BERINGIAN LATE CENOZOIC BASIC AND ULTRABASIC VOLCANISM

THE ORIGIN OF THE BERING SEA BASALT PROVINCE, WESTERN ALASKA

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ABSTRACT

The Bering Sea basalt province consists of at least 15 late Cenozoic (less than 6 Ma) volcanic fields that occur on islands in the Bering Sea and along the adjacent west coast of Alaska. Correlative rocks have also been dredged from the submerged continental margin of western Alaska beneath the Bering Sea. The fields are composed of widespread flows of tholeiitic and alkali olivine basalt and small cones, flows, and maar craters of more alkalic basalt, basanite, and rare nephelinite. The more alkalic rocks commonly contain inclusions of peridotite.

Although the volcanic fields do not lie along a hot-spot trace, the rocks are compositionally similar to ocean island basalts (OIBs). Total alkalis (Na_2O+K_2O) range from 3.8 to 8 wt.% and are negatively correlated with SiO_2 (44 to 52 wt.%). Trace-element data from volcanic fields on St. Lawrence, Nunivak, and St. Michael Islands and from the Imuruk Lake and Candle areas suggest that all of the rocks are enriched in light rare earth elements (LREEs) and that LREE contents increase with increasing alkalinity. Mg numbers (Mg/(Mg+Fe)) are usually between 50 and 72. Although the rocks show some evidence for fractionation, the dominant control on composition is by varying degrees of partial melting of a mantle source. Trace-element and isotopic data further constrain the mantle source. When normalized to chondritic abundances the rocks have anomalously high Nb and Ta contents relative to alkali and LREE elements, similar to other OIBs. New Pb-isotope data from St. Lawrence Island plot within the field for N-MORB(mid-ocean ridge basalts) on $^{207/204}$Pb/$^{206/204}$Pb diagrams and at higher $^{208/204}$Pb than the field for N-MORB on $^{208/204}$Pb/$^{206/204}$Pb diagrams. Trace-element ratios (Zr/Nb, Ba/La, K/Nb, Th/Nb) and Pb isotope data plot on mixing lines between a high $^{206/204}$Pb mantle source (HIMU) and the composition for pelagic or terrigenous sediments. The chemical and isotopic data indicate that the rocks formed in a depleted or HIMU mantle that was contaminated by varying amounts of previously subducted sediments.

INTRODUCTION

The Bering Sea basalts province consists of at least 15 late Cenozoic volcanic fields that occur in a broad region behind the active Aleutian arc (Fig. 1). The volcanic fields are exposed on islands in the Bering Sea, along the west coast of Alaska, and along the east coast of northeast Russia (Fig. 1) and have also been dredged from the extension of Shirshov Ridge (Bogdanov et al., 1987) and from the submerged continental margin of western Alaska (Davis et al., 1993). The fields occur between 250 and 1300 km behind the Aleutian arc. Most of the fields are younger than 6 million years old, but some K-Ar ages from Bering Sea basalts on the Seward Peninsula are as old as 29 Ma (Swanson et al., 1981). The Aleutian arc is considerably older, by some estimates as old as 55-50 Ma (Scholl et al., 1986).

This short report summarizes data on the Bering Sea basalts in Alaska including fields at Imuruk Lake on the Seward Peninsula, in the Candle area of the Yukon-Koyukuk basin, on St. Lawrence Island, at St. Michael, at Ingakslugwat, near the town of Bethel, on Nunivak Island, and on the Pribilof Islands (Fig. 2). Bering Sea basalt fields in Russia occur on the Chukchi Peninsula (Akinin and Apt, 1994), at Cape Navarin (Fedorov, et al., 1994), and on the offshore extension of Shirshov Ridge (Bogdanov, et al., 1987).

RESULTS

Most of the Bering Sea basalt fields consist of large volumes of tholeiitic and alkali olivine basalt flows and small volumes of basanite and rare nephelinite, but some of the fields are composed of only tholeiitic or alkalic rocks. In most of the volcanic fields the less alkalic tholeiitic and alkali olivine basalts comprise 97-98 percent of the rocks, whereas 2-3 percent of the rocks are more alkalic ba-sanite and nephelinite. The less alkalic rocks usually erupt as thin, broad pahoehoe flows that build broad shield volcanoes, whereas the highly alkalic basanite and nephelinite form steep-cones, short highly vesicular flows, and ash deposits from maar craters. Highly alkalic rocks generally were erupted early and late in the history of a volcanic field, and underlie and overlie voluminous sequences of less alkalic basalt.

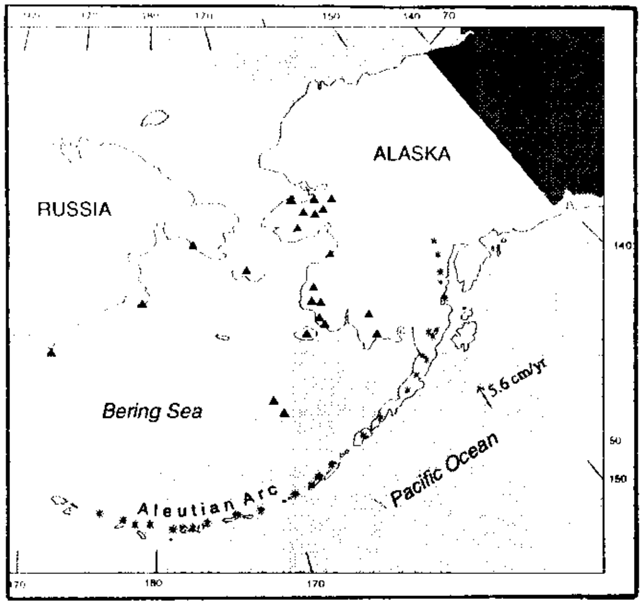

Fig. 1. Map showing the location of the Bering Sea basalt fields (triangles). The Bering Sea basalts occur in a broad region between 600 and 1200 km behind the active Aleutian arc (stars). The Pacific plate is being subducted northward beneath the Aleutian arc at about 5.6 cm/year.

The highly alkalic rocks contain megacrysts of anorthoclase, clinopyroxene, and kaersutite, and xenoliths of lherzolite, pyroxene granulite, dunite, harzburgite, chromite, gabbro, or bedrock. The less alkalic rocks do not contain megacrysts or xenocrysts. There is some evidence from a Sr isotope study of the Bering Sea basalts from Nunivak Island that the less alkalic rocks have slightly higher $^{87}Sr/^{86}Sr$ (0.70311) than the more alkalic rocks (0.70286) (Mark, 1971; Menzies and Murthy, 1980). The data indicate a complete continuum in Sr isotope composition and incompatible element contents from least alkalic to most alkalic.

