PETROLOGY OF QUATERNARY BASALT FROM THE BERING SEA CONTINENTAL MARGIN

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ABSTRACT

Quaternary basaltic lavas were erupted at the continental margin of the Bering Sea near Navarin Basin and in the Pribilof Islands region, both on the islands and adjoining submarine ridge. Lavas from near Navarin Basin are highly vesicular basanite flows and hyaloclastites whereas lavas from the Pribilof Islands and Pribilof Ridge range from mildly alkalic basalt to strongly alkalic nephelinite. Chemically, all of the lavas are intraplate basalts similar to those erupted from oceanic islands and in some continental settings. Trace element data indicate the lavas have been generated by small, but variable, amounts of partial melting of a metasomatized lherzolite source. The preponderance of primitive compositions (MgO > 9%), presence of mantle-derived xenoliths in some alkalic lavas, and forsteritic olivine with low CaO and high NiO suggest that magmas rose rapidly from great depth without spending time in large, long-lived magma chambers. Although lavas from different volcanic centers in the Bering Sea region are similar with respect to major elements and many trace element ratios, isotopic compositions indicate heterogeneities in the source. The isotopic compositions of Pribilof basalt are nearly MORB-like and indicate a more depleted source than other islands in the Bering Sea, such as Nunivak and St. Lawrence Islands. The Navarin basanites have higher $^{87}Sr/^{86}Sr$ and lower $^{143}Nd/^{144}Nd$ values than any other lavas so far reported from this region, indicating a more enriched source. The $^{207}Pb/^{204}Pb$ isotopic ratios of Navarin basanites suggest involvement of a crustal component which may have resulted from metasomatism associated with subduction-related magmatic activity during the early Eocene in this region. Although some volcanic episodes are roughly synchronous at geographically widely separated centers, no large scale regional extension nor presence of large mantle plumes are indicated. Instead, volcanism apparently resulted from upwelling and decompressional melting of small isolated mantle diapirs in response to local lithospheric attenuation associated with structural adjustment to regional stresses.

INTRODUCTION

Quaternary basaltic volcanism was widespread in the Bering Sea region. Small isolated volcanic centers are located at the continental margin near Navarin Basin and the Pribilof Islands, at Nunivak and St. Lawrence Island, as well as in mainland Alaska (Barth, 1956; Hoare et al., 1968; Patton and Csejtey, 1980; Moll-Stalcup, 1994). Eruption of predominantly alkalic basalt occurred repeatedly at geographically widely separated sites over a period spanning at least several million years. The alkalic basalt eruptions commonly are small in volume, either forming short, blocky flows erupted from fissures or cinder cones, or consisting largely of tephra deposits erupted from maars or tuff rings (Barth, 1956; Hoare et al., 1968). Tholeiitic and transitional basalts also erupted from some of the older and larger volcanic centers (Hoare et al., 1968; Patton and Csejtey, 1980, Moll-Stalcup, 1994). Although located behind the Aleutian arc, these lavas are not back-arc basin basalts but chemically resemble intraplate basalts erupted on oceanic islands and in continental settings. During the Cretaceous to early Eocene, this region was the site of subduction-related volcanism (e.g. Marlow et al., 1976; Davis et al., 1989) and volcanic arc rocks underlie the alkalic basalt in some locations along the continental margin (Davis et al., 1989).

This report summarizes petrologic data for Quaternary basanites dredged from the continental margin of the Bering Sea near Navarin Basin and for basaltic rocks from the Pribilof Islands and submarine ridge on which the islands are located, which is informally referred to as Pribilof Ridge. The compositions are compared with other alkalic rocks from the Bering Sea region and the implications for tectonic processes in this region are examined.

GEOLOGIC SETTING

The continental margin in the Bering Sea extends about 1500 km northwestward from the Alaska Peninsula to eastern Siberia (Fig. 1). The continental slope, ranging in depth from about 200 to 2800 m, terminates a large, shallow shelf that extends as far as 600 km from the coast of Alaska. The outer shelf edge and continental slope are incised by several large submarine canyons.

The southern part of the outer Bering Sea shelf is characterized by a series of bedrock ridges and narrow basins extending northwestward from the Alaska Peninsula (Marlow and Cooper, 1980; Cooper et al., 1987). Parts of one of the ridges, Pribilof Ridge, project above sealevel as the Pribilof Islands. The Pribilofs consist of two larger islands, St. George and St. Paul, located about 70 km apart and several islets near St. Paul. Both islands are composed largely of Quaternary basaltic lava flows erupted from numerous vents scattered around the islands. Flows are intercalated with fossiliferous marine sediment in some places (Barth, 1956). On St. George Island the volcanic flows and sedimentary beds rest on serpentinized peridotite which is cut by an Eocene quartz diorite dike with subduction-related chemical affinity (Davis et al., 1989). A magnetic anomaly across the outer edge of the shelf suggests the presence of a large, buried, ultramafic body which may be similar to the peridotite exposed on St. George Island (Marlow and Cooper 1980).

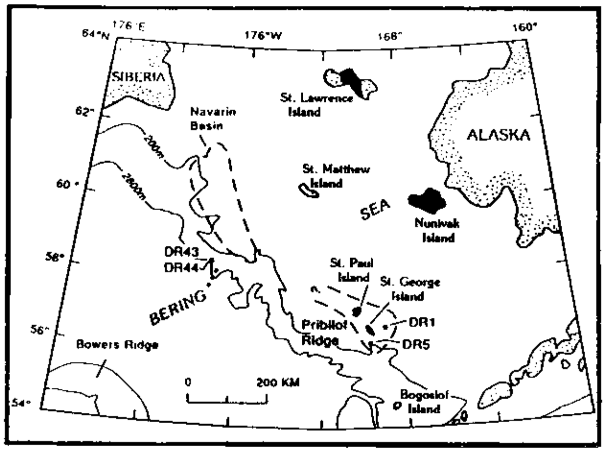


Fig. 1. Map of the Bering Sea continental margin showing dredge locations (stars) and location of other late Cenozoic volcanic centers (black). The location of the seismic profile, shown in figure 2, is indicated by a dashed line.

The central and northern parts of the Beringian margin are partly composed of arcuate volcanic ridges (Fig.2). Seismic reflection data suggest that a fossil subduction zone may be buried beneath the base of the continental slope (Marlow and Cooper, 1980). Volcanic rocks dredged in deeper water near Navarin Basin, close to where the Quaternary basanites were recovered, represent an Eocene island arc suite ranging from tholeiitic and calc-alkalic basalt to andesite and dacite (Davis et al., 1989).

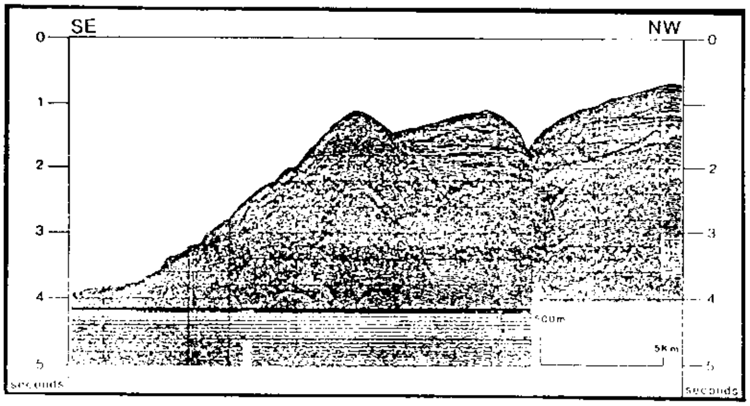


Fig. 2. Multichannel seismic reflection profile across the continental margin near Navarin Basin shows arcuate volcanic ridges. Deep dredges (2200-900 m) recovered Eocene age (>50 Ma) subduction-related volcanic rocks. Dredges in shallow water depths (~120 m) recovered Quaternary alkalic basanite flows and hyaloclastite breccias.

