	80	74	111	74	74	75	71	81	138	100	66	110	85
Ratios																
K/Rb	nd	486	415	491	224	383	483	407	401	385	466	412	448	369	363	409
Rb/Sr	nd	.02	.03	.03	.42	.09	.03	.04	.05	.05	.04	.09	.05	.05	.10	.08
$(Eu/Eu^*)_N$	.82	.97	.90	.98	.89	.79	.87	.92	.85	.88	.84	.81	.86	.80	.80	.87
$(Ce/Yb)_N$	3.34	3.32	3.35	3.35	3.29	2.37	3.97	4.05	3.79	4.16	4.33	2.41	3.13	3.82	3.25	3.31

Table 3. Average trace-element content (parts per million) and ratios for flow and dike rocks of the Admiralty Island Volcanics—Continued

	C. High-SiO_2 andesite flows								
Field No.	91AF098A	91AF104A	92AF029A	92AF027B	92AF025A	92AF028A	91AF090B	91AF100A	average
Plot symbol	24	25	26	27	28	29	30	31	AN-H
	K-group elements								
Ba#	510	350	415	445	365	390	300	310	386
CsΔ	.44	<.16	.33	.39	.34	.87	.55	.33	.46
RbΔ	33	11	23	25	8.6	29	21	<9	22
Sr#	310	315	355	355	410	250	395	245	329
	REE-group elements								
LaΔ	25.4	17.4	20.8	17.8	19.3	17.6	16.9	27.7	20.4
CeΔ	52.4	35.1	41.0	34.6	38.1	27.6	33.4	59.5	40.2
NdΔ	27	17	21	17	20	16	15	35	21
SmΔ	7.30	4.11	5.29	4.26	4.60	3.93	3.55	9.12	5.27
EuΔ	2.0	1.3	1.6	1.3	1.6	1.1	1.1	2.7	1.6
GdΔ	8.0	5.3	6.4	4.8	5.6	4.5	4.2	9.4	6.0
TbΔ	1.20	.66	.85	.72	.71	.60	.564	1.48	.85
TmΔ	nd	nd	nd	nd	nd	nd	nd	nd	nd
YbΔ	4.0	2.2	2.9	2.4	2.1	1.8	1.8	5.3	2.8
LuΔ	.57	.310	.434	.352	.290	.271	.250	.75	.40
Sum REE	127.30	83.07	99.84	82.89	92.01	73.13	76.55	150.20	98.12
Y#	43	25	39	26	25	28	25	57	34
	Th group								
ThΔ	4.15	3.29	3.50	3.52	2.90	2.70	3.72	3.28	3.38
UΔ	1.4	1.1	1.5	1.3	1.7	.9	1.3	1.3	1.3
	Ti group								
Zr#	245	164	215	172	158	146	168	320	199
HfΔ	5.32	3.59	4.50	3.81	3.57	3.13	3.50	6.71	4.27
Nb#	22	14	19	18	12	15	18	26	18
TaΔ	1.16	.84	1.00	.844	.829	.654	.82	1.50	.96
	Compatible group								
CoΔ	17.1	19.6	21.0	24.2	21.5	20.5	24.7	17.1	20.7
CrΔ	10	13	6	61	13	121	101	2.2	41
Ni#	<10	<10	5	26	5	46	62	<10	29
ScΔ	21.6	19.7	21.6	21.4	18.3	19.2	16.8	24.7	20.4
V@	150	150	197	145	150	124	130	37	135
	Chalcophile group								
Cu#	19	18	22	30	16	35	12	15	21
ZnΔ	102	73	77	78	90	72	69	168	91
	Ratios								
K/Rb	350	340	415	372	299	366	289	nd	347
Rb/Sr	.11	.03	.06	.07	.02	.12	.05	nd	.07
$(Eu/Eu^*)_N$	.80	.86	.84	.89	.97	.80	.91	.89	.87
$(Ce/Yb)_N$	3.33	4.06	3.60	3.67	4.61	3.90	4.72	2.86	3.65

weight percent between rocks of andesitic and dacitic composition, which is similar to the gap recorded in other rocks of the Tkope-Portland Peninsula magmatic belt. The flows were probably fed from fissure eruptions that are represented by numerous dikes that cut the volcanic sequence. Although the rocks show enrichments in incompatible elements that are characteristic of a within-plate extensional setting and lack the Ta and Nb depletions that typify subduction-related rocks, the major-element geochemistry is similar to that of subduction-related oro-