Some of the volcanic fields have groups of highly alkalic cones that are aligned east-west defining a zone of weakness or fault.

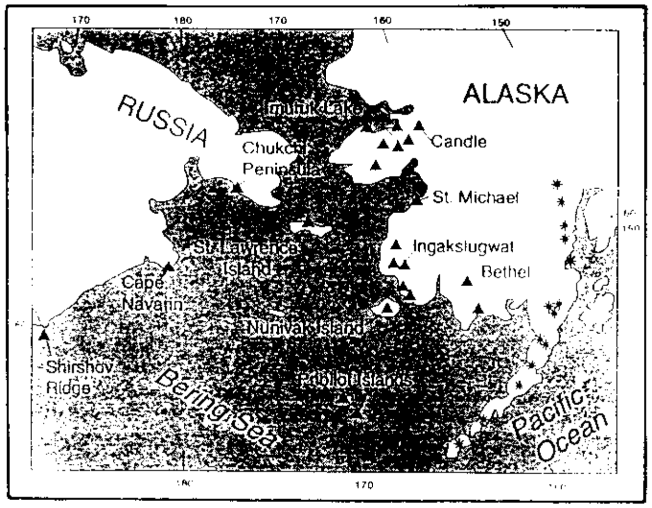

Fig. 2. Location of individual Bering Sea basalt fields discussed in this report. Bering Sea basalt fields are shown as triangles; Aleutian volcanoes are shown as stars.

The best example is the volcanic field on St. Lawrence Island, which consists of an large oval shield volcano of alkali olivine and tholeiitic basalt flows overlain by over 70 small cones and short flows of mostly basanite and nephelinite (Fig. 3). Others, such as the fields on the Pribilof Islands are cut by high angle east-west trending faults.

The Bering Sea basalts have compositions that are generally similar to Hawaiian basalts, but tend to be more alkalic. Total alkalis decrease with increasing SiO_2 (Fig. 4) similar to Hawaiian basalts. The rocks have high MgO contents (Fig. 5) with fairly high Mg numbers: Mg/(Mg+Fe)= 54-72 for St. Michaelvolcanic field, 61-67 for St. Lawrence Island, 57-66 for Imuruk Lake, and 49-68 for the Candle area, 55-59 for the Bethel area, and 57-83 for the Ingakslugwat volcanic field. Highly alkalic rocks contain deep-seated inclusions such as lherzolite, which indicate that the magmas rose quickly to the surface from mantle depths.

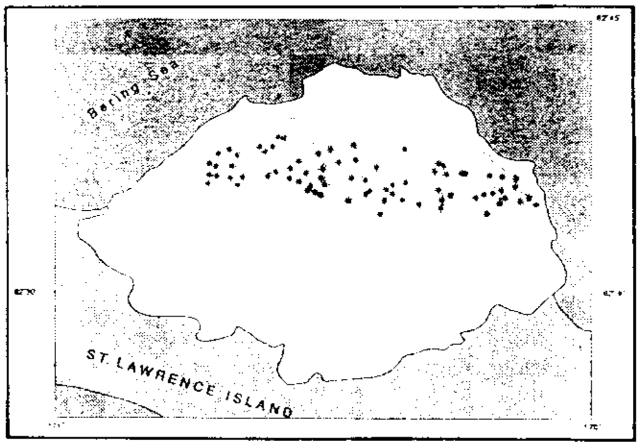

Fig. 3. Schematic map of the Kookooligit volcanic field on St. Lawrence Island in the Bering Sea, after Patton and Csejtey (1980). 500, 1000, and 1500 foot contour interval shown as faint oval lines of decreasing size within the volcanic field. The main part of the volcanic field is a large oval-shaped shield volcano built of tholeiitic and alkali-olivine basalt flows. Overlying the shield volcano are over 70 cones (shown as stars) and short flows of chiefly basanite and alkali basalt.

