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Recent volcanic rocks from Jan Mayen: Low-degree melt fractions of enriched northeast Atlantic mantle

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Abstract. Isotopic and trace element analyses of recent alkaline volcanic rocks from Jan Mayen were used to characterize their mantle source. The samples, ranging in composition from ankaramites to trachytes, are isotopically homogeneous with 11 of 12 samples within the following ranges: $^{87}Sr/^{86}Sr$ 0.7035–0.7036, $^{143}Nd/^{144}Nd$: 0.51285–0.51290, $^{206}Pb/^{204}Pb$: 18.54–18.76, $^{207}Pb/^{204}Pb$ 15.45–15.49, and $^{208}Pb/^{204}Pb$: 38.19–38.51. Geophysical data indicate that the Jan Mayen Ridge represents a microcontinent rifted off the east Greenland continental margin at 36 Ma. The isotopic homogeneity and poor correlation between the degree of magmatic differentiation and Sr-Nd isotopic composition show that the recent Jan Mayen magmas escaped significant contamination by Precambrian or Lower Paleozoic continental crust. A pervasive Tertiary to recent magmatic infrastructure may explain the lack of contamination with old crustal material. The Jan Mayen alkali basalts have similar trace element and isotopic composition to other oceanic plume basalts and are dominated by low-degree melts from an enriched mantle component prevalent in the NE Atlantic. The Icelandic alkali basalts are derived from similar sources but are more diluted with picritic or tholeiitic melt fractions formed by progressive melting at shallower levels. Minimum dilution of the incipient low-degree melts occurs when the melting column is truncated by a thick lithosphere. The mantle source sampled by the Jan Mayen and other alkaline volcanic systems in the NE Atlantic is strongly enriched in high field strength elements like Nb, has a relatively high μ value, and has $^{207}Pb/^{206}Pb$ ratios below and $^{208}Pb/^{206}Pb$ ratios above the Northern Hemisphere Reference Line. Such a Pb isotopic composition fits well with an old mantle domain with a time-integrated low μ value, enriched by a Paleozoic high μ (HIMU) component. The young HIMU-component in the NE Atlantic upper mantle could represent recycled oceanic crust entrained in the ancestral Iceland plume and distributed laterally by the ancestral plume head.

1. Introduction

The island of Jan Mayen represents the northern and most elevated part of the Jan Mayen Ridge. The SE trending Western Jan Mayen Fracture Zone contacts the northeastern end of the 54-km-long island (Figure 1). The volcanically active island consists of a potassic trachybasaltic suite of volcanics [*Imsland*, 1984; *Maaløe et al.*, 1986; *Thy et al.*, 1991], ranging from ankaramites via basalts and tristanites to trachytes. The last eruption from fissures on the northern slope of Beerenberg occurred in January 1985 [*Imsland*, 1986]. *Maaløe et al.* [1986] suggested that the entire magma series evolved mainly by low-pressure crystal fractionation. *Imsland* [1984] and *Thy et al.* [1991], however, concluded that the tristanites and trachytes were produced by crustal anatexis of hydrated basalts.

Dredging along the southern part of the Mohns Ridge and on seamounts and hills between Jan Mayen and Kolbeinsey Ridge shows that trachybasaltic volcanics are widespread in the vicinity of the Jan Mayen Fracture Zone [*Neumann and Schilling*, 1984; *Haase et al.*, 1996; *Thy et al.*, 1991, and references therein]. A geochemically enriched mantle source is indicated for the volcanism in the vicinity of Jan Mayen. *Haase et al.* [1996], *Neumann and Schilling* [1984], and *Waggoner et al.* [1981] found a strong increase in the concentration of incompatible elements combined with increasing $^{87}Sr/^{86}Sr$ and decreasing $^{143}Nd/^{144}Nd$ along the southern part of the Mohns Ridge toward Jan Mayen. This increase has been ascribed to a local mantle plume centered near Jan Mayen [e.g., *Neumann and Schilling*, 1984], although there is no geophysical evidence for this. The bathymetry, seismic velocitiy distribution, and earthquake epicenters in the Jan Mayen region do not support either a plume swell or significantly elevated upper mantle temperatures [*Havskov and Atakan*, 1991; *Zhang and Tanimoto*, 1993; *Haase et al.*, 1996]