METHODS

The samples from near Navarin Basin were recovered in two dredge hauls during the U.S. Geological Survey cruise L9-82-BS of the R/V S.P. Lee from the continental margin at latitude 58°39.0'N and longitude 177°12.9'W, in a water depth of 122-120 m. The samples from Pribilof Ridge were collected on two U.S. Geological Survey cruises of the Sea Sounder in 1976 and 1977. Samples from St. George and St. Paul Island were collected by D. Hopkins in 1964 and 1975. More details concerning sampling are given in Davis et al. (1993) for the Navarin basanites and by Lee-Wong et al. (1979) for the Pribilof basalts.

Bulk chemical analyses were performed in the analytical laboratories of the U. S. Geological Survey. Major element chemistry was determined by wave-length dispersive X-ray fluorescence (XRF) and abundances of Rb, Sr, Zr, Ba, Y, and Nb by energy-dispersive XRF, using methods described in Baedecker (1988). FeO, CO_2, and H_2O were determined by standard wet chemical techniques (Peck 1964). Abundances of Hf, Ta, Th and the rare earth elements (REE) were determined by instrumental neutron activation analysis (INAA) using the methods described in Baedecker (1988). Olivine, clinopyroxene, plagioclase, and glass were analyzed with a 9-channel ARL electron microprobe. Operating conditions, standards, and data reduction methods used are described in Davis and Clague (1987).

PETROGRAPHY AND MINERAL CHEMISTRY

Representative analyses of mineral phases are given in Table 1. Additional mineral chemistry is given in Davis et al. (1987) and Lee-Wong et al. (1979).

Navarin Basanite

Except for two hyaloclastite samples (44-8, 44-9) composed of fresh, pale-brown sideromelane lapilli, in a crushed, partially devitrified glass matrix, all samples are highly vesicular (30-55%) flow rock with olivine and clinopyroxene microphenocrysts in a cryptocrystalline or tachylite matrix . Except for the devitrified glass in the hyaloclastites, the dredged samples are fresh and show only traces of clay minerals, calcite, and zeolites in fractures and some vesicles.

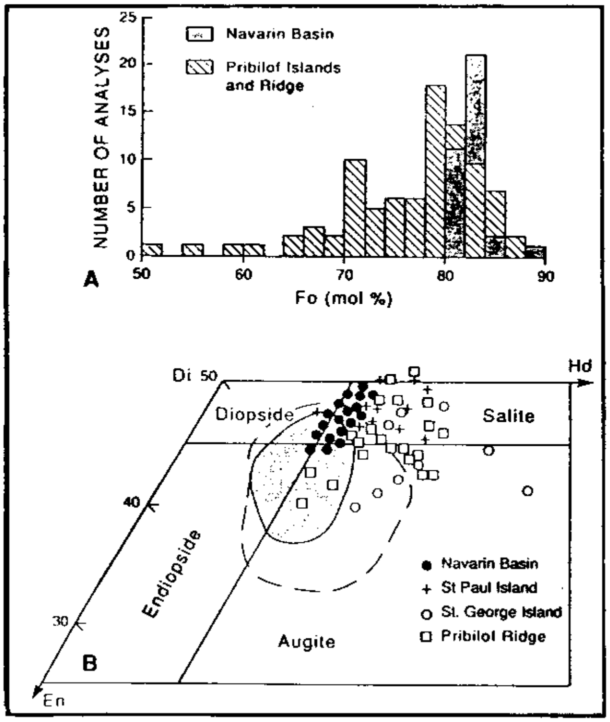


Fig. 3. (**A**) Histogram of forsterite content (Fo % molar) of olivines in basalts from the Bering Sea continental margin. (**B**) Ternary Ca-Mg-Fe diagram for clinopyroxene in basalts from the Bering Sea continental margin. Clinopyroxene in Eocene lavas dredged from the same location as the basanites (shaded field) and from Aleutian arc lavas (dashed) are shown for comparison. Data for Aleutian clinopyroxene from Kay and Kay (1985); for Eocene volcanic arc samples from near Navarin Basin from Davis et al. (1989).

Olivine is fresh and has no iddingsite alteration rims. Most crystals are small euhedral microphenocrysts with rare cuspate margins. Olivine has a compositional range from Fo_{81} to Fo_{89} but most analyses cluster between Fo_{82} to Fo_{84} (Table 1, Fig. 3a) and appear to be in equilibrium with their host lavas. The high Fo_{89} content is only found in cores of rare phenocrysts and is correlated with low CaO and high NiO contents, suggesting crystallization in a more primitive melt and probably at greater depth. Compositional zoning is slight and may be normal and reverse with both occurring in the same sample. Clinopyroxene is mostly salite with a limited compositional range (Wo $_{45\text{-}49}$ En $_{39\text{-}46}$ Fs $_{8\text{-}12}$, Table 1, Fig. 3b). Clinopyroxene crystals are euhedral and similar in size to olivine, suggesting that they cocrystallized with olivine. Compositional zoning is slight (2% max.) and may consist of more magnesian cores, rimmed by somewhat more iron-rich compositions, or the reverse. Due to the limited differentiation of the lavas, Ca-Mg-Fe composition has a narrow range (Fig. 3b), however the range in TiO_2, Al_2O_3, and Cr_2O_3 is considerable, ranging from 1.2 to 3.0%, 2.2 to 6.1%, and 0.01 to 0.92%, respectively.

Pribilof Basalt

Unlike the Navarin basanites, basalts from the Pribilof Islands and Pribilof Ridge are predominatly plagioclase-phyric. Variable amounts of clinopyroxene and olivine phenocrysts accompany the plagioclase phenocrysts in either a holocrystalline groundmass consisting of plagioclase, clinopyroxene, and opaque minerals or in a groundmass containing small amounts of glass (tachylite or sideromelane). Modal nepheline was found in two of the most strongly alkalic samples (DR1-25, G-142) from Pribilof Ridge and St. George Island. Secondary minerals, mostly limited to filling fractures and vesicles, include clays, zeolites, carbonate, and rare quartz. Ultramafic inclusions are present in some samples (Barth, 1956; Lee-Wong et al., 1979) .

Olivine, in accord with a greater range in host rock compositions, ranges from Fo_{89} in the core of phenocrysts to nearly Fo_{50} (Fig. 3a) for anhedral crystals in the groundmass. Clinopyroxene compositions are either augite in the mildly alkalic samples or salite in the more alkalic ones. TiO_2 ranges from $<1\%$ to 5.5%. Plagioclase compositions are mostly labradorite but range from An_{69} to An_{55} for phenocryst cores and from An_{64} to An_{47} for rims and microlites (Table 1). Compositional zoning is typically normal and of limited extent (~ 3%) but reaches a maximum of 8%.

MAJOR ELEMENT CHEMISTRY

Navarin Basanite

The samples dredged from near Navarin Basin have a limited compositional range (Table 2). Compositions are relatively primitive with MgO ranging from 9% to 11% in the whole rock samples. Fresh sideromelane within the hyaloclastite is more differentiated with MgO of about 5%. Fractional crystallization calculations (Stormer and Nicholls, 1978) indicate that the observed difference in composition between whole-rock and glass can result from crystal fractionation of about 10% olivine and 5% clinopyroxene. The general lack of alteration of the flow samples is indicated by water contents of less than 1%, whereas the hyaloclastite samples contain as much as 15% H_2O, caused by alteration of some of the glass matrix. Likewise, Fe_2O_3/FeO ratios of less than 0.5 for the flow samples compared to 1.7 for the hyaloclastite is indicative of the degree of oxidation of the latter. Except for the whole-rock hyaloclastite analyses, all samples are strongly nepheline-normative (8% to 12%). Normative compositions calculated for the whole-rock analyses of the hyaloclastites are hypersthene normative because of high ferric iron content due to the oxidation of the glass matrix. The fresh sideromelane compositions have more that 11% normative nepheline, calculated with $Fe^{3+} = 0.25$ Fe total. On an alkalis vs. silica plot (Fig. 4), all samples are clearly alkalic (Macdonald and Katsura, 1964). Na_2O, K_2O, TiO_2, and Al_2O_3 contents generally increase with decreasing MgO, and FeO generally decreases but shows lots of scatter (Fig. 5).