Table 1. Representative analyses of rocks from Bering Sea basalt volcanic fields

	St. Lawrence Island				Imuruk Lake area				Candle area				Bethel area	
Sample	66Hr156	66Hr122	66Hr132	66Hr193	90ML001	90ML006	90ML009B	90ML011	90ML017	90ML018	90GG004D	90GG008B	88SB059	87SB106
Major elements (weight percent)														
SiO2	47.70	47.70	45.40	47.80	43.6	46.40	52.4	49.6	49.7	45.3	40.1	46.1	51.90	49.40
Al2O3	14.40	15.50	14.70	14.80	13.6	16.10	15.1	14.1	15.3	13.3	11.8	14.1	15.20	14.10
Fe2O3	2.60	2.40	3.80	2.10	3.55	2.94	1.28	1.60	4.12	4.61	5.90	4.66	1.53	2.23
FeO	8.90	8.80	8.80	9.70	9.05	7.62	8.67	9.55	6.92	8.64	8.47	6.70	8.80	8.71
MgO	10.00	7.30	7.80	9.00	10.4	7.64	7.62	9.48	6.53	7.81	10.1	11.0	7.00	7.41
CaO	8.90	7.00	7.70	9.00	9.07	7.62	8.63	8.77	9.13	9.07	9.38	9.15	8.92	8.84
Na2O	3.01	5.03	4.81	3.24	3.42	4.13	3.15	3.01	3.41	4.51	4.40	3.07	3.28	3.80
K2O	0.81	2.73	2.33	1.02	1.52	2.73	0.72	0.89	1.48	1.78	2.38	1.67	0.63	1.40
TiO2	1.80	2.10	2.40	2.10	3.21	2.11	1.84	2.18	2.43	2.49	3.02	2.38	1.90	3.23
P2O5	0.36	0.93	1.10	0.41	0.69	0.64	0.22	0.30	0.43	1.31	1.27	0.48	0.28	0.63
MnO	0.20	0.19	0.21	0.19	0.17	0.19	0.14	0.17	0.15	0.21	0.22	0.17	0.15	0.16
H2O+	0.79	0.41	0.77	0.78	0.61	1.38	0.14	0.25	0.15	0.23	1.58	0.34	0.41	0.17
H2O-					0.41	0.40	0.03	0.11	0.07	0.28	0.78	0.35	0.16	0.08
CO2	0.00	0.00	0.00	0.00	< 0.01	0.02	< 0.01	0.04	0.03	0.02	< 0.01	0.02	<0.01	<0.01
SUM	99.47	100.09	99.82	100.14	99.30	99.92	99.94	100.05	99.85	99.56	99.40	100.19	100.16	100.16
Trace elements (ppm)														
Nb (XRF)	20	65	70	23	46	60	12	20	22	72	106	36	16	34
Rb (XRF)	12	58	53	18	16	26	14	12	26	26	28	12	16	20
Rb	14.3	61.6	57.7	18.4	16.4	19.9	15.1	17.0	23.0	16.3	17.7	9.7	8.1	14.3
Sr (XRF)	510	1000	1050	550	590	750	330	380	520	1100	1300	590	590	890
Sr					664	800	342	338	541	1280	1390	602	631	877
Ba (XRF)	270	760	780	320		215							132	345
Ba					199	209	187	196	261	216	252	112	130	267
Cs	0.149	0.586	0.524	0.127	0.125	0.434	0.145	0.258	0.272	0.175	0.266	0.171	0.192	0.181
Zr (XRF)	144	360	360	166	265	335	124	160	186	345	435	182	100	205
La	16.0	55.8	62.3	19.7	26.8	33.9	13.4	14.2	20.1	52.9	62.3	17.5	8.3	20.0
Ce	32.9	98.2	115.5	39.5	63.1	70.7	30.4	34.5	48.5	120.0	140.0	39.0	19.6	43.4
Nd	16.4	41.0	51.7	21.3	32.9	31.2	16.5	19.1	26.2	59.7	65.8	21.7	13.8	27.3
Sm	4.62	8.50	10.83	5.47	7.65	6.47	4.54	5.02	6.52	13.00	13.20	5.05	4.01	7.32
Eu	1.54	2.40	3.05	1.75	2.41	1.99	1.52	1.61	1.91	3.85	3.83	1.58	1.41	2.80
Gd					7.43	6.41	4.93	5.37	6.23	11.90	10.90	4.55	4.18	7.92
Tb	0.6	0.9	1.1	0.7	0.960	0.819	0.700	0.737	0.893	1.430	1.280	0.647	0.551	1.130
Ho					1.040	1.050			1.040	1.290		0.817	0.667	
Tm							0.276	0.297	0.370				0.225	
Yb	1.49	1.51	2.11	1.58	1.65	2.21	1.60	1.69	2.07	1.75	1.06	1.40	1.30	1.83
Lu	0.2	0.2	0.3	0.2	0.219	0.295	0.213	0.227	0.283	0.205	0.128	0.189	0.165	0.226
Y (XRF)	17	18	32	18	28	30	18	24	26	34	26	12	16	32
Hf	3.11	6.82	7.10	3.61	5.66	5.99	2.99	3.44	4.17	6.67	8.18	3.70	2.10	4.55
Ta	1.3	4.7	5.2	1.6	3.380	3.980	0.756	1.030	1.760	4.460	7.700	2.210	0.909	2.37
Th	1.5	6.9	6.2	1.9									0.766	2.110
U	0.2	1.5	1.8	0.4	0.986	1.620	0.547	0.579	0.749	1.780	2.340	0.951	0.36	0.602
Sc	21.3	13.9	15.2	21.3	20.1	19.0	18.7	19.3	21.1	15.8	10.5	23.6	19.1	17.1
Cr	332	192	198	274	277	123	245	258	168	180	283	367	178	170
Co	52.7	41.4	43.8	49.7	58.2	39.8	40.9	44.7	37.7	43.4	52.2	61.5	40.6	37.4
Ni					251.0	126.0	137.0	135.0	74.1	141.0	253.0	308.0	115.0	98.1
Zn	91.5	104.8	114.1	91.5	113.0	82.3	101.0	102.0	99.8	144.0	143.0	95.6	107.0	105.0
As	<0.50	1.60	<2.10	<0.80	0.796	1.640	0.000		1.280	1.150	0.547	0.517		
Sb	<0.13	0.12	0.13	0.13	0.195	0.119	0.067			0.062	0.088	0.077	0.030	

Trace elements by instrumental neutron activation unless otherwise noted by the acronym XRF for x-ray fluorescence.

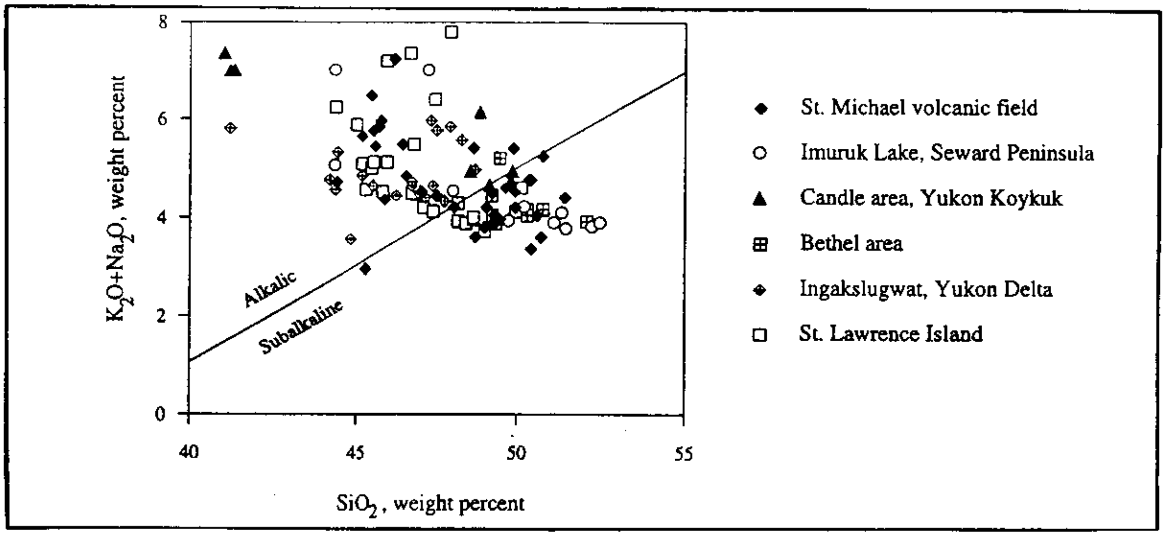

Fig. 4. Plot of total alkalis ($Na_2O + K_2O$) vs. SiO_2 for the Bering Sea basalts showing the decrease in total alkalis with increasing SiO_2. These trends are produced by varying degrees of partial melting. The line dividing alkalic from sub alkaline is divides rocks that are hypersthene normative from those that are nepheline normative. Data or St. Michael, St. Lawrence Island, and Ingakslugwat volcanic field from Hoare, J. M, unpublished data. Additional data for St. Michael volcanic field, for Imuruk Lake, Candle area, and Bethel area from Moll-Stalcup, unpublished data, 1988-1991.

All of the Bering Sea basalts are enriched in light rare earth elements (LREE) and the degree of LREE-enrichment increases with increasing alkalinity (Fig. 6). Most of the rocks show no correlation between alkalinity and HREE content which seems to be anchored at about 5-10 times chondritic abundances. Rocks from the Candle area in the Yukon-Koyukuk basin field are the most alkalic samples in the Alaskan part of the Bering Sea basalt province and, as expected, have the highest LREE contents. REE patterns for highly alkalic rocks from the Candle volcanic field cross REE abundance patterns for the less alkalic rocks at about Ho (Fig. 7), indicating the presence of considerable garnet in their source (Budahn and Schmitt, 1985).

