CHAPTER 3

Chemical Compositions of the Volcanic Rocks on Unga Island and Some Inferences About Their Origins

By James R. Riehle

Contents

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INTRODUCTION

The chemical compositions of the Popof volcanic rocks and the Miocene volcanic rocks are discussed in this chapter. First, the types of alteration that have affected the rocks of Unga Island are considered and the criteria are described that were used to determine which compositions are likely to have been significantly altered. The major-element compositions of the rocks--the basis for assigning rock names--are then summarized. Last, selected minor- and trace-element analyses are interpreted towards the goal of determining whether parent magmas of the Unga Island volcanic rocks were subduction generated, or whether some other model such as within-plate or plume magmatism might better explain these rocks.

ALTERATION

Evidence for both propylitic alteration and secondary zeolites in the Popof volcanic rocks is widespread on Popof and Unga Island. Chlorite, calcite, and epidote occur as patches replacing groundmass, as veinlets, and as partial to complete replacement of phenocrysts. Propylitic alteration occurs most commonly in lava flows of units Tpu and Tpz and to a lesser extent in domes, tuffs, and volcaniclastic sedimentary rocks of units Tpd, Tpt, and Tps. Propylitic alteration also occurs in the Miocene volcanic rocks, but is not so common nor as intensively developed as in the older volcanic rocks. Zeolite occurs locally as patches replacing the groundmass or as veinlets, in all of the aforementioned units of the Popof volcanic rocks but especially in the domes and tuffs. Secondary zeolites may be more common in the younger Miocene volcanic rocks and deposits, in particular the tuffaceous deposits, than in the Popof volcanic rocks. Because of their widespread occurrence, no attempt has been made to map the distribution of either propylitic or zeolitic alteration. Both types of alteration may reflect the shallow marine environment in which at least some of the Popof and Miocene volcanic rocks were deposited: The presence of seawater would promote their alteration.

Three other types of alteration are mapped separately: argillic, iron-oxide discoloration (gossans), and silica replacement. Argillic alteration is identified based on the occurrence of kaolinite; x-ray diffraction patterns show strong peaks at 7.1 and 3.5 angstroms and no peak at 14 angstroms, which would indicate chlorite. Besides kaolinite, argillicly altered rocks also have quartz, pyrite, and sericite; our data are not sufficiently detailed to determined whether a separate sericitic alteration could be mapped. One of the largest areas of argillic alteration is along the coast east of Acheredin Bay (see geologic map; Riehle and others, Chapter 2), where aeromagnetic data indicate the presence of a strongly magnetic body beneath the alteration that may be a buried pluton. If so, the alteration is probably the result of hotsprings developed above the intrusive body. Other areas of argillic alteration that are not mapped separately occur locally adjacent to hypabyssal intrusives and in peperites of unit Tps.

Iron-oxide staining (gossan) is widespread on southern Unga Island, where it occurs chiefly in lava flows of unit Tpu. The distribution of mapped areas suggests an association with lineaments and with areas of silica replacement in the southeastern part of the island, although many smaller, unmapped areas occur on both Unga and Popof Islands as well. The discoloration is due to oxidation of secondary pyrite, so the gossans are probably areas of incipiently developed, argillic alteration.

Several areas of silica replacement of volcanic rocks are large enough to be mapped. Most occur in southeastern Unga Island, near the mineralized Shumagin and Apollo trends (see Riehle, Chapter 1, fig. 1). Unlike widespread quartz veins, which fill pre-existing fractures, the replacing silica has so pervasively flooded the countryrock within the map units that original textures are ghostly outlines or completely gone (see Riehle and others, Chapter 2, fig. 3). Several bulk-rock samples (results not tabulated here) have 80-97% SiO_2; the remaining constituents are chiefly Fe_2O_3, Al_2O_3, and TiO_2. Alkalis and CaO are nearly completely absent, indicating that the silica flooding was not simply addition of SiO_2 to rocks that retained the other chemical constituents in their original proportions. The bodies of replacing silica may be "disseminated" equivalents of quartz veins in the Apollo and Shumagin trends. Detailed mapping to show precisely the relations among faults and veins in and near the silica-replacement bodies has not been done and would be worthwhile.

The occurrence of adularia in the Apollo vein system suggests that potassic alteration is present on Unga and Popof Islands. Thin sections were stained for potassium and indeed, about 25% have distinct groundmass patches or veinlets of high potassium content. Other thin sections have a secondary mineral replacing primary pyroxene: typically very fine-grained, slightly radiating aggregates, distinct brown pleochroism, and parallel(?) extinction. Such optical characteristics suggest biotite, but electron microanalyses attempted of several such clots are more suggestive of amphibole than of mica.

White and Queen (1989) classify the Shumagin trend as an adularia-sericite hydrothermal system: The presence of adularia in the Apollo trend suggests that it is a similar system. Adularia-sericite together with the absence of alunite indicate that southeastern Unga Island belongs to the low-sulphidation type of epithermal system, the fluids of which are thought to be dominated by meteoric water (Sillitoe, 1993, p. 404). Silicification in such systems is typically stratabound, occurs beneath acid-leached bedrock zones, and consists of opal or chalcedony (Sillitoe, 1993, p. 411). The occurrence of crystalline quartz (see Riehle and others, Chapter 2, fig. 3) rather than opal or chalcedony in the bodies of replacement silica on Unga Island is not presently understood.

In view of common alteration of these rocks, the following criteria were used to identify analytical results that probably do not represent primary igneous compositions:

* Analytical results that have Loss on Ignition, or where specifically determined, $\Sigma(H_2O^+, H_2O^-,$ and CO_2), in excess of 4% for lava samples and 6% for pyroclastic samples, are suspect of alteration. A higher cutoff for pyroclastic samples is adopted because minor secondary hydration of glass, which is more common in pyroclastic rocks, can occur without significant changes of the other components.

* Rocks in which Fe^{+++} exceeds Fe^{++} have likely suffered secondary oxidation; typically, Fe_2O_3 is about equal to (TiO_2 + 1.5) and is much less than FeO (Irvine and Baragar, 1971).

* Al_2O_3 in excess of that needed to form normative feldspar molecules generates normative corundum (CO), which causes the rock to be classified as peraluminous. Mildly peraluminous arc lavas are not unheard of--samples having up to 2% CO comprise 15% of the arc andesites studied by Gill (1981, p. 113)--but excess alumina can also result by leaching of mobile alkalis and CaO and so provides a warning of potential alteration. About 5% of the Unga Island samples have >2% CO (Table 2). When plotted against analytical total (not shown here), samples having negative CO have a correlation coefficient "r" of 0.13, that is, there is essentially no correlation of CO with total. But the coefficient is 0.39 for samples having positive CO, which supports an inference of potential alteration.

* All K_2O analytical results are suspect, both for being potentially lowered by leaching during propylitic alteration as well as potentially elevated by potassium metasomatism. Potassium abundances are discussed in greater detail in the following section on minor and trace element contents.

MAJOR-ELEMENT COMPOSITIONS

Major-element analyses of samples selected to represent each of the geologic map units and judged to be unaltered are given in Table 1. All available analyses including those that may have been altered are listed in Table 2, arranged by geologic map unit. Major oxides are plotted against SiO_2 in Figs. 1 and 2 for all analyzed samples that pass the criteria for alteration listed in the preceding section. Total alkalis plotted against SiO_2 provide the basis for assigning rock names (Peccerillo and Taylor, 1976).