Pribilof Basalt

The samples from the Pribilof Islands and Pribilof Ridge are mostly alkalic basalt but range from mildly alkalic basalt to strongly alkalic nephelinite (Tables 3,4; Fig. 4). Most samples from St. George and the submarine ridge are mildly alkalic but minor nephelinite was also recovered from both places. Samples from St. Paul are generally more alkalic than most of the basalt from St.George, but do not include nephelinite. Na_2O, K_2O, and TiO_2 generally increase with differentiation (decreasing MgO). Three generalized trends with progressively increasing K_2O and TiO_2 are suggested for mildly, moderately, and strongly alkalic compositions (Fig. 5). FeO vs. MgO shows even more scatter and no well definded trends. Scatter in major oxide concentrations and crystal fractionation calculations (Stormer and Nicholls, 1978) indicate that compositions erupted at a given site are not related by simple crystal fractionation.

TRACE ELEMEMT CHEMISTRY

Navarin Basanite

Table 2 includes trace element data for nine whole-rock samples; fresh sideromelane was not abundant enough to separate for trace element analyses. Chondrite-normalized rare earth element (REE) abundances are shown in figure 6. All of the samples plot within a narrow range with light REE enrichment relative to the heavy REE that is typical for alkalic lavas. The REE patterns of the hyaloclastites are parallel to, and plot within, the narrow band defined by the whole-rock samples, supporting the contention of Staudigel and Hart (1983) that REE compositions of volcanic glasses are not significantly changed during small to moderate amounts of alteration. Alteration-resistant high field strength elements such as Y, Zr, and Nb are also nearly identical for whole-rock and hyaloclastites with constant Zr/Nb (4.0±0.2) and Zr/Hf (43 ±2) ratios (Table 2). Abundances of Hf, Ta, and Th are somewhat lower in the more differentiated hyaloclastites but show no significant change in proportions to each other.

All samples plot in a tight cluster in the alkaline within-plate field of the Hf-Ta-Th diagram, in contrast to Eocene-age samples dredged from greater depth at the same site which plot within the field for convergent plate margins (Fig. 7). Likewise, a spidergram for the Quaternary basanites shows Ta and Nb abundances that are typical of oceanic island basalt whereas the Eocene volcanic suite shows the Ta and Nb depletion (Davis et al., 1989) characteristic of volcanic arc lavas (Fig. 8). K/Rb ratios of about 300 to 500 and high Rb, Ba, and Th abundances suggest partitioning of incompatible elements into the melt that is compatible with small amounts of partial melting.

The sulfur content of fresh glass in the hyaloclastites is about 400 ppm (Table 2), indicating that they are partially degassed. Although sulfur is typically retained in tholeiitic magmas erupted in deep water (> 1000 m), the relationship between sulfur contents and eruption depth is not straightforward and sulfur contents of undegassed basaltic magmas are different for basalts from different tectonic settings (Davis et al., 1990). However, basanites of similar compositions from Loihi Seamount, erupted at greater than 1000 m depth, have over 1300 ppm sulfur while subaerially erupted Hawaiian basalts typically have less than 250 ppm (Davis et al., 1990 and references therein). Therefore, sulfur contents of about 400 ppm suggests that these samples represent partially degassed lavas that were probably erupted in shallow water or under ice.

Table 1. Mineral chemistry of selected samples from the Bering Sea continental margin

Location	Navarin Basin										Pribilof Ridge		
Sample	44-6					44-8			44-13		DR5-88		
Phase	Cpx C	Cpx R	Ol C	Ol R	Ol C	Cpx R	Cpx C	Ol C	Cpx R	Cpx C	Ol R	Ol C	Cpx C
(wt.%)													
SiO_2	51.5	47.0	39.7	40.0	40.3	49.0	51.0	39.5	49.3	50.3	39.3	39.6	49.7
Al_2O_3	3.04	5.83	---	---	---	4.40	2.77	---	4.04	3.55	--	---	4.24
TiO_2	1.26	2.68	---	------	---	2.07	1.63	---	1.99	1.52	---	---	1.22
Cr_2O_3	0.67	0.22	---	---	---	0.92	0.34	---	0.81	0.90	---	---	0.82
FeO	4.95	6.96	15.4	16.6	10.9	5.89	6.21	15.1	6.03	5.46	20.3	18.0	6.75
MnO	0.07	0.06	0.19	0.25	0.14	0.08	0.10	0.18	0.07	0.08	0.28	0.24	0.12
MgO	15.4	13.4	44.1	42.9	47.8	14.5	15.5	44.6	14.5	15.0	40.7	42.6	15.0
CaO	22.9	22.7	0.24	0.42	0.08	22.7	22.2	0.20	22.7	22.6	0.25	0.31	21.2
Na_2O	0.49	0.57	---	---	---	0.45	0.35	---	0.46	0.45	---	---	0.42
NiO	---	---	0.24	0.15	0.35	---	---	0.27	---	---	0.11	0.16	---
Total	100.2	99.4	99.9	99.7	99.5	100.0	100.0	99.8	100.0	99.9	100.8	100.9	99.4
(mol.%)													
Fo	---	---	83.7	82.2	88.7	---	---	83.9	---	---	78.1	80.8	---
Wo	47.5	48.5	---	---	---	47.8	45.7	---	47.7	47.4	---	---	44.7
En	44.5	39.9	---	---	---	42.5	44.3	---	42.4	43.7	---	---	44.7
Fs	8.0	11.6	---	---	---	9.7	10.0	---	9.9	8.9	---	---	10.6

	Pribilof Ridge					Pribilof Islands							
Sample	DR5-88					G-201			P-48				
Phase	Pc R	Pc C	Pc mc	Ol C	Ol mc	Ol C	Pc C	Pc mc	Pc C	Pc R	Ol mc	Cpx C	Cpx R
SiO_2	53.0	50.5	53.7	39.6	37.2	40.2	52.4	55.5	50.4	52.4	37.5	43.4	43.7
Al_2O_3	29.4	30.0	29.2	---	---	---	29.0	26.6	30.4	29.2	---	7.40	8.04
TiO_2	---	---	---	---	---	---	---	---	---	---	---	5.52	5.10
Cr_2O_3	----	---	---	---	---	---	---	---	---	---	---	0.01	0.06
FeO	0.48	0.50	0.54	18.0	24.2	10.3	0.41	0.51	0.45	0.45	23.8	9.12	8.67
MnO	----	----	---	0.24	0.35	0.15	---	---	---	---	0.35	0.17	0.14
MgO	0.15	0.17	0.16	42.6	37.6	47.9	0.18	0.09	0.08	0.08	37.1	10.1	10.6
CaO	12.3	13.8	12.1	0.31	0.31	0.05	12.6	9.63	13.4	12.0	0.47	22.6	22.4
Na_2O	4.51	3.63	4.45	---	---	---	4.26	5.85	3.75	4.42	---	0.66	0.58
K_2O	0.24	0.16	0.26	---	---	---	0.19	0.42	0.46	0.46	---	---	---
NiO	---	---	---	0.16	0.11	0.33	---	---	---	---	0.04	---	---
Total	100.1	98.8	99.5	100.9	99.8	99.2	99.1	98.6	98.7	99.0	99.2	99.5	99.2
Fo (mol.%)	---	---	---	80.8	73.5	89.2	---	---	---	---	73.6	---	---
Wo	---	---	---	---	---	---	---	---	---	---	---	51.9	50.6
En	---	---	---	---	---	---	---	---	---	---	---	31.6	34.2
Fs	---	---	---	---	---	---	---	---	---	---	---	16.5	15.2
An	59.2	67.1	59.2	---	---	---	61.4	46.5	65.5	58.4	---	---	---
Ab	39.4	32.0	39.3	---	---	---	37.5	51.1	33.2	38.4	---	---	---
Or	1.4	0.0	1.5	---	---	---	1.1	2.4	1.3	2.7	---	---	---

Cpx, clinopyroxene; Ol, olivine; Pc, plagioclase.