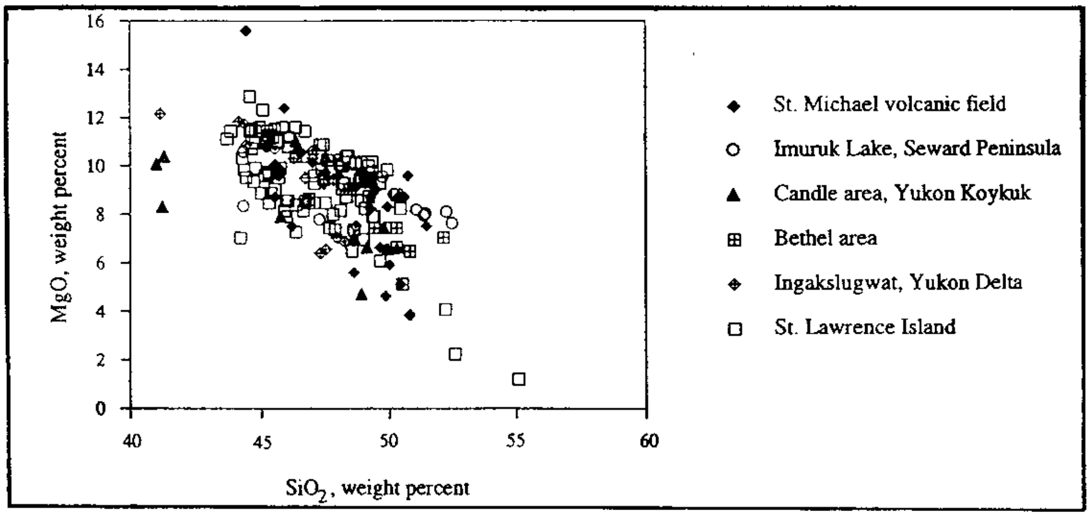

Fig. 5. Plot of MgO vs. SiO_2 for the Bering Sea basalts. Most of the rocks have high MgO contents that decrease with increasing SiO_2. Data sources the same as figure 4.

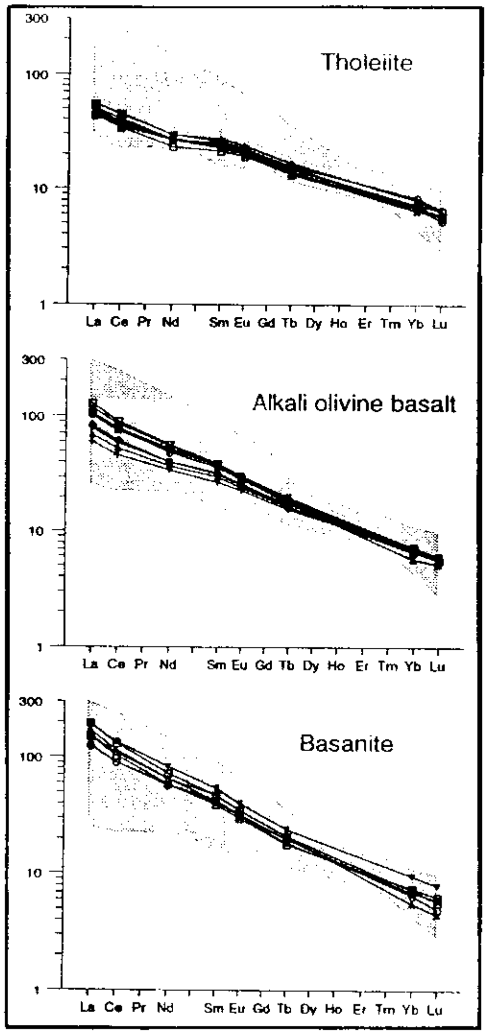

Fig. 6. REE plots for rocks from the Kookooligit volcanic field on St. Lawrence Island group by composition. The gray field represents the range of known compositions for Bering Sea basalts and contains REE data for St. Lawrence Island, St. Michael volcanic field, the Bethel area, the Candle area, and the Imuruk Lake area (Moll-Stalcup, unpublished data, 1981-1991). LREE contents increase with increasing alkalinity while the HREE contents remain approximately constant throughout this range.

Bering Sea basalts have anomalously high Nb and Ta contents relative to alkali and LREE elements (Fig. 8), similar to other ocean-island basalts and complementary to the patterns found in arc volcanic rocks. These positive Nb and Ta anomalies cannot be produced by crustal contamination because continental crust typically has negative Nb and Ta anomalies. The occurrence of a positive Nb and Ta anomaly in oceanic basalts led Weaver (1991) to conclude that the source of oceanic basalts may be the residual parts of the subducted slab left in the mantle after arc magmas are generated. In this model water-soluble elements are released from the slab, including subducted sediments, as they sink to increasingly higher temperatures and pressures (Ishikawa and Nakamura, 1994). The slab-derived fluid melts or metasomatizes the overlying mantle wedge. Nb and Ta are left behind in the slab during dehydration reactions because they are fixed in anhydrous minerals (probably rutile; Deer et al., 1966, p. 416-417). The Nb and Ta-rich residue is later incorporated into OIB-type magmas. The slab-residue will have the same Sr, Nd, and Pb isotopic composition as the slab-derived fluid, but not the same elemental composition.

Sr and Nd isotopic data also show a range of compositions from MORB-like values represented by the samples from the Pribilof Islands, Nunivak, and the Bethel area, to moderately evolved samples represented by the rocks from St. Lawrence Island, to rocks that plot near the field for Bulk Silicate Earth (Fig. 10).

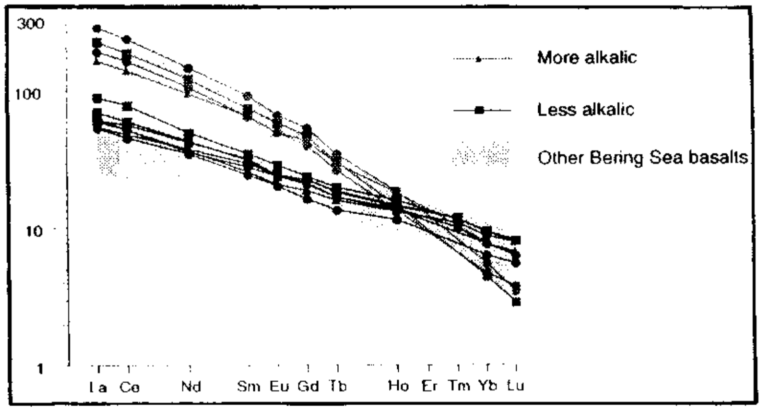

Fig. 7. REE data for rocks from the Candle area in the Yukon Koyukuk basin. These rocks are the most alkalic of all the rocks sampled in the Alaskan part of the province.