Some oxides such as Fe_TO_3 (total iron calculated as Fe_2O_3) and CaO show a tight linear variation with SiO_2, which suggests that Ca and Fe have not been substantially altered (orange-stained gossans being an obvious exception). A linear variation could be the result of mixing of a basaltic magma and a silicic magma such as a crustal partial melt. However, the scatter of Al_2O_3 and K_2O versus SiO_2 and the curving plot of MgO versus SiO_2 all rule out mixing as the sole process to account for the Popof andesitic magmas.

The few samples that are strongly peraluminous (>2% CO; Table 2) are excluded from discussion for being potentially altered. Yet several high-Al_2O_3 samples are only mildly peraluminous, thus, the scatter in the alumina variation plot is apparently not the result of preferential leaching during alteration. Moreover, it is notable that all samples of unit Tpz have high alumina contents (fig. 1). Gill (1981) suggests that some high alumina contents in arc andesites are the result of plagioclase accumulation: The density contrast between plagioclase and magma is much less than that between olivine, pyroxene, magnetite, or ilmenite and magma. This possibility is evaluated further in the following section on Trace Elements.

K_2O in the Popof volcanic rocks shows considerable scatter against SiO_2, some K_2O values extending into the high-K field (fig. 1). Aleutian lavas from oceanic crust to the west of Unga Island are exclusively low- to medium-K (Kay and Kay, 1994), and those from continental crust northeast of Unga Island extend into the high-K field only at silica contents greater than 64% (Miller and Richter, 1994). Thus, the high-K values of the Popof samples suggest potassium metasomatism. This possibility is evaluated further in the following section on Trace Elements.

The ratio of total iron as FeO to MgO, plotted against SiO_2 (Fig. 3), may be used to discriminate tholeiitic from calc-alkaline series. By this parameter, both the Popof volcanic rocks and the Miocene volcanic rocks are dominantly calc-alkaline. The modest scatter into the tholeiitic field is known in other Aleutian lavas (Kay and Kay, 1994; Miller and Richter, 1994). The chief significance of a calc-alkaline classification is that the Popof magmas probably rose slowly and assimilated significant amounts of crustal partial melts, in contrast with less common, tholeiitic Aleutian centers where mantle-derived basalts rose quickly and had limited crustal interaction (Kay and others, 1982).
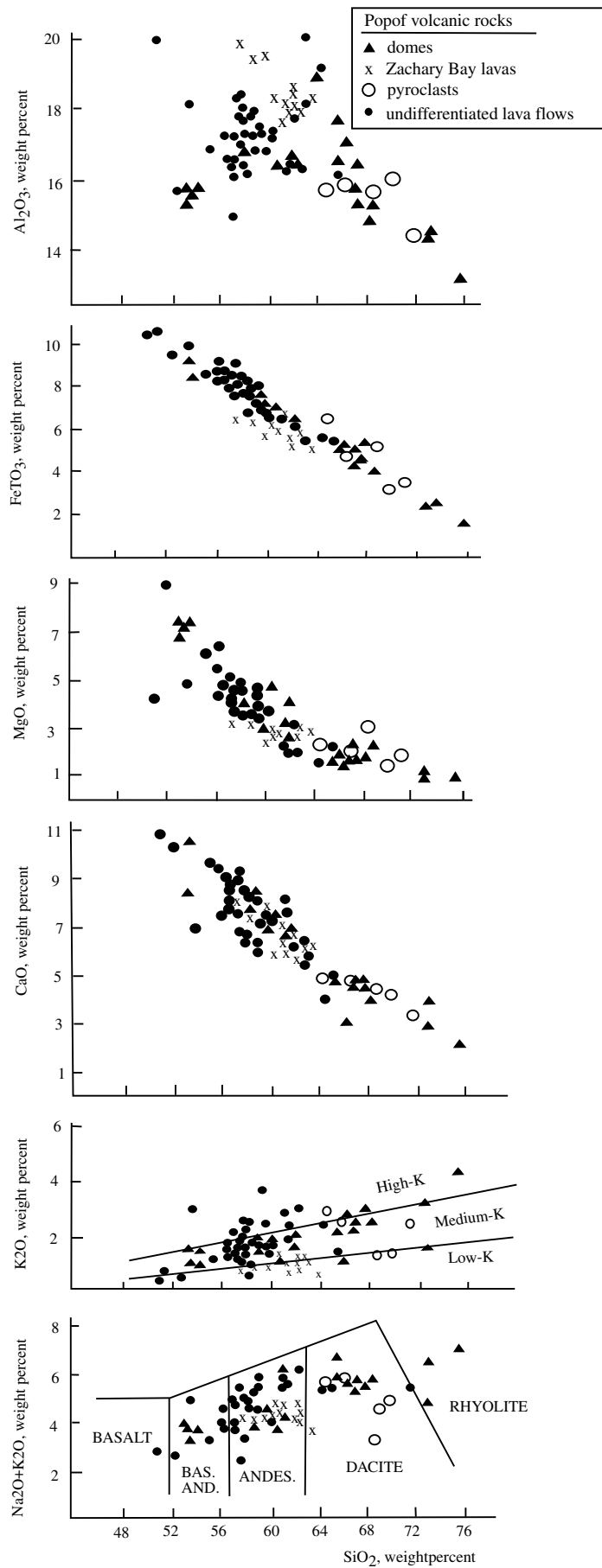
Figure 1. Variation of the major oxides against SiO_2 for the Popof volcanic rocks, Unga Island and northwestern Popof Island. Fields of high-, medium-, and low-K series are from Peccerillo and Taylor (1976); classification based on total alkalis and silica is from Le Bas and others (1986).
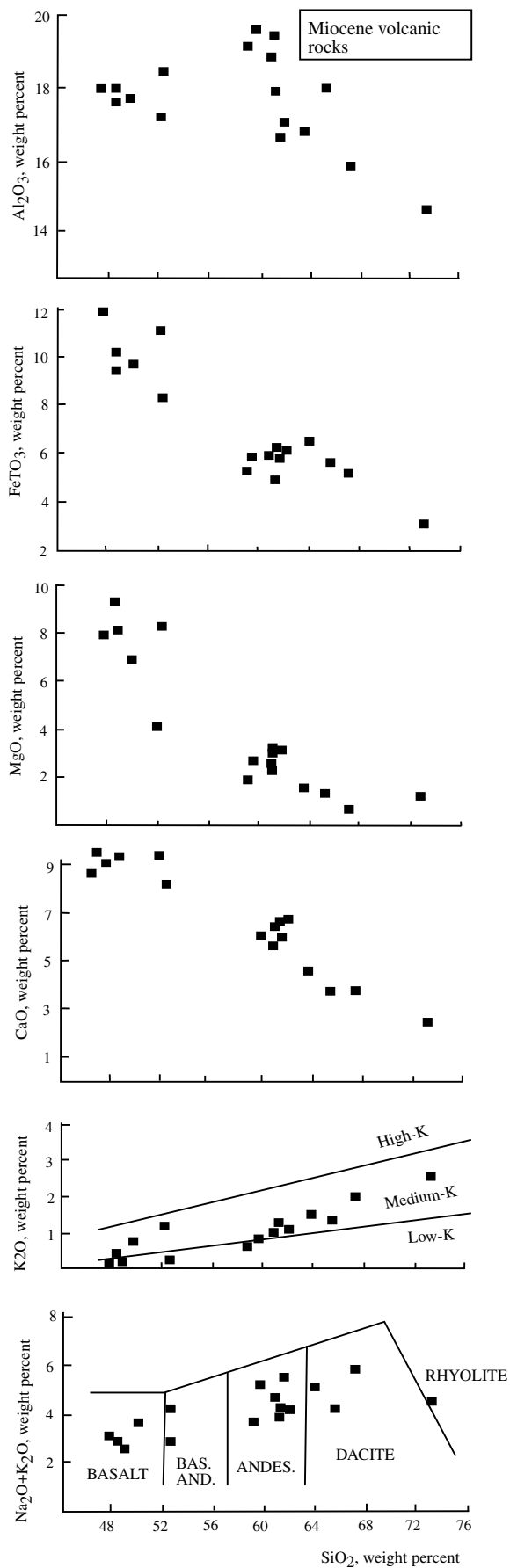
Figure 2. Variation of the major oxides against SiO$_2$ for the Miocene volcanic rocks of Unga Island. Same field boundaries as for Figure 1.
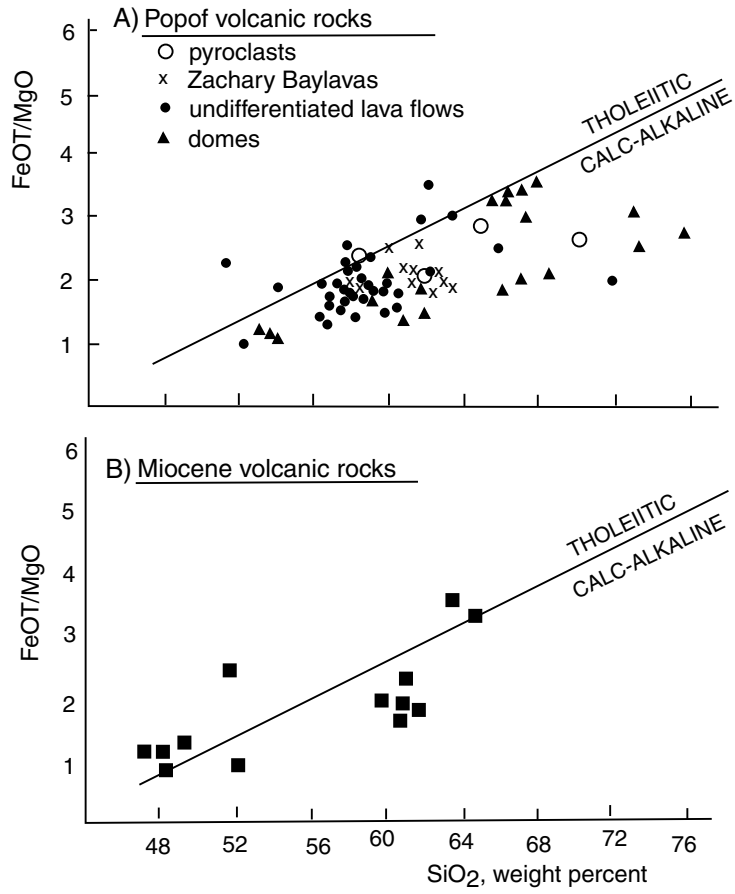
Figure 3. Classification of the Popof volcanic rocks and the Miocene volcanic rocks of Unga Island according to their FeOT/MgO ratios plotted against SiO₂. Classification boundary from Miyashiro (1974).