The effect of the continental crust of the N–S trending Jan Mayen Ridge on the magma evolution has been uncertain. If the island of Jan Mayen is underlain by Precambrian or early Phanerozoic lower crust, the volcanic products may show tendencies toward elevated $^{87}Sr/^{86}Sr$ and lowered $^{143}Nd/^{144}Nd$. In particular, the evolved end-members of the volcanic suite, in the form of tristanites and trachytes, are likely to have interacted with the crust by fractional crystallization in combination with partial melting of wall rocks. The scarcity of isotope geochemical data for the Jan Mayen volcanics has made it difficult to exclude the possibility of a continental crustal contribution to the magmas, although all of the recent petrologic studies have favored a mantle source [*Imsland*, 1984; *Maaløe et al.*, 1986; *Thy et al.*, 1991, and references therein]. The present study contributes new Sr-Nd-Pb isotopic ratios and

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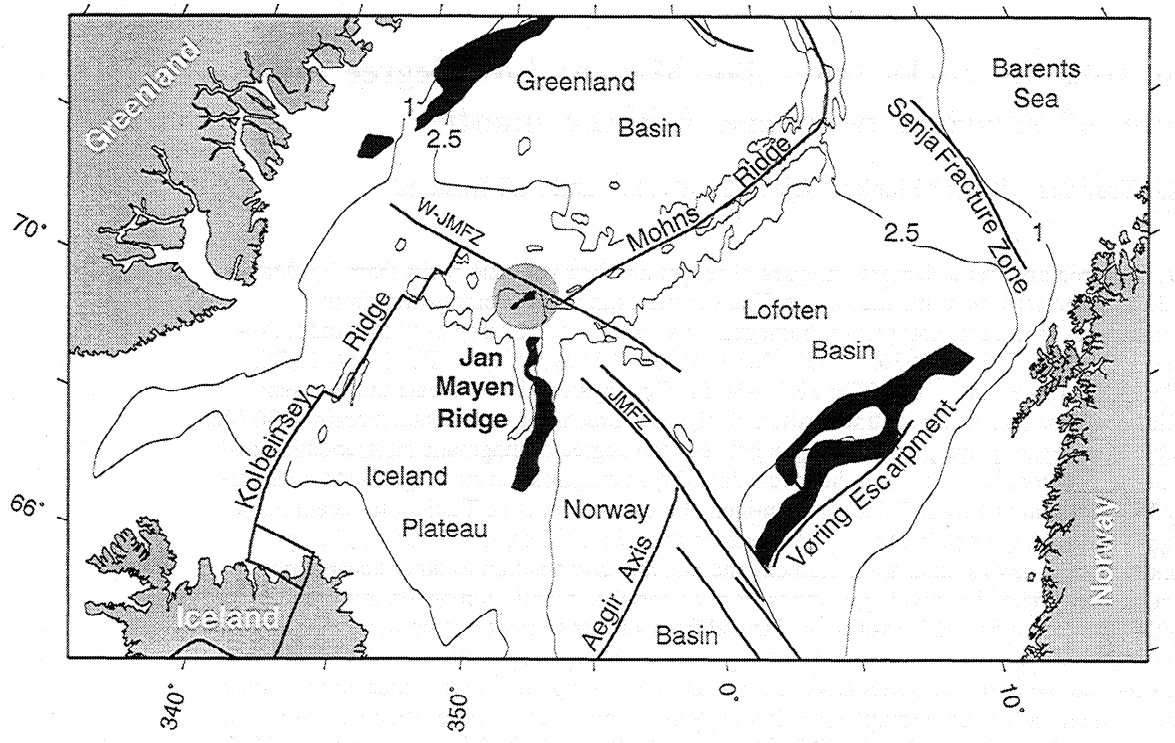


Figure 1. Tectonic elements of the Greenland and Norwegian Seas. Bathymetric contour lines for 1 km and 2.5 km depth are shown. Solid areas indicate volcanic margins. JMFZ, Jan Mayen Fracture Zone.

trace element concentrations of a selection of previously studied Jan Mayen-samples [*Imsland*, 1984] in an attempt to further constrain the origin of the magmas. The new isotopic and trace element data for Jan Mayen show insignificant crustal contributions to the magmas, and instead, they provide important insight into the spectrum of mantle sources in the NE Atlantic area.