Table 3. Average trace-element content (parts per million) and ratios for flow and dike rocks of the Admiralty Island Volcanics—Continued

D. Silicic flows					
Field No.--	92AF027A	91AF096A	91AF099A	91AF086A	average
Plot symbol-	32	33	34	35	SIL
K-group elements					
Ba#--------	970	740	1500	880	1023
CsΔ--------	1.0	1.5	1.3	.94	1.2
RbΔ--------	51	158	64.8	129	101
Sr#---------	180	25	84	53	86
REE-group elements					
LaΔ--------	51.1	36.6	37.6	38.2	40.9
CeΔ--------	89.0	68.0	73.7	58.0	72.2
NdΔ--------	47.1	29.0	34.0	28.0	34.5
SmΔ-------	11.70	7.05	3.58	6.53	7.22
EuΔ--------	2.50	1.14	1.25	.391	1.32
GdΔ--------	13.0	7.6	9.6	7.3	9.4
TbΔ--------	1.80	1.20	1.52	1.09	1.40
TmΔ-------	nd	nd	nd	nd	nd
YbΔ--------	6.10	4.90	6.30	4.74	5.51
LuΔ--------	.879	.690	.894	,618	.770
Sum REE-	222.3	155.5	167.6	144.3	172.4
Y#----------	73	53	68	52	62
Th group					
ThΔ--------	6.60	13.10	9.37	16.50	11.39
UΔ---------	3.00	5.19	3.86	5.87	4.48
Ti group					
Zr#---------	450	385	455	220	378
HfΔ--------	9.30	9.10	9.83	6.34	8.64
Nb#--------	35	21	19	17	23
TaΔ--------	2.00	1.56	1.30	1.07	1.48
Compatible group					
CoΔ--------	4.10	.62	.46	.77	1.49
CrΔ--------	2.0	<1.7	2.1	1.6	1.9
Ni#---------	5	<10	<10	<10	5
ScΔ--------	12.0	5.44	10.7	2.18	7.6
V@--------	31	<10	<10	<10	31
Chalcophile group					
Cu#--------	11	<10	12	<10	12
ZnΔ--------	100	84.6	98.4	65.1	87.0
Ratios					
K/Rb	413.4	258.0	393.3	302.5	341.8
Rb/Sr	.28	6.32	.77	2.43	2.45
$(Eu/Eu^*)_N$	.62	.48	.62	.17	.47
$(Ce/Yb)_N$	3.71	3.53	2.98	3.11	3.32

genic andesite and basalt. The subalkaline character of the rocks differs from the typically alkalic character of intracontinental-rift volcanic rocks.

The volcanism on Admiralty Island occurred about 10 m.y. after termination of Kula plate convergence and during right-lateral transform motion of an ancestral Queen Charlotte-Fairweather fault between the Pacific and North American plates. The Admiralty Island Volcanics is part of the Tkope-Portland Peninsula magmatic belt that extends along most of southeastern Alaska. Although the major-element composition of the Admiralty Island field and spatial distribution of the Tkope-Portland Peninsula magmatic belt are broadly suggestive of subduction-related volcanism, the trace-element composition and the age of the belt are inconsistent with such an origin. The position, timing, and trace-element composition instead suggest that the Admiralty Island Volcanics is the result of magmatic processes in a setting continentward of a transform fault. The Admiralty Island Volcanics differs from other transform-related volcanic fields in that rocks of andesitic composition are abundant. We suggest that the magmatism of the belt may be related to asthenospheric upwelling in a slab-window region following change from subduction to transform tectonism. Although coeval with early phases of arc volcanism of the Wrangell volcanic field, the Oligocene volcanism of the Admiralty Island field marks the cessation of subduction magmatism in southeastern Alaska and the onset of transform motion that continues in the area today.