Samples that plot within the MORB field on Sr-Nd isotopic diagrams are the same samples that plot within the MORB field on Pb isotope diagrams. Although all of the rocks are LREE-enriched, their isotopic compositions indicate that all were derived from a source that was depleted in Rb/Sr and Sm/Nd relative to bulk earth for most of its history. Furthermore data from Nunivak show an inverse correlation between alkalinity and $^{87}Sr/^{86}Sr$ as well as Rb/Sr and $^{87}Sr/^{86}Sr$ (Mark, 1974), though the range of $^{87}Sr/^{86}Sr$ is small. Like the Pb isotope data, the Sr and Nd isotope data also fall within a triangular-shaped field defined by lines connecting the compositional fields for DM, HIMU, and Gough.

Most of the Pb isotope data for the Bering Sea basalts plot in the field for N-MORB on a plots of $^{207}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb/$ $^{206}Pb/^{204}Pb$ (Fig. 9), or above the field for N-MORB toward more enriched $^{208}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ compositions. Although there is some variation in Pb isotopic composition within a given volcanic field, most of the variation is from one field to another. Pb isotope data for the Pribilof Islands plot below the field for N-MORB on $^{207}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ diagrams (Fig. 9) and have the lowest $^{207}Pb/^{204}Pb$

relative to $^{206}Pb/^{204}Pb$ of any published data on ocean island basalts (Zindler and Hart, 1984). The more enriched samples plot above MORB and seem to define two trends that extend from the MORB field toward the field for enriched ocean-island basalts like Gough or toward pelagic sediment, along the same trend defined by the Aleutian data.

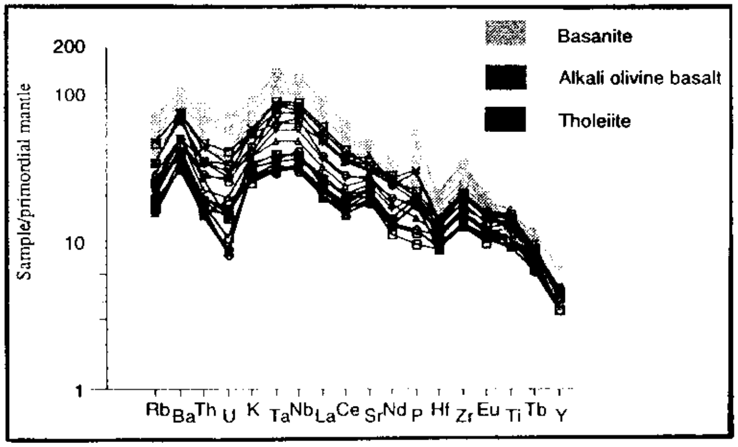

Fig. 8. Spiderplots for data from St. Lawrence Island normalized to the values for MORB given in Wood et al. (1981). The Bering Sea basalts have positive Nb-Ta anomalies relative to the LREE (La) or the alkali elements. Positive Nb and Ta anomalies like these are found only in oceanic island basalt suites and are opposite the negative anomalies found in arc magmas (Weaver, 1991).

Ba/La and Ba/Nb ratios for most of the Bering Sea basalts plot on mixing lines between ratios for N-MORB, HIMU and the composition for pelagic or terrigenous sediments or rocks from the Aleutian arc (Fig. 11). Most of the Bering Sea basalts have Ba/La and Ba/Nb ratios that are intermediate between those of the Aleutians and N-MORB.

DISCUSSION

Many oceanic island basalts suites, including Hawaiian basalts and Bering Sea basalts, show trends of decreasing total alkalis with increasing SiO_2. These trends are typically attributed to varying degrees of partial melting of a mantle peridotite, usually a primitive lherzolite (Clague and Frey, 1982). The most alkalic rocks are generated by small amounts of partial melting, the least alkalic rocks by larger amounts of partial melting. Although some of the Bering Sea basalts show evidence for olivine fractionation, most of the compositional variation appears to have originated by varying degrees of partial melting. This general model accounts for the high incompatible element contents of the most alkalic rocks as well as their relatively small volumes. The increase in LREE content with alkalinity suggests that the source was probably a garnet lherzolite. However, several lines of evidence suggest that the mantle source of the suite is not homogenous, nor is it primitive. The Nd isotopic data and REE data indicate that the source of the magmas is not primitive because it was depleted during a previous melting event and later metasomatized within the last 200 Ma (Menzies and Murthy, 1980). The Nd isotope data require a LREE depleted source, but the REE data cannot be modeled using a LREE-depleted source. Even models using a source with a flat REE abundance pattern require unrealistically large proportions of garnet (10-20 %) to fit the REE data (Fig. 12). Furthermore, the modeled source must have very high REE contents, between 7.5-10 chondritic abundances. If the source has less than 10% garnet it must be LREE-enriched. Alternatively the source of the more alkalic rocks may be more LREE-enriched than the source of the less alkalic rocks.

Limited Sr isotopic evidence suggests that the mantle under individual volcanic fields is not homogeneous and that the more alkalic lavas come from a source that has slightly lower $^{87}Sr/^{86}Sr$ than the source of the less alkalic rocks (Mark, 1974). At the same time this source produces rocks that have higher Rb/Sr ratios, as well as higher concentrations of incompatible elements than the less alkalic rocks. This disparity suggests that the most alkalic rocks originate from small amounts of partial melting of the most strongly metasomatized parts of the mantle. To preserve the low $^{87}Sr/^{86}Sr$ composition of the more alkalic rocks the source must have either lower Rb/Sr than the magmas or have high Rb/Sr from metasomatism that was too recent to produce significant radiogenic ^{87}Sr from decay of ^{87}Rb. Hydrous mantle xenoliths from Nunivak Island (Menzies and Murthy, 1980) contain pargasitic amphibole and mica that formed during mantle metasomatism, as well as kaersutite megacrysts that are thought to be parts of disrupted mantle veins (Francis, 1976). These amphiboles and micas have higher Rb/Sr than anhydrous co-existing minerals such as clinopyroxene (Menzies and Murthy, 1980). If these xenoliths represent fragments of the mantle that partially melted to produce the highly alkalic rocks, the hydrous minerals would be the first to melt. With small amounts of partial melting these early melts could have high Rb/Sr ratios and low $^{87}Sr/^{86}Sr$ if they come from mantle that was recently metasomatized, especially if the metasomatic fluid had N-MORB-like $^{87}Sr/^{86}Sr$ compositions.