MINOR AND TRACE ELEMENTS

Analytical results for selected minor- and trace-element contents (Table 3) may be used to further evaluate the potential effects of alteration, and to classify the Popof magmas as to their tectonic environment.

In order to identify possible effects of potassium alteration, K/Rb ratios plotted against Rb (Fig. 4) are compared with fields from Andean-arc volcanic centers (Hildreth and Moorebath, 1988). The plots include samples judged to have been potentially altered by the criteria of the preceding section. There are two possible origins of the wide scatter of K/Rb ratios at low to intermediate Rb contents, compared with individual Andean centers:

    (1) The K and Rb values represent primary magmatic compositions, in which case the Unga Island magmas have far greater variability than occurs among different Andean volcanic centers.

    (2) More likely is that some Unga rocks have been altered from their primary compositions, probably both to higher and lower potassium contents. (The absence of an obvious correlation between K and Rb contents and samples judged to have been potentially altered is not critical because different kinds of alteration are possible. For example, *addition* of K to a rock would serve to *reduce* normative corundum.)

The possibility that lavas of unit Tpz have accumulated plagioclase can be tested by plotting Al_2O_3 against Sr, a trace element that is preferentially concentrated in plagioclase (fig. 5A). Although the correlation is not tight, unit Tpz samples as a group do plot at the high end of the Popof volcanic rocks in both Sr and alumina. To have preferentially accumulated plagioclase requires loss of olivine, pyroxene, or oxides, minerals that all concentrate chrome but not barium. A plot of Cr against Ba (fig. 5B) shows that all unit Tpz samples are depleted in Cr relative to other Popof volcanic rocks, supporting the hypothesized plagioclase accumulation. It is unclear why Ba, which is not removed in any minerals that commonly crystallize from andesites, should show such a wide variation among the Popof volcanic rocks, but an erratic twofold variation of Ba is known in other arc andesites (Gill, 1981, p. 126). In any case, unit Tpz samples as a group plot at the low end of the Ba range for all Popof volcanic rocks. Plagioclase accumulation would dilute Ba but accumulation is unlikely to have exceeded 20% because Sr, which is concentrated in plagioclase by a factor of 2 over the magma, is not greatly higher in unit Tpz samples than in the other Popof volcanic rocks (fig. 5A). Thus, the lower Ba content of unit Tpz samples is probably a primary characteristic of their parent magmas.