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Table 3. Average trace-element content (parts per million) and ratios for flow and dike rocks of the Admiralty Island Volcanics—Continued

E. Dikes									
Field No.	91AF085B	91AF087B	91AF105C	92AF026B	91AF092B	91AF089B	92AF026C	91AF090C	average
Plot symbol	36	37	38	39	40	41	42	43	DK
K-group elements									
$Ba^{\#}$	435	600	205	290	610	510	405	750	476
Cs^{Δ}	.17	.56	<.09	1.60	.67	1.10	.64	.82	.79
Rb^{Δ}	5.5	5.4	<4	11	31	35	37	57	26
$Sr^{\#}$	850	760	390	610	340	530	310	285	509
REE-group									
La^{Δ}	20.5	21.5	19.6	24.2	16.1	24.2	39.5	30.1	24.5
Ce^{Δ}	47.0	46.8	38.4	50.0	36.0	45.5	70.0	57.8	48.9
Nd^{Δ}	27	23	19	25	20	19	29	24	23
Sm^{Δ}	6.33	5.76	4.73	5.74	5.61	4.55	6.14	5.62	5.56
Eu^{Δ}	1.90	1.70	1.35	1.70	1.71	1.32	1.20	1.29	1.52
Gd^{Δ}	5.9	6.3	5.6	6.4	7.1	5.1	6.7	5.4	6.1
Tb^{Δ}	.800	.722	.760	.730	.957	.630	.780	.830	.780
Tm^{Δ}	nd	nd	nd	nd	nd	nd	nd	nd	nd
Yb^{Δ}	1.90	1.80	2.62	2.00	3.23	2.00	2.65	3.10	2.41
Lu^{Δ}	.270	.270	.399	.320	.483	.290	.370	.440	.355
Sum REE	111.3	107.6	92.1	115.8	90.7	102.3	156.0	128.1	113.0
$Y^{\#}$	24	21	20	23	39	23	34	32	27
Th group									
Th^{Δ}	1.20	1.60	2.89	2.00	2.30	3.80	6.50	7.79	3.51
U^{Δ}	.51	.55	1.10	.80	1.10	1.40	2.50	3.00	1.37
Ti group									
$Zr^{\#}$	168	162	198	196	186	205	265	320	213
Hf^{Δ}	3.15	3.30	4.25	4.00	4.12	4.07	5.50	7.00	4.42
$Nb^{\#}$	20	15	14	20	15	19	20	17	18
Ta^{Δ}	.93	.97	.96	1.24	.849	1.10	1.40	1.40	1.11
Compatible group									
Co^{Δ}	32.4	29.1	27.2	29.5	24.2	20.4	13.3	10.9	23.4
Cr^{Δ}	170	88.8	51.4	140	12.0	87.8	3.0	28.6	72.7
$Ni^{\#}$	65	34	43	75	<10	41	5	17	40
Sc^{Δ}	27.5	22.5	19.3	17.9	31.1	13.9	11.5	10.8	19.3
$V^{@}$	250	210	160	128	250	110	79	59	156
Chalcophile group									
$Cu^{\#}$	34	31	40	33	<10	24	14	23	28
Zn^{Δ}	73.3	80.3	81.1	86	86	76.9	9.3	75	71
Ratios									
K/Rb	891	446	362	375	415	328	361	454	196
Rb/Sr	.01	.01	nd	.02	.09	.07	.12	.20	.07
$(Eu/Eu^{*})_N$	.94	.86	.80	.86	.83	.84	.57	.71	.80
$(Ce/Yb)_N$	6.29	6.61	5.79	4.74	2.83	3.73	6.36	6.72	5.16