2. Tectonomagmatic Setting of the Jan Mayen Ridge

The Jan Mayen Ridge is a 50–100-km-wide and 400-km-long bathymetric ridge complex extending southward from the island of Jan Mayen (Figure 1). The ridge is divided into three main structural elements. The northern segment encompass the area north of the westward projection of the Jan Mayen Fracture Zone (from 70°15'N), and is characterized by a wide, typically less than 200-m-deep platform, including the Jan Mayen island. The central N-S trending segment is more narrow and typically 1000 m deep. It continues southward to the prominent change in ridge trend from N-S to NE-SW south of 69°N. The southern segment is fragmented into several 1500-m-deep bathymetric highs.

Regional studies have generally concluded that the Jan Mayen Ridge is a microcontinent rifted off Greenland after continental breakup between Eurasia and Greenland near the Paleocene/Eocene transition [*Talwani and Eldholm*, 1977; *Bott*, 1985; *Skogseid and Eldholm*, 1987; *Larsen*, 1988]. At Chron 20 time (45 Ma) a northward propagating rift or spreading axis was initiated west of the Jan Mayen Ridge, with simultaneous fan-shaped spreading on the Aegir Axis and an axis west of the Jan Mayen Ridge. The two spreading axes remained active until the time of anomaly 7 (26 Ma), when the Aegir Axis became extinct and spreading became restricted to the Kolbeinsey Ridge.

The plate tectonic reconstruction of Greenland and Eurasia at Chron 22 time (about 53 Ma) shows that the central and southern Jan Mayen Ridge segments are conjugate to the Møre Margin (Figure 2). On the other hand, the northern Jan Mayen Ridge segment is conjugate to the southern Vøring Margin. A smooth transition in the trend of bathymetric contours from NE-SW to NW-SE takes place on the part of the Vøring Margin which is conjugate to the northern Jan Mayen Ridge segment (Figures 1 and 2). This part of the Vøring Margin is located in a shear rift corner setting, where the Vøring and Møre Margins are offset by about 100 km along the Jan Mayen Fracture Zone. No significant offset is seen between the conjugate central and northern Jan Mayen Ridge segments, although the bathymetrically defined ridge is much wider in the northern segment than in the two segments farther south (Figure 1).

Extensive seismic reflection data across the Jan Mayen Ridge reveal a distinctly different western and eastern margin [*Gudlaugsson et al.*, 1988; *Åkermoen*, 1989]. The eastern margin is flexured and shows well-developed intrabasement sequences of seaward dipping reflectors. In contrast, the western margin is characterized by brittle block faulting, being related to the separation of the Jan Mayen Ridge and Greenland. Furthermore, wide-angle seismic data reveal a structure of the central ridge segment that is similar to those in continental areas [*Johansen et al.*, 1988; *Kodaira et al.*, 1998]. The crustal structure of the northern ridge segment is poorly constrained, though, because abundant volcanic rocks inhibit imaging of the crustal structure.

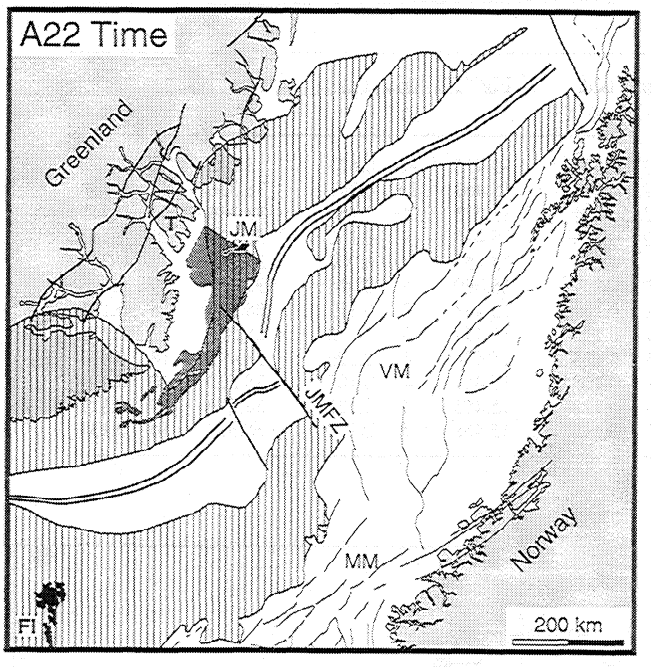


Figure 2. Plate tectonic reconstruction at anomaly 22 time (53 Ma). Dark shaded area shows the outline of the Jan Mayen Ridge, and the vertically hatched areas are volcanic breakup complexes. T, Traill Ø; JM, Jan Mayen; JMFZ, Jan Mayen Fracture Zone; VM, Vøring Margin; MM, Møre Margin; FI, Færøy Islands.