R , C, rim and core of larger phenocrysts, respectively; mc, core of microphenocrysts.

Table 2. Chemistry of Navarin basanite

Sample	44-3	44-6	44-7	44-8	44-8 Gl	44-9	44-9 Gl	44-10	44-11	44-12	44-13
(wt.%)											
SiO_2	41.5	43.2	44.8	38.6	46.3	42.4	46.4	45.3	44.6	43.9	45.4
Al_2O_3	10.6	11.2	11.4	9.61	13.0	9.59	13.3	11.6	11.3	11.5	11.6
Fe_2O_3	4.84	3.64	3.63	7.68	--	8.17	---	3.01	3.59	4.46	3.69
FeO	7.34	8.87	8.97	4.34	11.5*	5.16	11.6*	9.08	9.10	8.04	8.74
MgO	10.6	10.5	9.24	10.2	5.13	8.96	5.03	9.58	9.40	9.47	8.91
CaO	11.0	10.9	10.5	5.03	10.6	5.67	10.4	10.4	10.3	10.3	10.1
Na_2O	3.09	3.54	3.45	2.59	4.22	2.94	4.33	3.42	3.51	3.52	3.41
K_2O	1.91	2.30	2.23	1.59	2.47	1.84	2.44	2.06	2.20	2.17	2.16
TiO_2	3.27	3.41	3.27	2.70	3.73	2.66	3.66	3.21	3.24	3.24	0.92
P_2O_5	1.24	0.86	0.84	0.78	0.79	0.80	0.87	0.90	0.82	0.88	3.16
MnO	0.16	0.16	0.15	0.13	0.16	0.11	0.16	0.15	0.15	0.15	0.92
H_2O	1.95	0.48	1.12	15.85	---	11.69	---	0.91	1.17	1.14	0.15
CO_2	0.21	0.21	0.12	0.31	---	0.19	---	0.08	0.08	0.12	1.29
Total	97.7	99.1	99.7	99.8	98.0	100.2	98.2	99.7	99.3	98.8	99.5
S (ppm)	---	---	---	---	450	---	350	---	---	---	---
Rb	46	60	56	23	---	35	---	56	51	59	67
Sr	916	874	831	451	---	513	---	822	796	838	789
Y	17	21	20	17	--	17	---	19	18	20	24
Zr	246	258	233	196	---	192	---	237	233	241	233
Nb	58	65	61	51	---	46	--	59	57	59	63
Ba	1012	793	689	542	---	477	---	696	644	702	643
Hf	5.7	5.8	5.5	4.6	---	4.4	---	5.4	5.4	5.8	5.3
Ta	4.2	4.4	4.2	3.4	---	3.3	---	3.9	4.0	4.3	3.9
Th	7.6	8.4	7.1	5.6	----	5.3	---	6.6	6.9	7.3	6.3
La	56.9	63.6	55.1	44.3	---	41.6	----	52.0	53.3	56.6	52.0
Ce	104	110	99.1	81.0	---	75.3	----	93.5	93.5	103	92.1
Nd	47	51	47	35	---	35	----	48	51	50	39
Sm	7.7	9.9	9.4	6.6	---	6.6	---	9.1	9.3	9.5	8.1
Eu	2.8	2.8	2.7	2.1	---	2.1	----	2.6	2.6	2.7	2.5
Tb	0.93	0.88	0.94	0.71	---	0.65	---	0.90	0.94	0.99	0.84
Yb	1.3	1.3	1.6	1.1	---	1.4	---	1.4	1.6	1.7	1.5
Lu	0.19	0.20	0.20	0.16	---	0.16	---	0.19	0.18	0.20	0.21
Zr/Nb	4.2	4.0	3.8	3.8	----	4.2	----	4.0	4.1	4.1	3.7
$^{87}Sr/^{86}Sr$	---	0.70428	---	----	---	---	---	0.70432	---	0.70434	0.70431
$^{143}Nd/^{144}Nd$	---	0.512665	---	---	---	---	---	0.512702	---	0.512661	0.512702
$^{206}Pb/^{204}Pb$	---	18.75	---	---	---	---	---	18.92	---	18.89	18.93
$^{207}Pb/^{206}Pb$	---	15.54	---	---	---	---	---	15.56	---	15.55	15.56
$^{208}Pb/^{206}Pb$	---	38.79	---	---	---	---	---	38.92	---	38.92	38.86

Gl, glass in hyaloclastite. * all iron as FeO.

Pribilof Basalt

The Pribilof basalts have trace element concentrations typical of oceanic island basalt. Most samples plot within the alkaline intraplate basalt field on the Ta-Hf-Th plot (Fig.7), although they are lower in Th than the Navarin basanites. Two hypersthene-normative basalts from St. George and Pribilof Ridge plot within the E-MORB and tholeiitic intraplate field (Fig. 7) Chondrite-normalized REE profiles (Fig. 6) also show typical light REE enrichment, but less than for Navarin basanites. Likewise, on spidergrams the patterns from the Pribilofs are similar to those of Navarin basanite, but the latter show greater incompatible element enrichment especially with respect to Ba, Th, and LREE (Fig. 8). On plots of Y and Zr/Nb vs. Zr abundance (Fig. 9) and (Ce/Yb)N vs. Ce abundance (Fig. 10) the Pribilof basalts have a larger range of Zr/Nb and Ce/Yb ratios than the Navarin basanite that is compatible with greater variation in degree of partial melting.

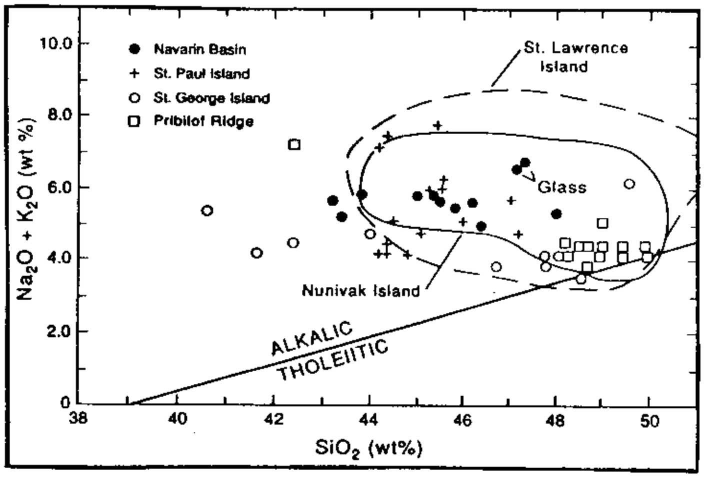


Fig. 4. Alkalis vs. silica plot for basalts from the Bering Sea continental margin. Compositions of lavas from Nunivak and St. Lawrence Islands are shown for comparison. Pribilof data include analyses of Barth (1956) and Lee-Wong et al. (1979); fields for Nunivak and St. Lawrence Islands from Moll-Stalcup (1994).