Arc basalts and andesites rarely contain more than 1.3% TiO_2 and most arc andesites contain 0.8-1.0% TiO_2 (Gill, 1981, p. 111). Of about 50 analyzed samples of Popof volcanic rocks, only one has more than 1.0% TiO_2 (1.09%) and the majority are in the range of 0.4-0.8%. Most arc andesites contain between 50 and 150 ppm Zr, the higher values occurring in high-K (and high Ba) suites, and 20-25 ppm Y, lower values occurring in andesites erupted through thicker crust (Gill, 1981, p. 132-134). Of 41 samples of Popof volcanic rocks for which Zr and Y analyses are available (Table 2), the average Zr content is 104 ppm (one sigma is 37), which supports a medium- to high-K suite. The average Y content is 18 ppm (one sigma is 5), suggestive of a thicker crust. In summary, TiO_2, Zr, and Y are all consistent with a subduction origin of the Popof volcanic rocks, and together with low Ba/La ratios (discussed following), indicate an influence of continental crust on subduction-generated magma compositions.
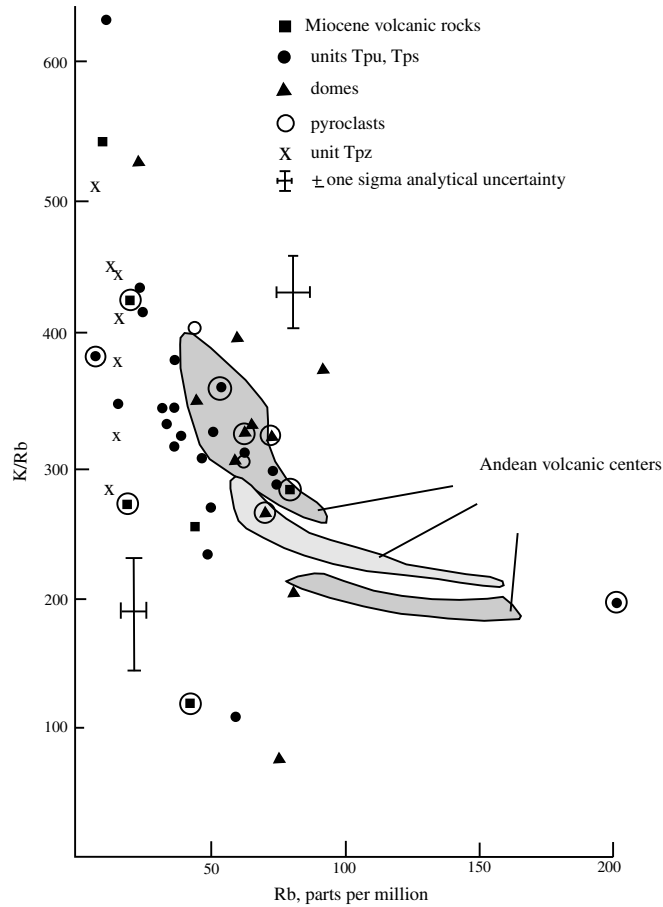
Figure 4. K/Rb ratios of Popof volcanic rocks and the Miocene volcanic rocks of Unga Island plotted against Rb. Encircled sample points are potentially altered for having low analytical totals and (or) normative corundum in excess of 2%. Dark fields are values for three different volcanic centers of the southern Andean volcanic arc (Hildreth and Moorbath, 1988);. The main point is the wide scatter of K/Rb values for the Popof volcanic rocks compared with these Andean centers.
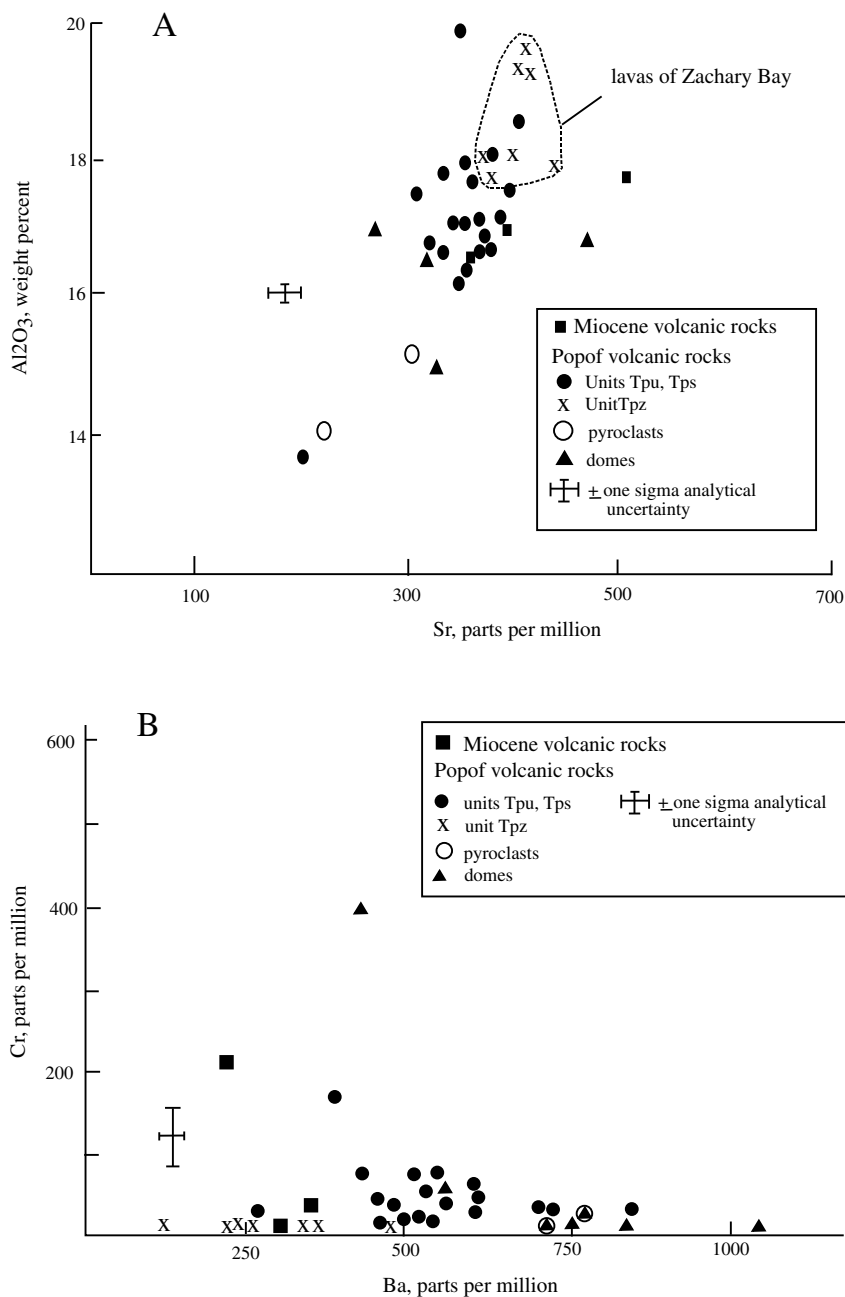
Figure 5. Different chemical plots for the Popof volcanic rocks intended to test the hypothesis that plagioclase has accumulated in the lavas of Zachary Bay (unit Tpz). (A) Samples of unit Tpz are uniformly high in both alumina and Sr, elements that are high in plagioclase. (B) A probable mechanism for plagioclase accumulation is by loss of dense mafic minerals and oxides, minerals that are high in Cr but not Ba. Unit Tpz samples are uniformly low in Cr, independant of their Ba content.

Various minor and trace elements contents and their ratios in young lavas have been correlated to the tectonic environment of formation. Ba/La ratios, for example, are higher in arc lavas than in oceanic or within-plate lavas, ranging from 30 to 40 in western Aleutian-arc lavas located on oceanic crust (Gill, 1981, Table 5.4). The 11 samples of Popof volcanic rocks for which La exceeds the analytical detection limit (Table 3) have Ba/La ratios that range from 6 to 17 and average about 12, values that are low compared with these other Aleutian andesites. Although the analytical uncertainty of La near its detection limit is about 50%, nonetheless these ratios do not attain the 30 to 40 range even assuming that Ba/La ratios of all samples are too low by a factor of 2. Because of the La detection cutoff, however, the average value for the Popof samples may be biased in favor of lower Ba/La ratios. Assuming the remaining samples have La contents of 30 ppm--an assumption that yields a *minimum* Ba/La ratio--the other samples have Ba/La ratios of *at least* 15 to 25. Alternatively, Hildreth and Moorbath (1988) report Ba/La values of 15 to 30 for Andean arc andesites, the lower values being found at volcanoes that are located on thicker continental crust and that have higher Ba contents of 500-600. The median Ba content of the Popof volcanic rocks (fig. 5B) is about 500 ppm. Thus, despite the uncertainty that arises from the analytical uncertainty of La, it is clear that most--perhaps all--of the Popof volcanic rocks have a lower Ba/La ratio than Aleutian lavas from oceanic crust to the west of Unga Island. This difference most likely reflects the presence of continental crust beneath Unga Island.