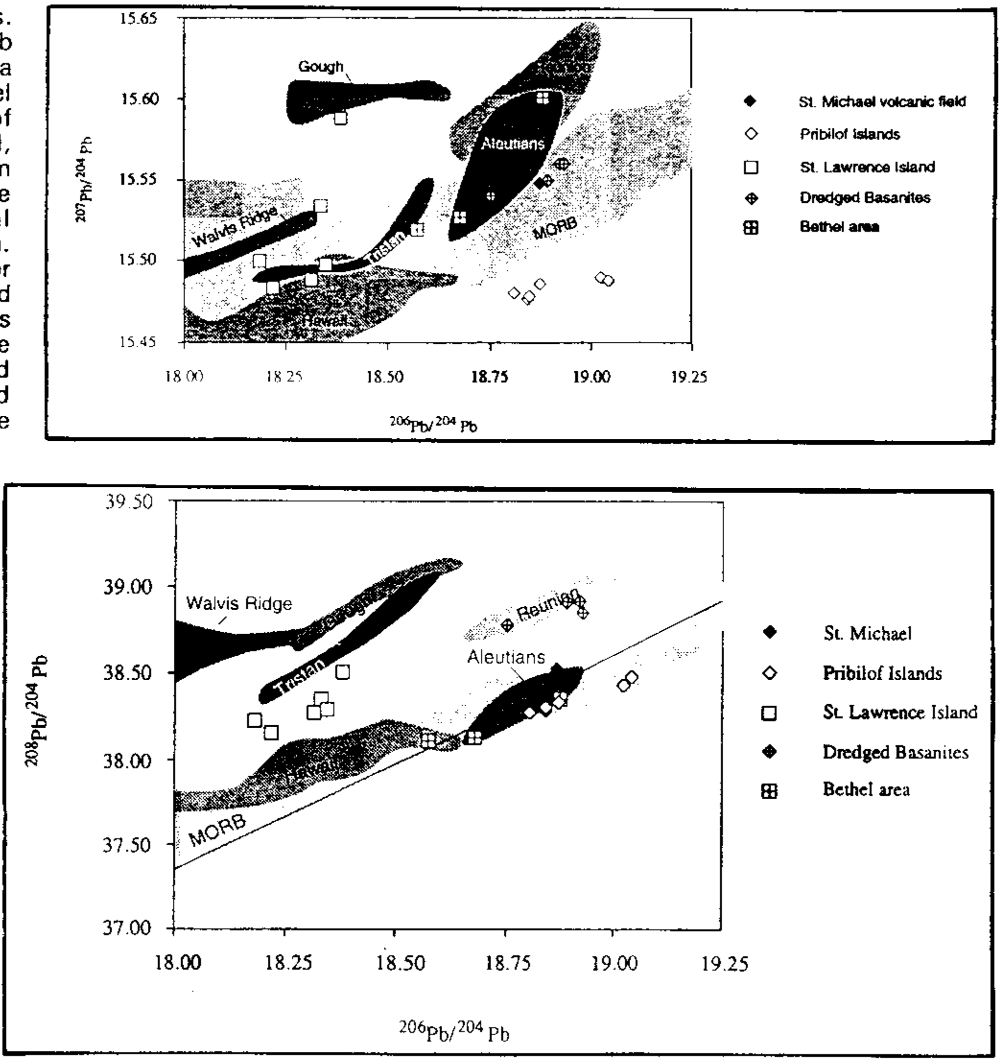

Fig. 9. *A* ^{207}Pb/^{204}Pb vs. ^{206}Pb/^{204}Pb and *B* ^{208}Pb/^{204}Pb vs. ^{206}Pb/^{204}Pb for Bering Sea basalts from St. Michael volcanic field, the Pribilof Islands, St. Lawrence Island, the Bethel area, and from basanites dredged from the submerged continental margin of western Alaska. Also shown are fields for MORB, the Aleutian arc, and selected oceanic islands (Gough, Reunion, Tristan de Cunha, Walvis Ridge, and Hawaii) from Zindler and Hart (1986). Data from the Pribilof Islands from Kay et al. (1978). Data from the dredged basanites from Davis et al. (1993). Data for the Aleutians from Kay et al. (1978) and Myer and Marsh (1987).

The Sr isotopic compositions and incompatible elemental contents within individual volcanic fields are completely gradational from most to least alkalic. Both highly alkalic and less alkalic rock types require at least some metasomatism to satisfy the Nd isotopic data. If the metasomatic fluid was related to previous periods of subduction in the Bering Sea region the fluid would be rich in Ba, Rb, Sr, Th, and, LREE derived from dehydration of the slab. The more strongly metasomatized parts of the mantle would be highly enriched in these elements. Subducted sediments comprise only a few percent of the elements that make up the slab-generated fluid that goes into arc magmas (Vidal et al., 1989). The rest of the subducted sediment may be carried deeper into the mantle. The Sr and Nd isotopic composition of the dehydration fluid from the slab is dominated by MORB compositions, because basaltic oceanic crust contributes much more Sr and Nd than the small amount of sediments. In contrast the Pb isotopes are dominated by the isotopic composition of the sediments because the mantle and oceanic crust contain very little Pb compared to subducted sediments.

The Pb isotope data require at least three, and possibly four, isotopically distinct components to explain the range of observed compositions because all of the Pb isotope data fall within a triangle defined by lines connecting the fields for HIMU, DMM A, and Gough or EMII (Fig. 13). Two of these components may be common to the source of MORB basalts, because many of the Bering Sea basalts have Pb isotopic compositions that plot within the field for MORB between the values for depleted mantle and HIMU (Fig. 13). Pb, Sr, and Nd isotopic differences between individual volcanic fields in the Bering Sea basalt province are greater than the differences within volcanic fields. In the Bering Sea basalt province the Pb isotopic compositions of individual volcanic fields appear to correlate with the age of the lithosphere under each field. Rocks from St. Lawrence Island, which is underlain by Paleozoic lithosphere (Till and Dumoulin, 1994), have lower ^{206}Pb/^{204}Pb than rocks from the other Bering Sea basalt fields, as well as moderate ^{143}Nd/^{144}Nd and ^{87}Sr/^{86}Sr. Rocks that plot at the high ^{143}Nd/^{144}Nd and low ^{87}Sr/^{86}Sr end of the spectrum such as the Pribilof Islands, Nunivak Island and the Bethel area have higher ^{206}Pb/^{204}Pb and are underlain by accreted Mesozoic oceanic crust. Variations in isotopic composition between individual volcanic fields reflect long-lived geographic variations in the age and composition of the underlying mantle lithosphere.