ISOTOPIC COMPOSITION

Sr, Nd, and Pb isotopic compositions for basanites (Davis et al., 1993) are included in Table 2 and shown in figure 11. Isotopic data of Kay et al. (1978) and Von Drach et al. (1986) for Pribilof basalts are also included for comparison (Fig. 11). The $^{87}Sr/^{86}Sr$ ratios of Navarin basanites range from 0.70428 to 0.70434 and $^{143}Nd/^{144}Nd$ ratios range from 0.512665 to 0.512702. The $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, and 208Pb/204Pb ratios display a range from 18.75-18.93, 15.54-15.56, and 38.79-38.92, respectively. The $^{87}Sr/^{86}Sr$ ratios of Navarin basanites are considerably higher and the $^{143}Nd/^{144}Nd$ ratios are lower than for other late Cenozoic samples from the Bering Sea region (Fig. 11a). The four basanite analyses form a tight cluster toward the enriched end of the oceanic island trend, but appear slightly displaced toward continental intraplate basalts, such as those from the Rio Grande Rift. The $^{207}Pb/^{204}Pb$ ratios are displaced from the oceanic trend toward that of continental detritus. Although the $^{207}Pb/^{204}Pb$ ratios are significantly higher, the $^{206}Pb/^{204}Pb$ ratios are similar to those from the Pribilof Islands, which plot within the MORB-field (Fig. 11b).

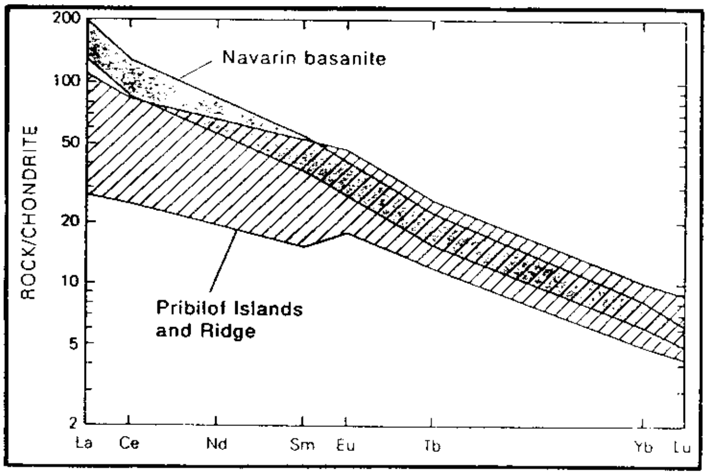


Fig. 5. Chondrite-normalized rare earth elements (REE) for Navarin basanites have a narrow range with light REE enrichment over heavy REE that is typical for alkalic basalts. The field of Pribilof basalts has a greater range in compositions but with less light REE enrichment.

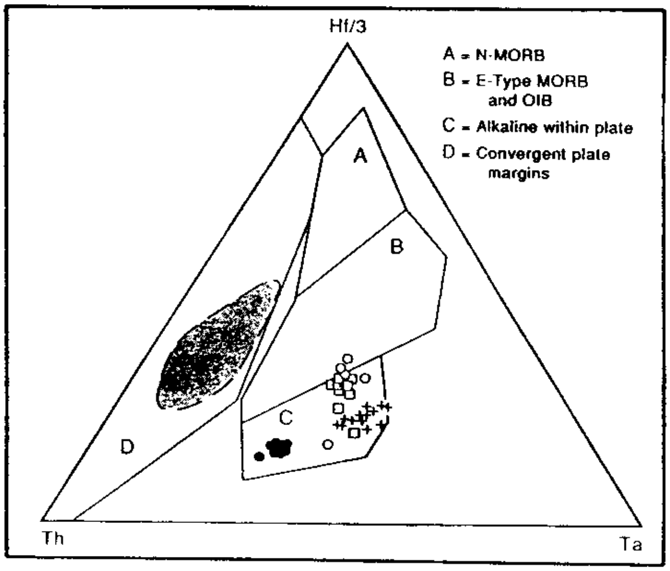


Fig. 6. On a Hf-Th-Ta plot the Navarin basanites form a tight cluster in the alkaline within-plate field (Wood 1980). Most of the Pribilof basalts fall into the same field but some of the less alkalic samples plot in or close to the oceanic island and E-MORB field. Eocene volcanics (shaded field), dredged from greater depths near the location from where the basanites were recovered, plot in the field for convergent plate margins. Symbols and data sources as in figure 3.

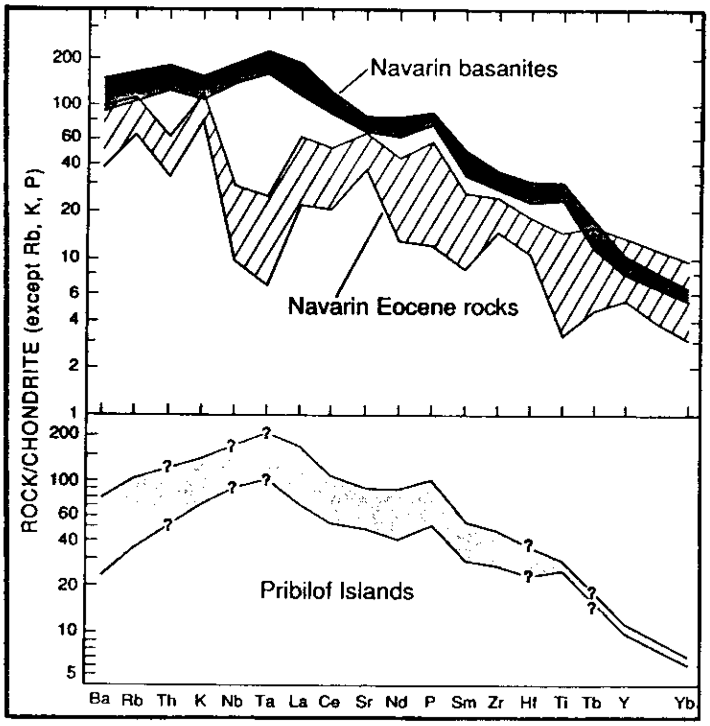
Table 3. Chemistry of representative Pribilov Ridge basalt.