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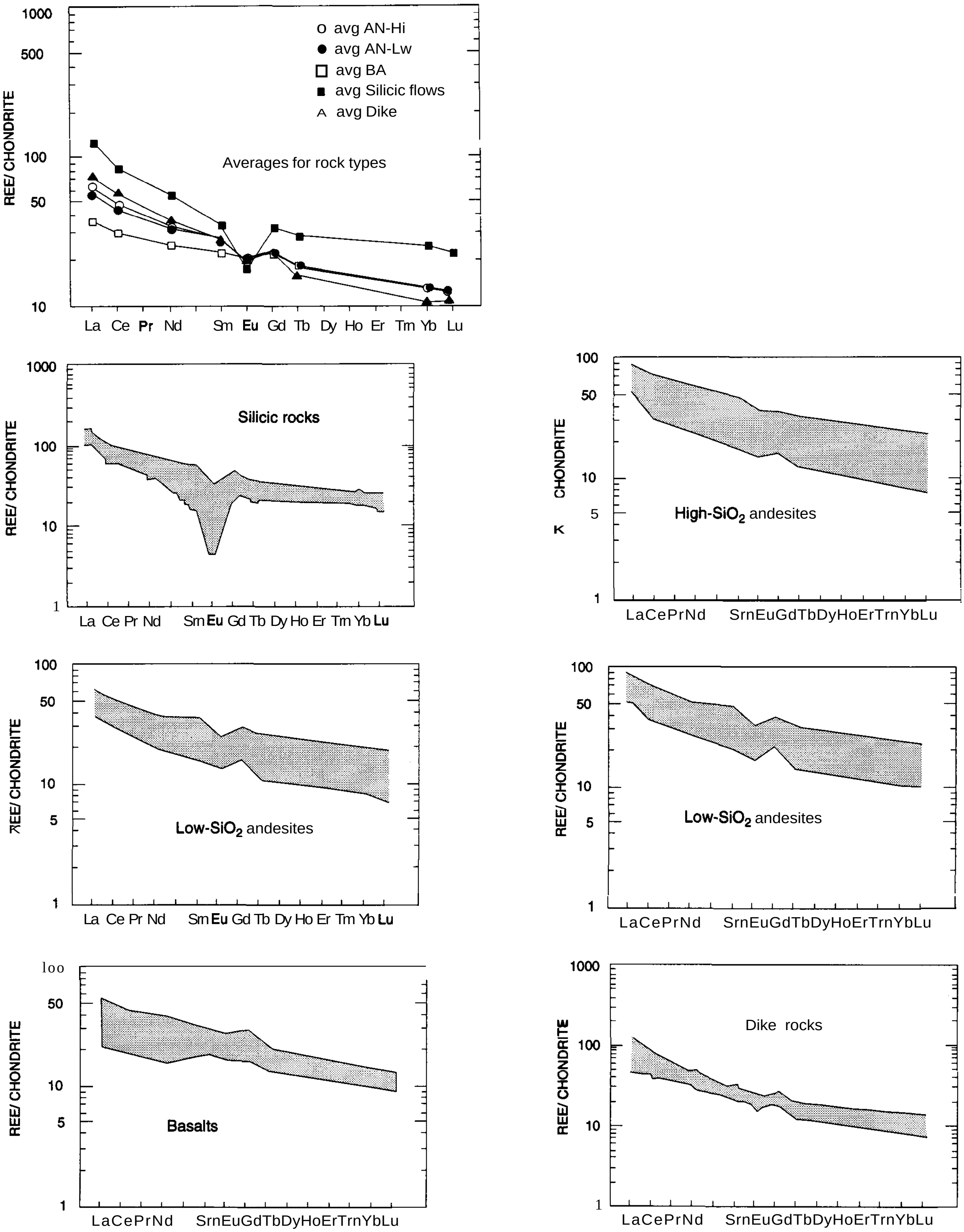

Figure 10. Rare-earth element abundances (log scale) in rocks of the Admiralty Island Volcanics **normalized** to chondritic meteorite values by method of **Wheatley** and Rock (1988).