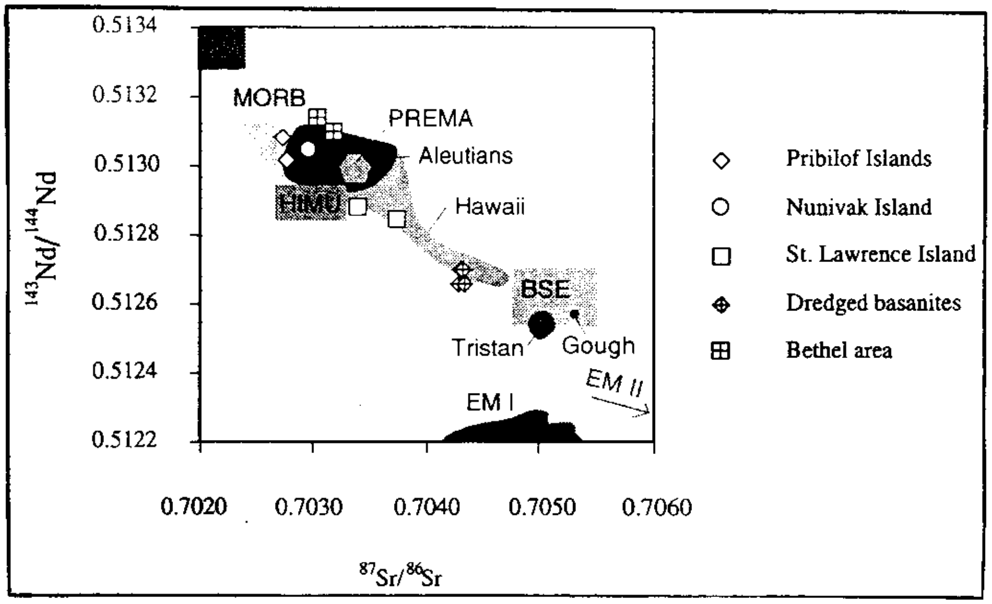

Fig. 10. $^{143}Nd/^{144}Nd$ vs. $^{87}Sr/^{86}Sr$ for Bering Sea basalts from the Pribilof Islands, Nunivak Island, St. Lawrence Island, the Bethel area, and basanites dredged from the submerged continental margin of western Alaska. Also shown are fields for MORB, DM (depleted mantle), PREMA (prevalent mantle), BSE (bulk silicate earth), EM I and EM II (enriched mantle one and two) and selected oceanic islands (Gough, Reunion, Tristan de Cunha, Walvis Ridge, and Hawaii) from Zindler and Hart (1986). Aleutian field drawn based on the data of McCulloch and Perfit, 1981, Morris and Hart (1986), and von Drach et al. (1986).

The third component has higher $^{207}Pb/^{204}Pb$ and is common to the source of arc volcanoes such as the Aleutians or enriched OIB-type magmas like Gough. This component probably represents mixing with small amounts of continental sediments that were deeply subducted during one or more previous subduction episodes in this region.

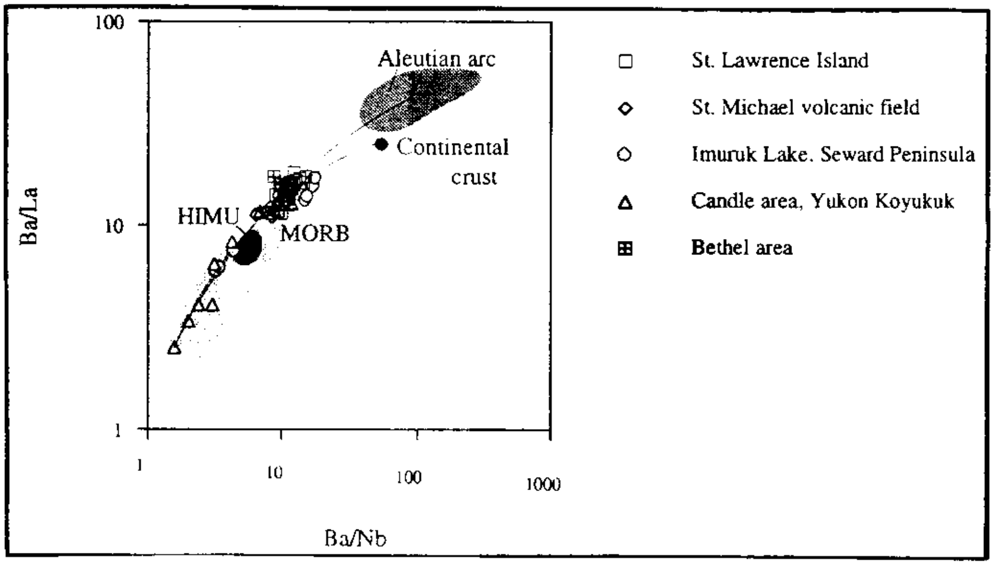

Fig. 11. Ba/La vs. Ba/Nb for samples from the Bering Sea basalt field. Also shown are fields for MORB, HIMU, the Aleutian arc, and continental crust. Fields for HIMU and continental crust from Weaver (1991); those for MORB from Basaltic Volcanism Study Project (1981) ocean-floor trace element suite, (Appendix A-5). Data for the Aleutian arc from DeLong et al. (1985) and Reid and Nye (1986).

SUMMARY AND CONCLUSIONS

The Nd isotopic data and REE data require that the source of both the alkalic and tholeiitic rocks be metasomatized at some time within the last 200 Ma (Menzies and Murthy, 1980) because both types of magmas have sources that were depleted in LREE for much of their history yet are now LREE-enriched. The source of the more alkalic lavas has lower $^{87}Sr/^{86}Sr$, higher LREE, Ba, Sr, and Rb than the source of the less alkalic lavas