Sample	DR1-19	DR1-24	DR1-25	DR1-27	DR5-4	DR5-8	DR5-32	DR5-34	DR5-88	DR5-111	DR5-116	DR5-121
(wt.%)												
SiO_2	48.7	48.3	42.4	49.1	48.3	48.5	50.0	49.0	48.7	49.1	49.4	48.7
Al_2O_3	14.8	14.8	14.0	16.5	15.1	15.0	14.1	15.0	15.2	14.1	14.9	14.8
Fe_2O_3	3.49	3.59	4.17	3.73	3.54	3.35	3.20	3.39	3.55	3.33	3.44	3.49
FeO	8.06	7.42	7.69	6.68	7.52	8.03	7.45	8.51	7.92	8,42	8.21	8.06
MgO	8.04	8.84	6.43	4.79	7.00	7.76	8.77	8.50	7.59	8.40	7.98	8.04
CaO	9.19	9.40	11.0	9.67	9.57	8.99	8.78	9.09	9.17	8.82	9.02	9.19
Na_2O	3.33	3.55	5.39	3.77	3.53	3.65	3.21	3.47	3.39	3.54	3.55	3.33
K_2O	0.68	1.08	1.75	1.41	0.73	0.89	0.91	0.80	1.03	0.78	0.84	0.68
TiO_2	1.99	2.09	2.67	2.23	2.04	1.85	1.70	1.89	2.05	1.83	1.94	1.99
P_2O_5	0.47	0.58	1.24	0.60	0.46	0.45	0.37	0.35	0.39	0.40	0.40	0.47
MnO	0.15	0.13	0.17	0.13	0.14	0.14	0.15	0.15	0.16	0.15	0.15	0.15
H_2O												
Total	98.94	99.73	96.93	98.59	97.96	98.67	98.66	100.09	99.11	100.22	99.84	98.94
(ppm)												
Rb	9	26	14	14	14	15	17	14	14	8	14	10
Sr	335	530	1000	570	460	365	295	315	390	300	310	355
Y	19	15	18	21	20	20	16	22	22	9	19	24
Zr	67	70	99	88	72	77	56	88	83	40	120	94
Nb	17	10	35	22	14	13	12	18	22	9	19	21
Ba	110	150	390	230	150	170	170	150	150	130	120	150
Hf	2.60	3.11	5.22	3.62	3.08	2.74	2.60	2.61	2.93	2.50	2.67	2.31
Ta	1.05	1.46	4.43	2.11	1.25	1.18	1.05	1.17	1.39	1.00	1.11	0.94
Th	1.01	1.38	4.22	2.19	1.34	1.24	1.29	1.18	1.36	1.05	1.02	1.07
La	10.8	14.1	41.8	20.8	13.2	11.9	11.7	11.2	14.1	10.7	10.9	10.8
Ce	23.6	28.3	83.0	38.9	28.7	28.9	24.2	25.5	31.7	21.8	22.2	21.0
Nd	14.1	16.1	41.40	20.9	16.6	16.8	13.8	15.7	20.8	13.9	12.3	13.2
Sm	3.33	3.89	8.16	4.57	4.39	3.98	3.48	3.78	4.35	3.32	3.42	3.27
Eu	1.36	1.53	3.11	1.68	1.56	1.40	1.28	1.37	1.54	1.33	1.37	1.31
Tb	0.68	0.75	1.16	0.87	0.79	0.73	0.65	0.66	0.77	0.66	0.70	0.58
Yb	1.77	1.83	1.41	1.95	1.83	1.81	1.59	1.61	1.85	1.62	1.72	1.68
Lu	0.27	0.26	0.19	0.30	0.28	0.26	0.26	0.25	0.26	0.25	0.27	0.25
Zr/Nb	3.9	7.0	2.8	4.0	5.1	5.9	4.7	4.9	3.8	4.4	6.3	4.5

Table 4. Chemistry of representative Pribilof Islands basalt

	St. George Island					St. Paul Island						
Sample	G-14	G-115	G-142A	G-186A	G-201A	P-5	P-8	P-22	P-27A	P-27B	P-39	P-48
(wt.%)												
SiO_2	48.1	48.5	40.6	47.8	47.7	44.2	44.8	46.0	45.3	44.5	45.6	45.6
Al_2O_3	13.6	14.4	13.2	14.5	14.1	12.7	12.6	14.9	16.1	13.6	17.0	16.3
Fe_2O_3	3.88	3.12	4.29	3.42	3.32	3.77	3.48	3.86	4.73	3.70	4.61	4.74
FeO	8.74	8.61	8.83	9.08	8.86	9.39	8.40	7.80	7.54	7.52	7.45	7.68
MgO	9.10	9.89	11.2	9.31	9.55	13.6	14.6	8.87	6.66	12.6	4.85	5.16
CaO	8.94	8.80	10.5	8.67	8.45	8.24	9.09	9.31	9.90	9.43	9.85	10.1
Na_2O	3.16	3.12	4.00	3.28	3.34	3.04	3.00	3.58	4.08	3.29	4.25	4.08
K_2O	0.91	0.46	1.27	0.63	0.81	1.01	1.13	1.47	1.84	1.67	1.90	1.92
TiO_2	2.38	1.62	2.79	1.92	1.82	2.27	1.98	2.36	3.23	2.20	3.11	3.24
P_2O_5	0.32	0.23	0.86	0.27	0.25	0.36	0.39	0.38	0.56	0.53	0.65	0.66
MnO	0.17	0.16	0.18	0.18	0.17	0.18	0.17	0.16	0.17	0.16	0.17	0.17
Total	99.29	98.84	97.71	99.00	98.38	98.83	99.69	98.75	100.09	99.18	99.48	99.55
(ppm)												
Rb	25	20	32	18	22	12	20	27	17	20	24	23
Sr	405	325	720	345	375	510	510	540	710	710	780	760
Y	20	15	20	15	15	15	10	15	10	15	15	15
Zr	100	100	200	70	70	100	100	100	100	100	100	150
Nb	15	15	30	10	15	10	10	10	15	10	10	15
Ba	100	70	200	100	100	150	100	150	200	200	200	200
Hf	3.26	2.17	5.24	2.60	2.51	2.70	3.15	4.23	4.26	3.54	4.25	4.83
Ta	1.45	0.75	4.70	0.96	0.95	1.77	2.09	2.88	2.72	2.52	2.91	3.28
Th	1.18	0.71	5.39	0.98	0.97	1.38	1.83	3.09	1.95	2.20	2.40	2.55
La	12.5	7.2	40.9	9.6	9.9	14.8	18.1	18.9	23.2	23.0	24.4	28.6
Ce	27.3	16.6	82.3	21.4	22.0	30.9	38.6	38.7	50.2	46.9	50.0	62.5
Nd	15.8	10.3	38.9	12.4	13.0	17.4	21.7	20.2	26.2	25.8	26.3	32.3
Sm	3.97	2.76	7.67	3.49	3.17	3.59	4.28	4.47	5.84	4.70	5.19	6.93
Eu	1.46	1.15	2.74	1.35	1.26	1.37	1.50	1.66	2.05	1.67	2.07	2.28
Tb	0.70	0.57	1.13	0.64	0.62	0.60	0.67	0.70	0.86	0.68	0.87	0.92
Yb	1.75	1.43	1.55	1.65	1.55	1.13	1.29	1.52	1.38	1.25	1.53	1.59
Lu	0.27	0.21	0.23	0.26	0.24	0.16	0.17	0.22	0.21	0.18	0.21	0.22
Zr/Nb	6.7	6.7	6.7	7.0	4.7	10.0	10.0	10.0	6.7	10.0	10.0	10.0

Fig. 7. Spidergram for Navarin basanites show Nb, Ta, and light REE abundances that are typical for alkalic within-plate lavas. The field for the Eocene basalt to dacite suite recovered in the deeper dredges shows the Nb-Ta depletion characteristic of island arc lavas (Davis et al., 1989). Sampels from the Pribilof Islands have similar patterns as the Navarin basanites but samples of comparable alkalinity have lower Ba, Rb, and LREE abundances. Data for Pribilof basalts includes data from Kay (1980); question marks indicate projected values for elements that were not reported. Normalizing values from Thompson (1982).