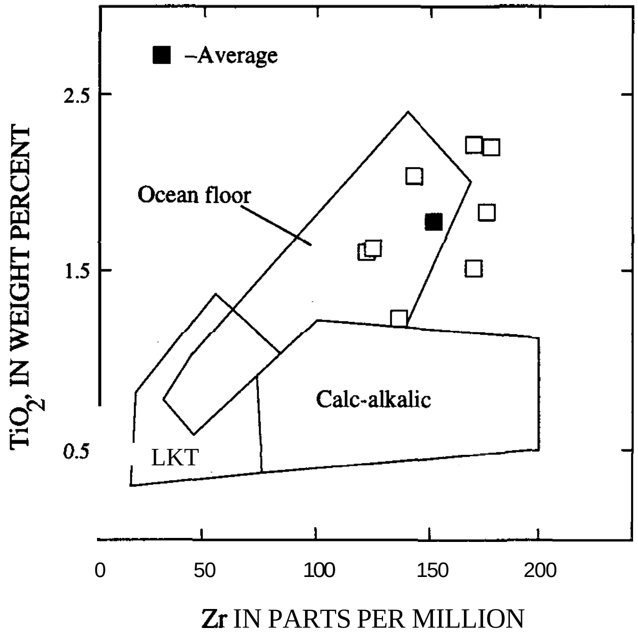

Figure 11. Variation between Zr, Y (×3), and Ti (/100) in basaltic flow rocks of the Admiralty Island Volcanics, showing Pearce and Cann's (1973) fields of low-K tholeiite (LKT), ocean-floor basalt (OFB), calc-alkalic basalt (CAB), and within-plate basalt (WPB).

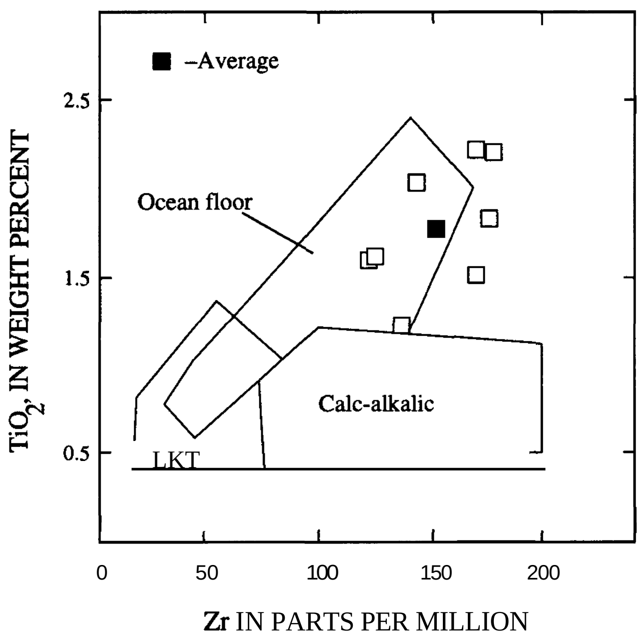

Figure 12. Variation between TiO_2 and Zr contents of basaltic flow rocks of the Admiralty Island Volcanics, showing Pearce and Cann's (1973) fields of low-K tholeiite (LKT), ocean-floor. and calc-alkalic rocks.