The three samples of Miocene volcanic rocks for which La exceeds detection limits (Table 3) also have low Ba/La ratios (5 to 7) that reflect low Ba contents (fig. 5B). The average Zr content of seven Miocene samples is 109, identical to that in the Popof volcanic rocks, and ranges from 56 to 192. Y ranges from <10 to 32 and averages 17 (assuming values of 9 for the two samples in which Y is present at less than detection limits). Titania ranges from 0.28% to 1.28% and averages about 0.8% in 15 samples. Like the Popof volcanic rocks, then, the Miocene volcanics have TiO_2, Y, and Zr contents that are typical of arc lavas. The Miocene lavas have even lower Ba/La ratios than the Popof volcanic rocks, reflecting their lower Ba contents.

CONCLUSIONS

 * Both the Popof volcanic rocks and the Miocene volcanics are dominantly calc-alkaline suites that range from basalt to rhyolite in composition.
 * Both volcanic suites have TiO_2, Y, and Zr contents that are consistent with generation in a subduction environment.
 * In the Popof volcanic rocks, Ba contents are high and Ba/La ratios are low, more similar to those of Andean arc lavas erupted through thick continental crust than to those of Aleutian arc lavas erupted through oceanic crust. Barium contents of the Miocene volcanics overlap the lowest of the Popof volcanic rocks, but Ba/La ratios are even lower than those of the Popof volcanic rocks.
 * Lavas of unit Tpz of the Popof volcanic rocks have high alumina and Sr contents and very low Cr contents, which can be explained by preferential accumulation of plagioclase as a consequence of settling of heavier mafic minerals. If plagioclase accumulation actually occurred, a crustal magma chamber beneath unit Tpz is implied, in which fractionation prior to eruption of a large volume of magma could proceed. Alternatively, plagioclase components could have accumulated due to delayed plagioclase crystallization, perhaps the result of high total pressure and (or) partial pressure of water. Barium contents of unit Tpz lavas are among the lowest of the Popof volcanic rocks, implying that in addition to plagioclase accumulation, unit Tpz lavas also had a different parental magma(s) than those of the other Popof volcanic rocks.
 * The range of Rb contents of the Popof volcanic rocks is similar to those of Andean volcanic centers built on continental crust. K/Rb ratios, however, vary by a factor of 2 to 3 more than

Andean values. Although some of the variation might reflect heterogeneous parent magmas, such a wide range is more likely to be the result of post-eruptive alteration of potassium contents.

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Table 1. Major-element contents of rock samples from Unga Island, Alaska, representative of each volcanic map unit.

[Methods: oxide concentrations in weight percent by x-ray fluorescence[1] except FeO by titration[2]; analysts are E.A. Bailey, A. Bartel, D. Kay, K. Lewis, B. Scott, D. Siems, and J.E. Taggart, Jr., U.S.G.S., Denver and Anchorage. Analytical results for sample 56454 provided by UNC Teton Exploration Drilling Ltd. (analysts: Bondar-Clegg Ltd., Vancouver B.C.). "n.d." means not determined.]

Unit	Tmb	Tmv	Tpdb	Tpda	Tpdd	Tpdr	Tpth	Tptb	Tpz	Tpu	Tpu
Sample	9Rj76	8Rj05	8Rj17	8Rj46B	9Mc12	8Rj31	56454	2Sh09	8Rj48	8Rj35	8Rj84D
SiO_2	48.3	60.3	52.5	57.5	64.1	72.1	63.5	66.2	61.5	58.2	50.2
Al_2O_3	17.2	16.4	15.5	16.7	16.5	12.5	15.3	15.0	17.7	17.0	19.6
FeO	0.04	3.88	5.76	4.27	1.4	0.27	0	0.92	2.81	3.37	6.03
Fe_2O_3	9.5	1.84	2.73	2.86	3.6	1.39	6.5	2.29	2.57	3.40	3.77
MgO	6.8	3.24	6.97	4.33	1.3	0.54	2.05	1.1	2.49	3.56	4.07
CaO	9.7	5.92	10.5	8.05	2.8	1.97	4.8	3.9	5.83	7.76	10.8
Na_2O	2.8	4.26	2.27	2.71	3.9	2.54	2.70	3.5	3.56	2.76	2.10
K_2O	0.75	1.26	0.79	1.79	2.5	3.89	2.70	1.1	0.92	1.46	0.57
TiO_2	1.2	0.88	0.72	0.66	0.54	0.14	0.40	0.37	0.39	0.60	0.87
P_2O_5	0.29	0.23	0.15	0.16	0.16	0.06	0.15	0.09	0.16	0.14	0.15
MnO	0.19	0.15	0.17	0.12	0.15	0.03	0.09	0.05	0.14	0.12	0.16
H_2O^+	1.0	0.88	0.99	0.61	1.6	2.04	n.d.	3.5	1.46	0.31	1.62
$H2O^-$	0.76	0.28	0.61	0.51	0.74	1.26	n.d.	2.0	0.26	1.04	0.25
CO_2	0.04	0.02	0.68	0.04	0.02	0.02	n.d.	0.02	0.10	0.03	0.02
Total	98.6	99.5	100.3	100.3	99.3	98.8	98.2	100.0	99.9	99.8	100.2

[1]One sigma analytical precision as a percent of the reported value (Taggart and others, 1987) is typically: SiO_2, 0.4%; Al_2O_3, 0.3%; Fe_2O_3, 0.2%; MgO, 1.7%; CaO, 0.3%; Na_2O, 2.8%; K_2O, 0.7%; TiO_2, 1.1%; P_2O_5, 1.7%; MnO, 5.6%.
[2]One sigma analytical precision as a percent of the reported value (Jackson and others, 1987) is typically 0.5%.

Table 2. Major-element analyses of Tertiary volcanic rocks from Unga and Popof Islands, Alaska.

[Blank means not determined. Normative corundum in excess of 2% suggests alteration and is in bold.]