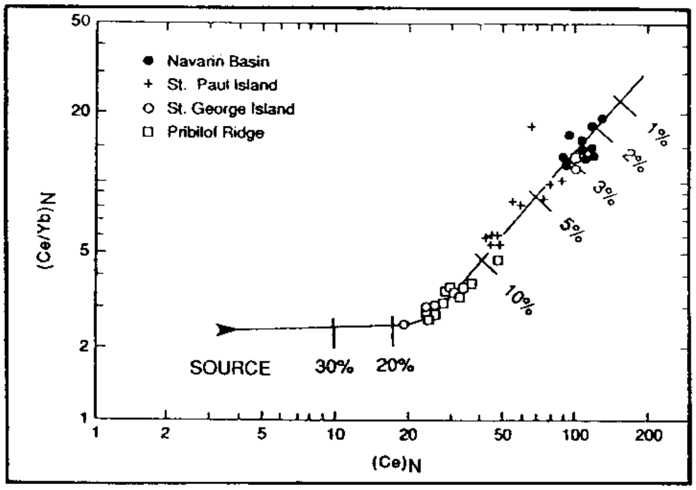


AGES

Whole rock conventional K/Ar ages for Navarin basanite were reported by Davis et al. (1993), for Pribilof Islands basalt by Cox et al. (1966), and for Pribilof Ridge by Lee-Wong et al. (1979); ages are summarized in Table 5. K/Ar ages of Navarin basanite indicate two episodes of volcanism at about 1.1 Ma and 0.4 Ma. Ages for the Pribilof basalts indicate at least three episodes of volcanism. One major episode at St. George Island lasted from about 2.2 Ma to 1.6 Ma; volcanism at the Pribilof Ridge was dated at about 0.8 Ma, and volcanism at St. Paul Island occurred from about 0.4 Ma to recent, with a historic eruption in 1892 (Barth, 1956). Although the precision of conventional K/Ar ages is such that some ages appear to overlap, the presence of interbedded sediments and weathering horizons observed between flows on the Pribilof Islands (Cox et al., 1966) suggest that eruptions occurred sporadically with considerable time elapsed between them. Other volcanic centers in the Bering Sea region also appear to have experienced multiple episodes or eruptive pulses separated by distinct hiatuses. At least four episodes of volcanism occurred on Nunivak Island, spanning at least 6 million years (Fig. 12).

Available age data suggest that chemically diverse volcanism in the Bering Sea may have been roughly synchronous at different volcanic centers during some episodes (Fig. 12).

Fig. 8. Plot of chondrite-normalized Ce/Yb ratios vs. normalized Ce abundance suggests smaller percentage of melting for the Navarin basanites and progressively increasing degree of melting for less alkalic lavas from the Pribilofs. The solid curved line indicates a batch melting curve for garnet lherzolite. Compositions at 30% to 1% partial melting are indicated. Due to the nature of the log-log plot the curve can be moved relative to its axes. Modified from Tarney et al. (1980).



DISCUSSION

Comparison with other Bering Sea lavas

Alkalic, intraplate volcanism has occurred repeatedly in the Bering Sea region. Similar late Cenozoic volcanism occurred on Nunivak (Hoare et al., 1968), St. Lawrence (Patton and Csejtey, 1980) and St. Michaels Island (Moll-Stalcup, 1994), and in several places in mainland Alaska (Moll-Stalcup, 1994). Unlike Hawaiian volcanism, which is characterized by eruption of large volumes of tholeiitic lavas, building a large shield over a long period of time, eruption on Nunivak was of small isolated batches of mostly alkalic basalt (Fig. 4) that erupted sporadically for at least the last six million years (Fig. 12, Hoare et al., 1968). On Nunivak

Island, and other volcanic centers in the Bering Sea region, limited amount of differentiation, lack of coherent fractionation trends, and presence of mantle xenoliths (Francis, 1976; Roden et al.,1984) indicate eruption of small batches through isolated conduits rather than from large, long-lived magma chambers. Variable isotopic ratios of lavas erupted in close proximity indicate heterogeneous mantle sources (Roden et al., 1984; Menzies and Murthy, 1980 a,b; Von Drach et al., 1986; Davis et al., 1993). On the Pribilof Islands, transitional to strongly alkalic lavas were erupted from about 2.2 Ma to 1.6 Ma on St. George. Mildly and strongly alkalic basalt was erupted on Pribilof Ridge around 0.8 Ma (Lee-Wong et al. 1979) and small volumes of moderately to strongly alkalic basalt were erupted sporadically on St. Paul from about 0.4 Ma to historic times (Cox et al., 1966).

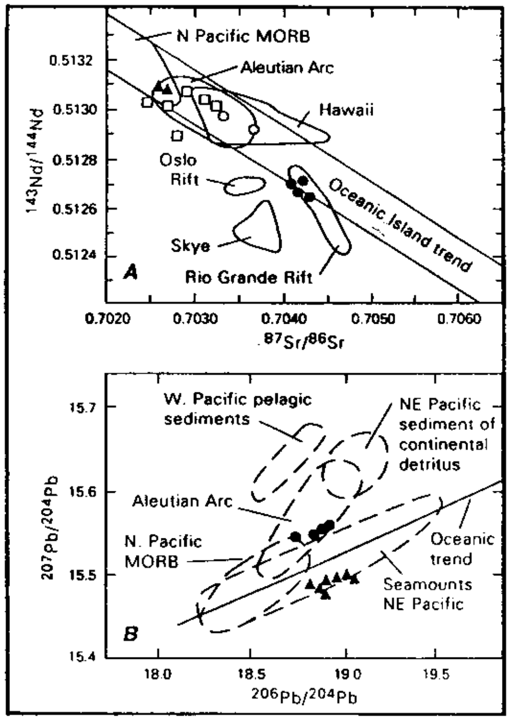


Fig. 9. (A) ^{87}Sr/^{86}Sr vs. ^{143}Nd/^{144}Nd isotopic ratios for Navarin basanites (filled circles) compared to basalts from Pribilof Islands (triangles), Nunivak Island (squares), and St. Lawrence Island (open circles) show the Navarin basanites with significantly higher ^{87}Sr/^{86}Sr and lower ^{143}Nd/^{144}Nd isotopic values. (B) ^{207}Pb/^{204}Pb vs. ^{206}Pb/^{204}Pb isotopic ratios show the Navarin basanites are displaced from the oceanic trend toward that of continentally derived sediments. Pribilof Islands basalts, although similar with respect to most trace elements and ^{206}Pb/^{204}Pb ratios, have significantly lower ^{207}Pb/^{204}Pb ratios. Fields for North Pacific MORB from Church and Tatsumoto (1975) and White et al. (1987), field for Aleutians includes data from Kay et al. (1978); Von Drach et al. (1986), and Singer et al. (1992). Analyses of Nunivak basalts are from Menzies and Murthy (1980) and Von Drach et al. (1986); for Pribilof and St. Lawrence Islands from Von Drach et al. (1986) and Kay et al. (1978).

Chemically, basalts from the Bering Sea continental margin are alkalic intraplate basalts indistinguishable from those erupted on many oceanic islands or in some continental settings. On a(Ce/Yb)N vs. CeN abundance plot (Fig. 10) the Navarin basanites lie on the extreme end of a coherent trend defined by the hypersthene- to nepheline-normative samples from the Pribilof Islands and Pribilof Ridge, suggesting that they were generated by very small percentages of melting of a similar source, yet isotopically they are very distinct. Based on a simple equilibrium batch melting model, shown by the solid line on the (Ce/Yb)N vs. CeN plot (Fig. 10), the Navarin basanites could be generated by < 3% of partial melting compared to ~20% for the least alkalic basalt from the Pribilof Islands from a garnet lherzolite source with Ce abundances of about 4 times chondrite and a (Ce/Yb)N ratio greater than 2. However, a similar trend can also result from mixing a depleted source with small amounts of enriched material. The Sr, Nd, and Pb isotopic compositions clearly indicate a more enriched source for the Navarin basanites than for the Pribilof basalts.