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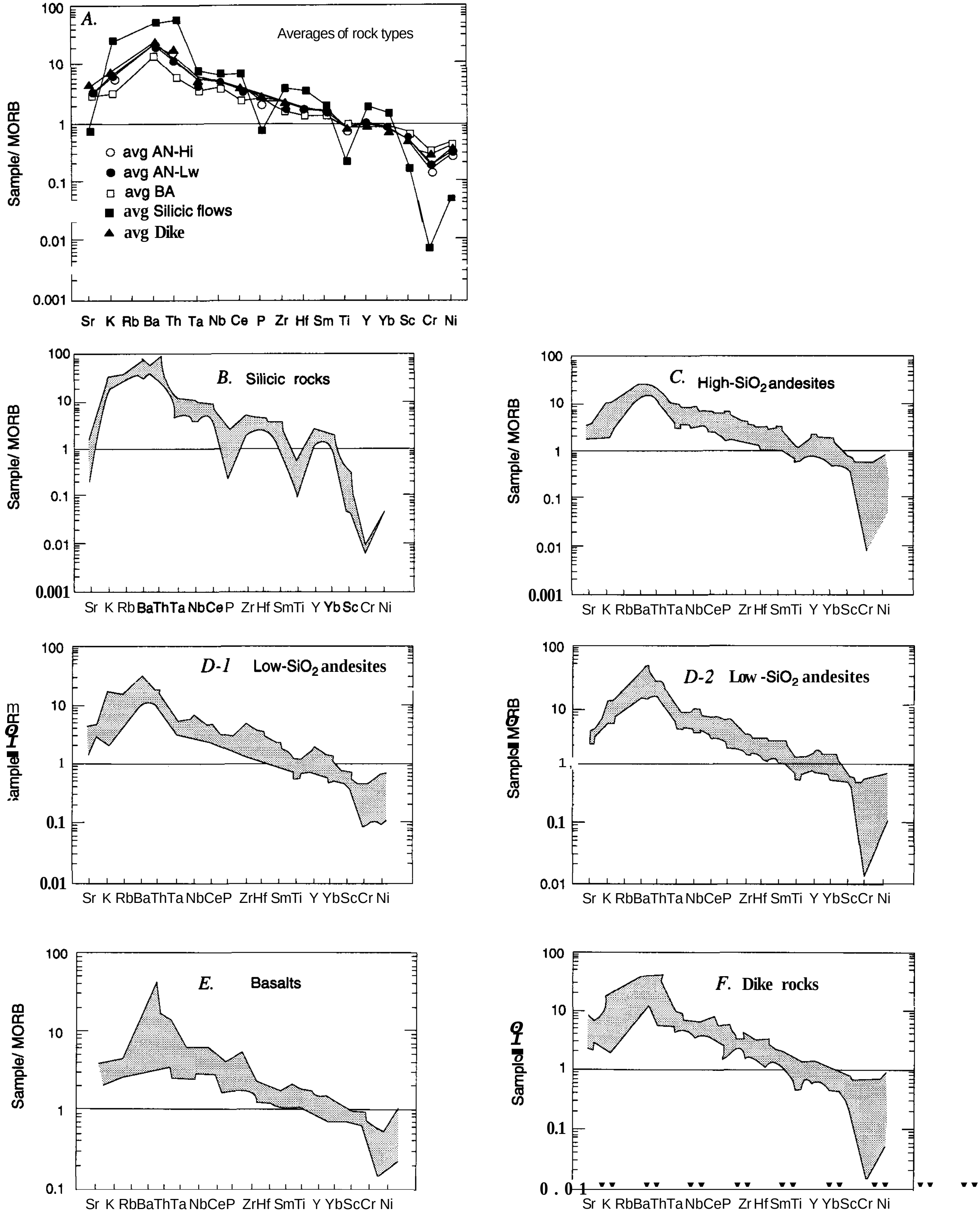

Figure 13. MORB-normalized element abundances (log scale) in rocks of the Admiralty Island Volcanics, by method of Wheatley and Rock (1988). MORB values of Pearce (1983).