Sample No.	SiO_2	Al_2O_3	FeO	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO	H_2O	CO_2	Volatile-free total	Map unit	Norm. Corund.
Popof volcanics, units Tpu and Tps																
8Rj023	55.6	17	3.74	4.71	3.1	7.3	2.28	1.58	0.75	0.14	0.12	3.3	0.15	96.3	Tpu	-1.09
8Rj035	58.2	17	3.37	3.4	3.56	7.76	2.76	1.46	0.6	0.14	0.12	1.35	0.03	98.4	Tpu	-2.85
8Rj037	58.4	16.6	2.77	3.65	3.93	7.19	2.66	1.16	0.54	0.14	0.2	2.55	0.06	97.2	Tpu	-1.66
8Rj039B	58.1	15.6	3.22	3.21	4.34	7.1	2.45	0.93	0.53	0.13	0.13	3.95	0.03	95.7	Tpu	-2.04
8Rj042A	55.6	17.2	4.03	3.26	3.93	8.86	1.87	0.44	0.69	0.14	0.13	2.71	1.43	96.2	Tpu	1.12
8Rj044	56.8	16.7	3.97	3.22	3.84	7.35	2.38	1.28	0.66	0.15	0.17	2.32	0.46	96.5	Tpu	-0.58
8Rj064	46.5	17.1	6.47	2.46	3.78	11.8	1.83	0.23	1.09	0.29	0.31	3.69	5.06	91.9	Tpu	**4.21**
8Rj065A	55.1	16.1	4.23	3.59	5.16	9.02	2.33	1.31	0.66	0.13	0.16	1.65	0.21	97.8	Tpu	-4.85
8Rj067	57.2	16.3	3.27	3.96	3.93	7.36	2.58	1.97	0.65	0.13	0.13	2.2	0.01	97.5	Tpu	-3.19
8Rj075A	57.3	17.4	3.56	3.67	3.72	8.42	2.58	1.34	0.63	0.14	0.13	1.04	0.01	98.9	Tpu	-3.26
8Rj080	57.1	16	1.84	4.83	4.14	7.05	2.45	1.42	0.56	0.15	0.12	3.05	0.38	95.7	Tpu	-1.22
8Rj084D	50.2	19.6	6.03	3.77	4.07	10.8	2.1	0.57	0.87	0.15	0.16	1.87	0.02	98.3	Tpu	-3.74
8Rj085	56.3	16.5	4.01	3.45	4.17	7.94	2.56	1.49	0.76	0.18	0.18	1.52	0.17	97.5	Tpu	-3.00
8Rj076	59	16.9	3.52	3	3.15	7.31	2.57	2.35	0.67	0.15	0.14	1.13	0.02	98.8	Tpu	-2.77
8Rj093	57	17.2	2.37	4.05	3.23	7.23	2.71	2.28	0.73	0.18	0.14	2.52	0.04	97.1	Tpu	-2.40
8Rj097	56.5	17.9	3.36	3.89	3.71	8.03	2.69	1.2	0.65	0.13	0.14	1.35	0.07	98.2	Tpu	-1.97
9Mc013	62.1	16	3	2.9	2.9	5.6	3	2.9	0.63	0.14	0.12	1.33	0.12	99.3	Tpu	-1.64
9Rj051	52.9	16.1	5	2.7	5.7	9.4	2	0.98	0.72	0.12	0.19	3	0.13	95.8	Tpu	-4.95
9Rj058	54.7	16.1	5.5	2	4.2	5.9	2.1	2.3	0.81	0.16	0.15	4.02	0.13	93.9	Tpu	0.12
79JR077	54.7	15.9	4.54	3.23	4.67	7.4	2.6	2.05	0.8		0.13	0.7		96.0	Tpu	-4.20
79JR082	63.1	15.4	2.7	2.51	1.96	4.6	4.07	1.12	0.54		0.14	1.05		96.1	Tpu	-0.89
79JR045	55.8	15.7	4.09	3.41	4.66	8.47	2.73	1.91	0.76		0.17	0.77		97.7	Tpu	-6.38
79JR116	56.4	16.3	3.06	3.98	3.66	6.55	2.94	1.37	0.59		0.15	1.97		95.0	Tpu	-2.01
79JR129	54.5	16.3	5.85	1.94	3.96	8.03	2.62	0.98	0.82		0.16	0.1		95.2	Tpu	-3.84
79JR152	58.9	17.7	2.23	3.51	1.62	6.54	4.04	0.8	0.64		0.11	1.17		96.1	Tpu	-1.75
79JR159	56.6	16.6	4.02	2.9	4.2	7.27	2.67	2	0.67		0.14	1		97.1	Tpu	-3.25
56963	60	17.1		5.45	1.6	5.9	3.8	0.5	0.3	0.17	0.12			94.9	Tpu	0.00
56972	57.5	17		8.5	3.3	6.65	2.9	2.4	0.7	0.01	0.14			99.1	Tpu	-2.44
56975	52	17.5		10	4.65	6.6	2	2.8	0.7	0.25	0.15			96.7	Tpu	-0.21
82Sh014	61.1	17.4	1.94	4.14	1.59	5.98	3.73	1.73	0.77	0.23	0.12	0.98	0.17	98.7	Tpu	-0.53
50883	57	16		8.45	4.3	7	3.1	1.2	0.7	0.22	0.15			98.1	Tpu	-2.63
51290	57.5	16.5		8.3	3.55	6.9	2.9	1.7	0.65	0.24	0.17			98.4	Tpu	-2.10
82Cc021	58.9	16.9	3.23	3.16	3.3	6.98	2.9	1.5	0.62	0.12	0.12	1.38	0.1	97.7	Tpu	-1.69
85Ws321	54.9	14.4	6.34	1.77	6.1	8.62	2.6	1.02	0.72	0.16	0.17	1.99	0.07	96.8	Tpu	-6.30
51509	58.5	15.5		6.6	2.7	5.5	2.9	2.6	0.6	0.27	0.14			95.3	Tpu	-1.49