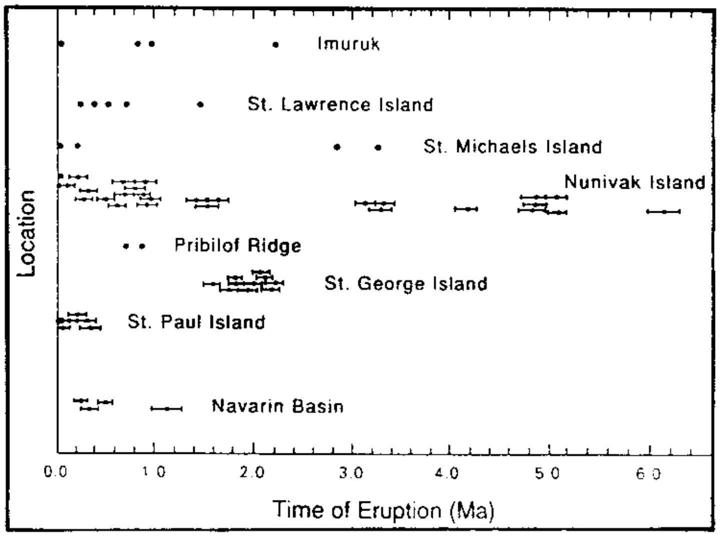


Fig. 10. K-Ar ages of basalts from the Beringian margin indicate that alkalic volcanism occurred sporadically in this region for at least the past six million years. Some episodes are roughly synchronous at several volcanic centers. Data for Pribilofs from Cox et al. (1966), for Pribilof Ridge from Lee-Wong et al. (1979), for Nunivak from Hoare et al. (1968), for St. Lawrence Island from Patton and Csejtey (1980), for St. Michaels and Imuruk from Moll-Stalcup (1994). Error bars have been indicated were data were available.

Isotopic ratios for the Pribilof Islands indicate a depleted, MORB-like source with low ^{87}Sr/^{86}Sr and high 143Nd/ 144Nd values (Fig. 11a) and Pb isotopic ratios plot at the depleted end of the oceanic trend (Fig. 11b). Other Bering Sea lavas indicate more enriched OIB sources. Nunivak lavas are isotopically more enriched and more heterogeneous than the Pribilof basalts, and basalts from St. Lawrence Island have still higher ^{87}Sr/^{86}Sr and lower ^{143}Nd/^{144}Nd ratios (Fig. 11) than those from Nunivak Island. The Navarin basanites have the highest ^{87}Sr/^{86}Sr and lowest ^{143}Nd/^{144}Nd values so far reported for this region and appear more similar to alkalic basalt erupted in continental settings such as the Rio Grande Rift (Fig. 11a). The elevated ^{207}Pb/^{204}Pb isotopic values of the Navarin basanites suggest contamination with a continental crustal component. The variable enrichment observed for Nunivak lavas has been attributed to preferential melting of amphibole-pyroxenite veins in a lherzolite host, such as observed in mantle xenoliths found in Nunivak lavas (Francis, 1976; Menzies and Murthy, 1980 a, b). More alkalic compositions would be generated by preferential melting of the metasomatized veins, whereas mildly alkalic compositions represent more extensive melting of the host rock (Francis 1976, 1991). A similar process could explain the variations observed for the Navarin basanites versus the Pribilof basalts. The transitional and mildly alkalic basalt from the Pribilof Islands could represent larger percentage of partial melting of the depleted peridotite host rock, while the more alkalic compositions include small but variable amounts of metasomatized material. However, compared to Pribilof samples of comparable alkalinity, the higher abundances of Ba, Rb, Th, LREE and especially the elevated ^{207}Pb/^{204}Pb ratios of the Navarin basanites suggest contamination with a crustal component which could have been derived from subducted sediments. Since this region was the site of subduction until the early Eocene (Davis et al., 1989) small amounts of deeply subducted sediment could have been melted and added to the depleted OIB source or the mantle source region could have been metasomatized by subduction-related volcanism during the Eocene.

Table 5. Summary of K-Ar ages for volcanic rocks from the Bering sea continental margin

Location	Age (Ma± 1σ)	Data source
St.George Island		
Cascade Point basalt sequence	2.2 - 2.0	Cox et al., 1966
Tolstoi Point basalt sequence	2.0 - 1.85	"
Myak basalt sequence	1.85 - 1.59	"
Pribilof Ridge		
S76-4 DR5 submarine basalt	0.84 - 0.77	Lee-Wong et al. (1979)
St. Paul Island		
Einahuhto Bluffs, oldest exposed flows	0.36 ± 0.08	Cox et al. (1966)
Pillow lava interbedded with marine sediments	0.15 ±0.02	"
Younger flows	0.13 - <0.01	"
Navarin Basin		
Dredged basanite (44-12)	1.1 ±0.2	Davis et al. (1993)
Dredged basanite (44-3, 43-2)	0.43 ±0.02 - 0.33 ±0.04	"

Implications for tectonic processes

Sporadic eruptions of small volumes of alkalic lavas from geographically widely separated centers probably reflect adjustment of tectonic blocks to regional stresses but no large scale lithospheric extension. Association with faulting appears indicated for some alkalic vents which show a NW alignment parallel to surface faults (e.g. Nunivak and Imuruk, Hoare et al., 1968), whereas location of other vents shows no correlation with surface faults. Evidence for large scale faulting has also been reported for parts of the outer continental margin (Cooper et al., 1987)

The relatively primitive compositions (MgO > 9%), the presence of mantle xenoliths in some lavas and forsteritic olivine with low CaO and high NiO content suggest that the magmas originated at considerable depth and ascended rapidly through fissures and conduits without long residence time in large magma chambers. The high vesicle content of many samples suggests that the magmas were volatile-rich, which may help small batches of melt to rise without requiring large scale extension. Eruption of small volumes of unrelated magma batches and absence of large, crustal magma chambers indicate that volcanism in this region is not due to long-lived mantle plumes, such as proposed for Hawaii or some other oceanic islands. Although some eruptive episodes appear to have been roughly coeval for geographically widely separated centers, sporadic eruption of small, genetically unrelated magma batches probably resulted form upwelling and decompressional melting of small amounts of metasomatized mantle in response to localized lithospheric attenuation associated with structural adjustment to regional stresses.

CONCLUSIONS

Quaternary basaltic rocks recovered from the continental margin of the Bering Sea are similar to other alkalic lavas erupted from geographically widely separated areas in the Bering Sea region. Eruption of volatile-rich alkalic lavas, forming short stubby flows or loose tephra deposits, occurred sporadically from fissures, small cinder cones, or explosion craters in this region for at least the past six million years. The K-Ar ages indicate at least two volcanic episodes at about 1.1 and 0.4 Ma near Navarin Basin and at least three at the Pribilof Islands, ranging from about 2.2- Ma to present. Trace element data suggest these alkalic lavas have been generated by small, but variable, amounts of partial melting of a metasomatized lherzolite source. The primitive nature (MgO > 9%), presence of mantle-derived xenoliths, and forsteritic olivine with low CaO and high NiO suggest that magma rose rapidly from great depth without spending time in large, long-lived magma chambers. Although many samples from the Bering Sea continental margin are similar with respect to major elements and many trace element ratios, isotopic compositions indicate highly heterogeneous sources. Isotopic compositions of Pribilof basalts indicate depleted, nearly MORB-like sources. St. Lawrence and Nunivak basalt indicate somewhat more enriched OIB sources. The Navarin basanites have the highest $^{87}Sr/^{86}Sr$ and lowest $^{143}Nd/^{144}Nd$ values for any lavas so far reported from this region. The $^{207}Pb/^{204}Pb$ isotopic ratios are displaced toward that of continental detritus, suggesting contamination with deeply-subducted sediment or a mantle source metasomatized by subduction-related processes. Although some volcanic episodes appear to have occurred roughly synchronously at geographically widely separated centers, no large-scale regional extension or presence of large mantle plumes are indicated. Alkalic volcanism apparently resulted from upwelling and decompressional melting of small isolated mantle diapirs in response to localized lithospheric attenuation associated with jostling of blocks, adjusting to regional stresses.

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