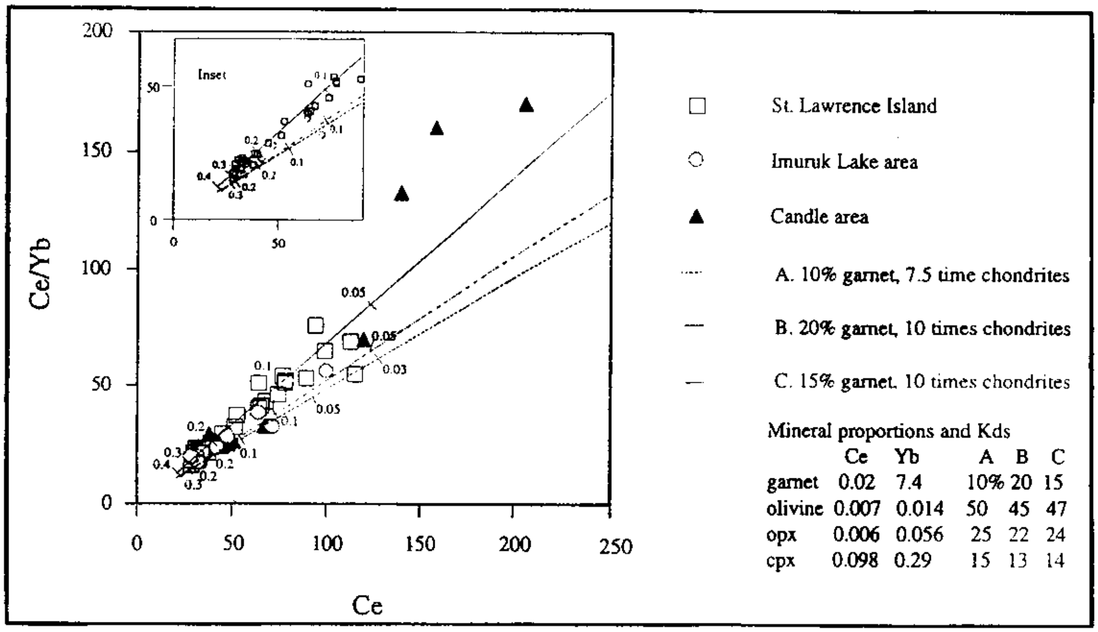

Fig. 12. Ce/Yb vs. Ce data for the Bering Sea basalt fields at St. Lawrence Island, the Imuruk Lake area, and the Candle area. Data from Moll-Stalcup, unpublished data (1991-1994). Also shown are the three most successful models for partial melting of a garnet lherzolite source. All of the models are for a source with a flat-REE abundance pattern that has REE concentrations that are 10 or 7.5 time chondritic abundances, as labeled. All of the models require at least 10 percent garnet to generate lines that have slopes similar to the data. Smaller amounts of garnet generate lines with lower slopes. If less garnet is in the source, then the source must be LREE-enriched or variably enriched. Dots of models mark degrees of F, as labeled. Calculations were made using the equation $C_l/C_o = 1/(D+(F(1-D))$ where C_l is the concentration in the liquid, C_o is the concentration in the source, D is the bulk distribution coefficient and F is the fraction of partial melting. Kds from Budann and Scmitt (1983)

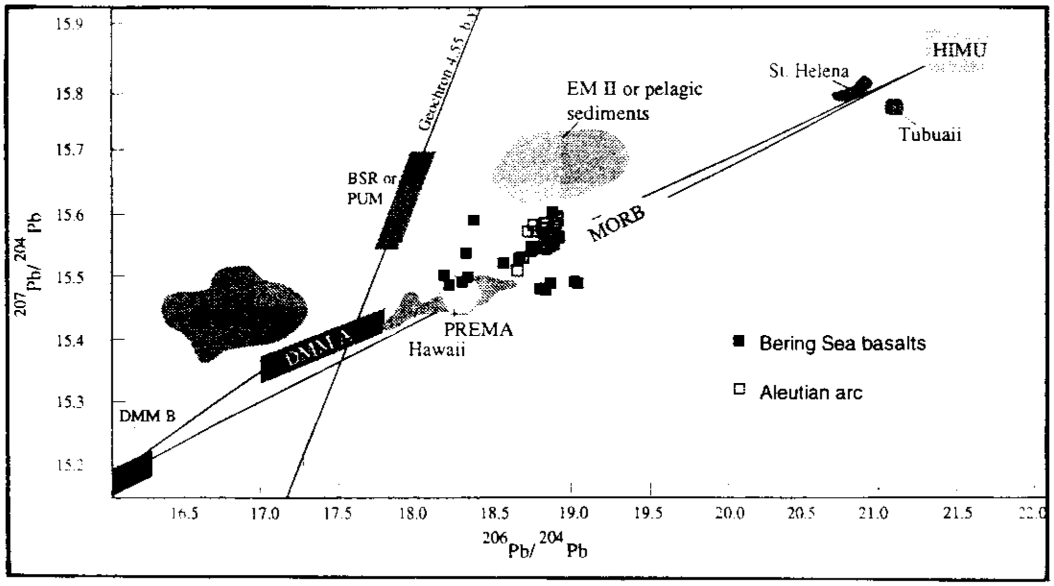

Fig. 13. ^{207}Pb/^{204}Pb vs. ^{206}Pb/^{204}Pb diagram showing data for the Bering Sea basalts, the Aleutian arc and fields from Zindler and Hart (1976). With the exception of the data from the Pribilof Island all the data for the Bering Sea basalts can be explained by three component mixing between DMM A, HIMU, and EM II or pelagic sediment. Data sources the same as figure 9.

because it was more strongly metasomatized by subduction-related fluids, possibly during several subduction episodes. Although the source of the most alkalic rocks produces magmas with higher Rb/Sr ratios, it has lower $^{87}Sr/^{86}Sr$ because most of it's Sr was derived from the previously subducted slab, both from metasomatic fluids and from the slab residue. In contrast, sediment contamination strongly affects the Pb isotopes because the mantle and oceanic crust contain very little Pb. Spidergrams for the Bering Sea basalts and adjacent Tertiary continental arc volcanic rocks give very similar patterns except for the pronounced positive and negative Nb and Ta anomalies. The Pb isotopic data and positive Nb and Ta anomalies indicate that at least some of the magmas have interacted with slab residues that have the Pb isotopic composition of pelagic sediments and high concentrations of Nb and Ta.

The isotopic and elemental data suggest that the mantle source of the Bering Sea basalts contains at least three isotopically distinct components. The three components are 1) weakly metasomatized garnet peridotite, 2) strongly metasomatized garnet peridotite, and 3) a slab residue having high HFSE contents and high $^{208}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ ratios. The strongly metasomatized mantle probably occurs as veins in the more weakly metasomatized mantle. The metasomatic fluid is similar to the slab component produced in subduction-zones and was probably produced during several subduction episodes within the last 200 Ma, including subduction in the Cretaceous, Early Tertiary, and the current Aleutian arc. The third component is probably isolated blebs of dismembered slab at the upper mantle-lower mantle boundary. Recent work (Lundgren and Giardini, 1994) on isolated deep earthquakes suggest that subducted slabs are deflected to a horizontal posture at the base of the upper mantle once they are past the well-defined Wadati-Benioff zone. The subducted lithosphere may extend for several hundred kilometers beyond the main Wadati Benioff zone (Lundgren and Giardini, 1994).

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Much of this study of the Bering Sea basalts builds on the earlier unpublished work of the late Joe Hoare. Joe mapped and collected samples from the volcanic fields at Nunivak Island, Ingakslugwat on the Yukon Delta, St. Lawrence Island, and St. Michael Island. I am still using his extensive collection of lavas, xenoliths, and megacrysts. I thank Rosalind Helz and Bruce Doe for helpful reviews.

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