51659	56.5	16.3		8.85	4.7	8.1	2.3	1.6	0.65	0.25	0.17			99.4	Tpu	-3.35
51679	57	15.8		8.6	3.45	7.1	2.5	2.4	0.8	0.25	0.14			98.0	Tpu	-3.27
8Rj030	57	18	5.29	2.21	3.23	7.76	3.27	0.79	0.79	0.19	0.15	1.55	0.01	98.7	Tps	-1.87
8Rj061B	56.2	17.9	1.91	4.85	2.66	6.83	2.87	2.5	0.59	0.18	0.12	2.53	0.02	96.6	Tps	-1.50
8Rj062	57.6	17.5	3.76	3.64	2.98	6.11	3.5	1.56	0.71	0.21	0.13	1.94	0.02	97.7	Tps	-0.50
82Ws016	50.7	15.1	4.67	4.39	8.54	9.94	2.17	0.32	0.62	0.12	0.17	2.9	0.13	96.7	Tps	-6.50
85Ws296A	74.7	11.7	0.09	1.15	0.35	1.02	0.45	6.32	0.08	0.02	0.02	2.35	0.41	95.9	Tps	**3.37**
Domes																
8Rj077	59.7	15.8	3.35	2.44	3.73	6.85	2.63	1.38	0.51	0.12	0.12	2.45	0.02	96.6	Tpda	-2.20
8Rj031	72.1	12.5	0.27	1.39	0.54	1.97	2.54	3.89	0.14	0.06	0.03	3.3	0.02	95.4	Tpdr	0.76
8Rj017	52.5	15.3	5.76	2.73	6.97	10.5	2.27	0.79	0.72	0.15	0.17	1.6	0.68	97.9	Tpdb	-6.60
9Mc016	62.3	18.4	0.92	4.5	1.2	3.7	2.8	2.2	0.57	0.1	0.12	3.43	0.04	96.8	Tpdd	**5.19**
9Rj080	64.2	16.1	3.2	1.6	1.4	4.6	3.8	1.9	0.59	0.19	0.12	2.08	0.08	97.7	Tpdd	0.08
9Mc012	64.1	16.5	1.4	3.6	1.3	2.8	3.9	2.5	0.54	0.16	0.15	2.34	0.02	97.0	Tpdd	**2.81**
79JR032	49.2	17.8	5.08	4.01	5.7	9.1	2.4	0.55	0.91		0.16	1.66		94.9	Tpdb	-3.44
79JR048	49.4	15.2	4.9	3.58	7.85	9.8	2.2	1.1	0.77		0.16	1.68		95.0	Tpdb	-7.80
79JR155	59.7	16.1	2.83	3.47	3.06	6.33	3.06	1.38	0.6		0.16	1.22		96.7	Tpda	-1.99
56966	66.5	14.5		5.45	1.35	4.25	2.7	2.7	0.3	0.13	0.09			98.0	Tpdd	-0.27
56969	53	15.6		9.3	6.85	10	2.7	0.9	0.5	0.05	0.14			99.0	Tpdb	-7.93
8Rj098	56.9	17.1	0.9	4.24	2.25	4.58	3.93	1.64	0.48	0.16	0.12	7.31	0.07	92.3	Tpda	1.17
82Cc023	71.7	14.3	0.5	2	0.9	3.78	3.3	1.28	0.3	0.06	0.04	0.93	0.14	98.2	Tpdr	1.11
56968*	52.7	15.4	4.7	3.39	7.1	9.66	2.3	1.32	0.64	0.12	0.15	1.9	0.14	97.5	Tpdb	-6.93
50849	58	15.2		8.15	4.1	5.8	2	3.5	0.6	0.19	0.15			97.7	Tpda	-2.00
51387	58	16.7		7.3	3.05	6.8	2.6	1.6	0.55	0.21	0.13			96.9	Tpda	-1.19
51722	51.5	15		9.5	7.2	8.2	2.4	1.4	1	0.27	0.18			96.7	Tpdb	-4.87
8Rj036	63.6	14.4	0.65	3.78	2.1	4.52	2.56	2.36	0.38	0.13	0.13	4.6	0.04	94.6	Tpdd	-0.18
8Rj046B	57.5	16.7	4.27	2.86	4.33	8.05	2.71	1.79	0.66	0.16	0.12	1.12	0.04	99.2	Tpda	-3.87
9Mc007	71.9	14.1	0.6	1.8	0.7	2.7	3.3	2.9	0.3	0.09	0.12	1.33	0.12	98.5	Tpdd	1.14
Lavas of Zachary Bay																
50851	59	17.6		6.45	2.65	5.6	3.7	1.1	0.65	0.21	0.12			97.1	Tpz	0.68
56957	60	17.6		6.1	2.6	5.6	3.6	0.9	0.7	0.17	0.1			97.4	Tpz	0.97
56960	60	17.1		6.85	2.4	6.1	3.8	0.5	0.4	0.13	0.12			97.4	Tpz	-0.47
79JR062	59.3	17.5	1.44	3.91	2.76	5.8	3.4	0.65	0.43		0.13	1.35		95.3	Tpz	0.71
79JR087	60	17.3	2.97	2.66	2.64	5.5	3.33	1.1	0.44		0.13	0.7		96.1	Tpz	0.67
79JR134	59.5	17	3.51	2.43	2.61	6.75	3.61	0.91	0.42		0.14	0.38		96.9	Tpz	-2.25
9Mc017A	61.3	17.4	2.8	2.1	2.6	5.9	3.1	0.36	0.45	0.12	0.19	3.39	0.13	96.3	Tpz	1.84
9Mc017C	60.2	17.5	2.7	2.5	2.7	6.3	3	0.87	0.48	0.11	0.15	2.89	0.13	96.5	Tpz	0.77
9Mc017B	61	17.3	2.6	2.7	2.5	6	3.6	0.95	0.44	0.19	0.15	2.3	0.13	97.4	Tpz	0.21
9Rj079	56.5	18.5	1.4	4.7	2.9	7.3	3.2	0.64	0.5	0.12	0.15	2.9	0.13	95.9	Tpz	-0.14
9Rj078	58	18.8	0.92	4.7	2.1	7.6	3.3	0.69	0.49	0.12	0.15	2.7	0.13	96.9	Tpz	-0.62
8Rj065B	55.9	19	2.64	3.43	2.89	7.89	3.4	0.63	0.56	0.14	0.11	3.43	0.04	96.6	Tpz	-1.22
8Rj048	61.5	17.7	2.81	2.57	2.49	5.83	3.56	0.92	0.39	0.16	0.14	1.72	0.1	98.1	Tpz	0.89

Oligocene pyroclastic deposits

Sample															Map unit	
8Rj061A	61.5	13.9	0.31	4.43	2.53	3.72	1.63	1.01	0.33	0.14	0.1	9.49	0.06	89.6	Tps*	**4.28**
8Rj075B	68.3	13.6	0.3	3.25	1.61	2.86	2.82	2.01	0.31	0.1	0.1	4.1	0.02	95.3	Tpth*	1.97
8Rj086A	73.8	13.2	0.17	1.58	0.41	0.56	0.79	5.52	0.09	0.04	0.01	3.01	0.24	96.2	Tpu*	**5.76**
8Rj088	66.5	14.8	0.77	3.3	1.93	3.8	3.17	2.19	0.36	0.13	0.1	2.53	0.04	97.1	Tpth*	0.74
82Sh009	66.2	15	0.92	2.28	1.1	3.9	3.5	1.1	0.37	0.09	0.05	5.5	0.02	94.5	Tptb*	1.30
56454	63.5	15.3		6.5	2.05	4.8	2.7	2.7	0.4	0.15	0.09			98.2	Tpth*	-0.43
56977	64	15		5	1.3	4.3	3.3	2.2	0.5	0.08	0.08			95.8	Tptb*	-0.44

Miocene volcanic rocks and sediments

Sample															Map unit	
8Rj002	69	14	1.34	1.46	1.27	2.48	2.04	2.51	0.28	0.1	0.04	3.05	0.5	94.5	Tu*	**5.04**
8Rj003	61.4	16.9	2.8	3.08	3.18	6.86	3.11	1.15	0.53	0.14	0.13	0.7	0.07	99.3	Tmv	-1.43
8Rj004	57.5	16.8	2.2	3.24	2.89	6.41	3.01	0.96	0.53	0.14	0.13	5.86	0.12	93.8	Tmv	-0.25
8Rj005	60.3	16.4	3.88	1.84	3.24	5.92	4.26	1.26	0.88	0.23	0.15	1.1	0.02	98.4	Tmv	-2.16
8Rj009	56.2	18.3	1.95	2.84	1.78	9.86	2.92	0.62	0.54	0.12	0.17	3.29	1.35	95.3	Tmv	-1.90
8Rj012	67.9	13.7	0.46	1.12	1.73	3.54	3.03	0.47	0.25	0.04	0.74	3.12	2.47	93.0	Tmv	**7.74**
56225	64	15.1		5.3	0.8	3.65	4.1	2	0.4	0.01	0.09			95.5	Tmv	-0.43
56227	58.5	18.2		6	2.3	5.6	3.9	0.9	0.4	0.18	0.09			96.1	Tmv	1.12
56276	73.5	13.2		1.85	0.05	0.25	1	8.3	0.1	0.21	0.01			98.5	Tmv	**2.67**
56278	61	16.2		6.6	1.55	4.5	3.7	1.5	0.7	0.09	0.13			96.0	Tmv	0.56
9Rj076	48.3	17.2	0.04	9.5	6.8	9.7	2.8	0.75	1.2	0.29	0.19	1.76	0.04	96.8	Tmb	-5.22
56287	51.5	18.2		11.3	4.05	8.1	3.1	1.2	0.9	0.11	0.21			98.7	Tmv	-2.68
56954	46	17.4		12.15	7.7	8.8	3	0.05	1.1	0.1	0.28			96.6	Tmb	-3.45
56228*	59.4	19	1.8	3.16	2.45	6.45	3.4	0.89	0.48	0.13	0.09	2.57	0.08	97.3	Tmv	1.26
85Jm781	51.1	16.9	5.66	2.27	8.2	9.84	2.7	0.22	0.66	0.1	0.16	2.01	0.12	97.8	Tmv	-5.25
85Ws302	46.9	17.1	7.28	1.51	9.2	10.2	2.6	0.3	1.28	0.12	0.16	2.54	0.9	96.7	Tmb	-3.85
56953*	46	17	4.07	5.78	7.8	9.36	2.6	0.16	1.18	0.1	0.5	5.05	0.29	94.6	Tmb	-3.78
50882	68.5	14.6		3.7	0.95	3.15	4	2.7	0.35	0.18	0.05			98.2	Tmv	-0.19