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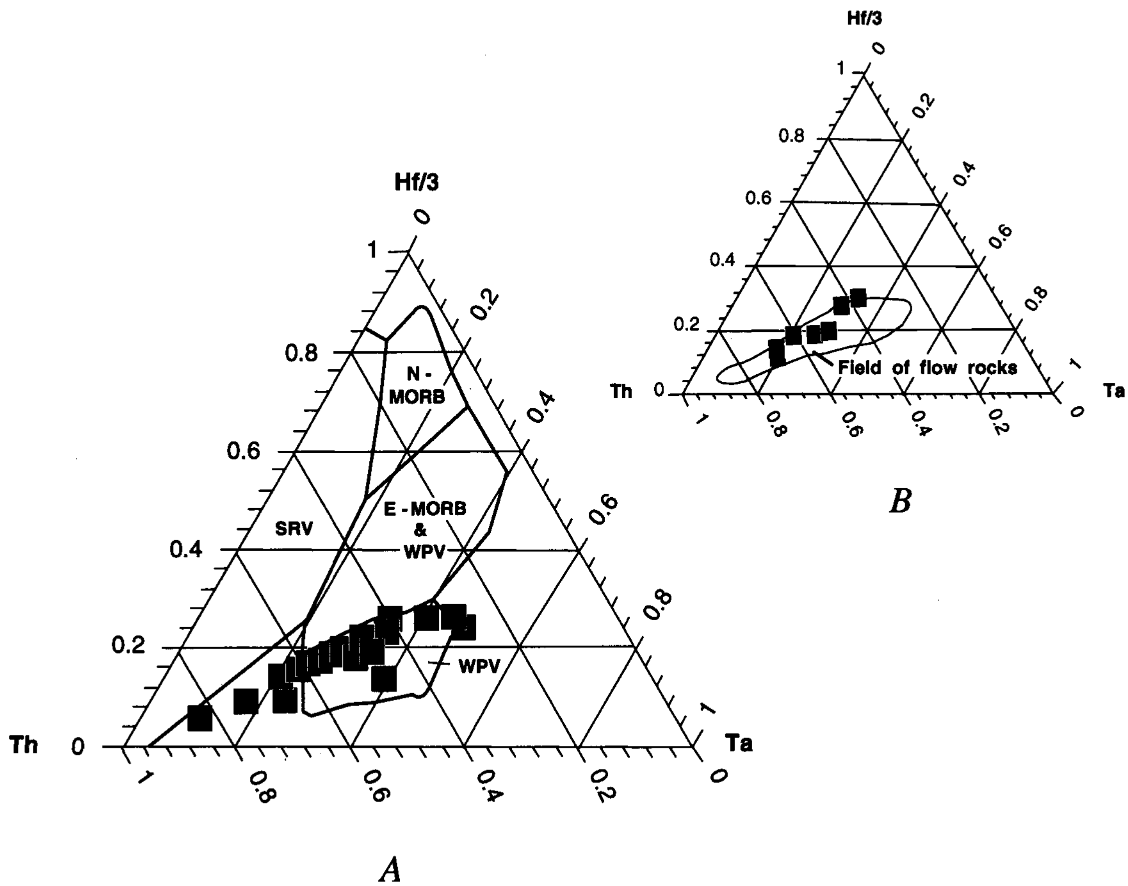

Figure 14. Variations between Th, Hf, and Ta in rocks of the Admiralty Island Volcanics, showing fields of volcanic settings of Wood (1980). Abbreviations: SRV, subduction-related volcanic rocks; WPV, within-plate volcanic rocks; N- and E-MORB, normal and enriched mid-ocean-ridge basalt. A, Flow rocks; B, Dike rocks, showing field of flow rocks.

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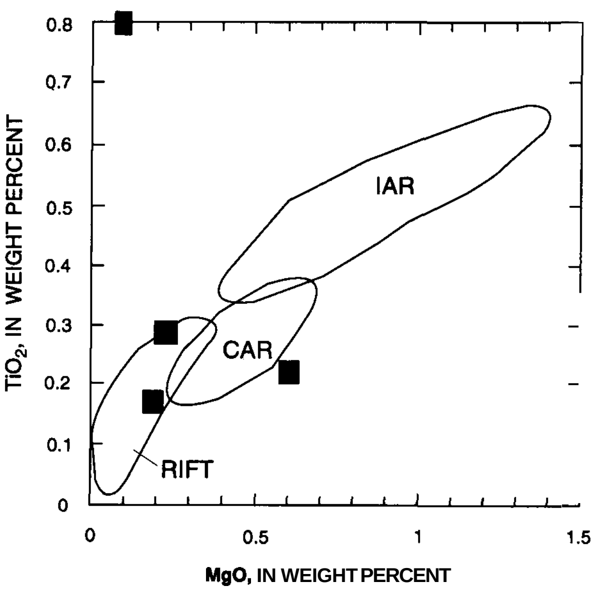

Figure 15. TiO_2 and MgO variation in silicic rocks of the Admiralty Island Volcanics, showing tectonic setting in fields of Condie and Shadel (1984). Abbreviations: IAR, island-arc rhyolites; CAR, calc-alkalic rhyolites; RIFT, continental-rift rhyolites.

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