SOURCES

1) Samples labelled "8Rj, 9Rj", or "9Mc": U.S.G.S. labs, see Table 1 for procedural details

2) Samples labelled "79JR": Riehle, Updike, and Carpenter, 1982

3) Samples labelled with only 5 numbers: analytical results provided by UNC Teton Exploration Drilling Ltd., analysts Bondar-Clegg Ltd., Vancouver B.C.

4) Samples preceded by "82" or "85", or labelled with 5 numbers followed by "*": U.S.G.S. labs, procedures basically similar to those listed in Table 1

Map unit: * denotes a pyroclastic sample

Table 3. SiO_2, K_2O, and minor and trace element contents of selected rock samples from Unga Island, Alaska.

[Sample labels in italics have low analytical totals and (or) normative corundum in excess of 2%, and so may have been altered. SiO_2 and K_2O reported as weight percent after normalization to 100% volatile-free (original summation reported as "total"), others as parts per million. Methods: SiO_2 and K_2O as in Table 1. Rb, Sr, Zr, Y, Ba, and La by energy-dispersive x-ray fluorescence, analysts J. Kent and M. Dyslin, U.S. Geological Survey, Menlo Park Ca.]

Sample	8R002	8R003	8R004	8R005	8R009	8R012	9R076	8R017	8R023	8R030	8R031	8R035	8R036	8R037	8R039B	8R042A	8R044
Unit	Tu	Tmv	Tmv	Tmv	Tmv	Tmv	Tmb	Tpdb	Tpu	Tps	Tpdr	Tpu	Tpdd	Tpu	Tpu	Tpu	Tpu
SiO_2	72.4	62.0	61.2	61.0	59.0	71.3	49.9	53.6	57.3	57.7	75.0	59.0	66.8	60.0	60.4	57.7	58.4
K_2O	2.64	1.20	1.02	1.27	0.65	0.49	0.78	0.81	1.63	0.80	4.05	1.48	2.48	1.19	0.97	0.46	1.31
Total	95.3	99.2	94.0	98.9	95.4	94.8	96.7	98.0	96.7	98.7	96.4	98.7	95.0	97.3	95.9	96.3	97.6
Rb	76	24	20	42	20	36	12	74	44	60	90	36	64	24	50	10	26
Sr	192	395	550	360	335	330	510	330	310	375	465	390	330	370	340	355	345
Zr	130	80	90	192	56	98	120	86	102	88	110	84	92	82	86	96	94
Y	14	<10	<10	32	14	14	25	16	20	18	10	12	10	14	14	20	22
Ba	900	315	174	350	280	162	225	425	460	495	1300	510	750	530	540	490	540
La	<30	42	<30	54	<30	30	<30	<30	<30	<30	<30	<30	<30	<30	<30	32	<30
Cr	<20	<20	<20	48	<20	<20	210	400	48	24	<20	30	<20	58	76	36	50

Sample	8R046B	8R048	8R061B	8R062	8R065A	8R065B	8R067	8R075A	8R075B	8R076	8R077	8R080	8R084D	8R085	8R086A	8R088
Unit	Tpda	Tpz	Tps	Tps	Tpu	Tpz	Tpu	Tpu	Tpth	Tpu	Tpda	Tpu	Tpu	Tpu	Tpu	Tpth
SiO_2	58.0	62.5	58.0	58.8	56.2	57.9	58.6	57.9	71.7	59.7	61.3	59.4	51.1	57.4	76.5	68.4
K_2O	1.81	0.94	2.58	1.59	1.34	0.65	2.02	1.35	2.11	2.38	1.42	1.44	0.58	1.52	5.72	2.25
Total	99.0	98.3	96.8	97.9	98.1	96.4	97.6	98.9	95.5	98.8	97.4	95.8	98.3	98.0	96.4	97.2
Rb	44	18	74	50	34	17	52	36	44	72	52	38	14	34	205	62
Sr	475	440	410	335	360	410	380	405	230	353	350	340	355	370	46	305
Zr	124	88	134	116	94	72	118	76	100	148	90	84	52	94	76	126
Y	18	14	22	24	18	16	20	12	12	20	16	20	18	22	10	16
Ba	550	485	720	540	435	250	600	490	710	600	610	480	260	530	780	770
La	<30	36	60	32	42	<30	<30	<30	48	<30	54	<30	44	<30	68	<30
Cr	56	<20	30	24	84	<20	66	30	<20	32	58	32	20	72	<20	<20

Sample	8R093	8R097	8R098	9R078	9M013	9M007	9R079	9M016	9M017B	9R080	9M017C	9M012	9M017A	9R051	9R058
Unit	Tpu	Tpu	Tpda	Tpz	Tpu	Tpdd	Tpz	Tpdd	Tpz	Tpdd	Tpz	Tpdd	Tpz	Tpu	Tpu
SiO_2	58.6	57.3	61.5	59.9	62.7	63.0	59.0	64.4	62.8	65.8	62.4	66.2	63.7	55.2	58.3
K_2O	2.34	1.22	1.77	0.71	2.93	2.94	0.67	2.27	0.98	1.95	0.90	2.58	0.37	1.02	2.45
Total	97.2	98.6	92.5	96.8	98.9	98.5	95.9	96.8	97.2	97.5	96.5	96.8	96.3	95.8	93.9
Rb	64	30	28	16	69	62	11	73	20	81	17	67	11	13	57
Sr	365	385	870	400	340	255	415	290	375	325	400	275	370	325	370
Zr	140	68	100	68	178	130	62	250	88	130	81	188	86	89	102
Y	26	16	14	16	24	15	21	37	17	23	18	24	20	18	22
Ba	700	480	510	255	840	830	240	800	365	780	350	810	148	390	465
La	54	44	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30	<30
Cr	38	24	<20	<20	32	<20	<20	<20	<20	<20	<20	<20	<20	168	32

See Table 1 for analytical uncertainty of SiO_2 and K_2O. Analytical uncertainty of Rb, Sr, Zr, Y, Ba, La, and Cr is about $\pm5\%$ relative where these trace elements are present in concentrations of 100 to 1,000 ppm, but decreases to as much as $\pm50\%$ at the lower detection limits, which are: Rb, 2 ppm; Sr, 2 ppm; Zr, 5 ppm; Y, 2 ppm; Ba, 5 ppm; La, 5 ppm; Cr, 20 ppm (Johnson and King, 1987).