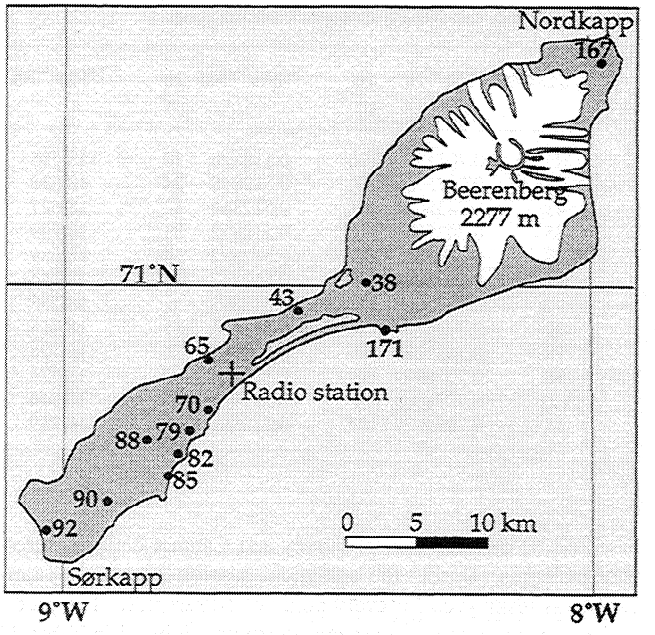


Figure 3. Sample locations on Jan Mayen. The samples are described by *Imsland* [1984] and comprise ankaramites (167 and 65), ankaramitic basalt (43), basalt (85), basaltic tristanite (70), tristanite (82), and trachytes (92, 90, 79, 38, 171, and 88).

Several phases of volcanism are interpreted in the Jan Mayen Ridge region [*Gudlaugsson et al.*, 1988; *Åkermoen*, 1989]. The seaward dipping reflector sequences along the eastern margin are likely breakup-related, subaerially emplaced flood basalts by analogy with the flood basalts found on the conjugate, mid-Norwegian margin. A very strong, flat reflector west of the ridge is further interpreted as related to voluminous volcanics erupted during earliest Miocene. Volcanism is an ongoing process on the island of Jan Mayen and along the western Jan Mayen Fracture Zone.

As suggested by *Haase et al.* [1996], the the Jan Mayen volcanism may be a result of the coincidence of a continental fragment, the fracture zone, and the nearby spreading axis. Ascent of magmas to the surface may be promoted by weakened lithosphere at the northern edge of the Jan Mayen Ridge [*Skogseid and Eldholm*, 1987].

3. Samples and Analytical Procedures

In this study we used a selection of the samples previously analyzed by *Imsland* [1984]. Sample locations and major element compositions are given in Figure 3 and Table 1, respectively. A summary of the petrography of the samples can be obtained from the authors. In order to investigate the possibility of minor crustal contribution, especially in the most evolved rock types, six of the 12 selected samples were trachytes.

The trace elements were analyzed by inductively coupled plasma mass spectrometry (fusion-ICP-MS) at Activation Laboratories Ltd., Ancaster, Ontario, Canada. Calibration was

Table 1. Major Element Composition

Sample	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	H_2O^+	H_2O^-
167	47.5	1.64	8.29	2.37	6.58	0.15	16.5	14.0	1.37	1.03	0.28	0.13	0.08
65	46.0	2.35	12.5	6.65	4.46	0.16	10.6	12.2	2.37	1.30	0.32	0.30	0.14
43	47.1	2.80	14.2	2.39	8.67	0.19	8.43	11.5	2.64	1.63	0.59	0.20	0.11
85	47.4	2.86	16.8	3.48	7.13	0.18	5.50	9.74	3.35	2.41	0.75	0.22	0.17
70	51.8	2.43	17.3	3.73	6.04	0.22	3.26	7.26	4.24	2.88	1.04	0.23	0.15
82	57.0	1.32	18.3	2.13	4.20	0.23	1.63	4.82	5.10	3.95	0.54	0.09	0.10
92	61.9	0.86	17.7	3.80	0.69	0.26	0.86	2.55	5.84	4.83	0.32	0.14	0.02
90	62.5	0.78	17.1	2.21	2.11	0.22	0.86	2.39	5.96	4.61	0.31	0.16	0.08
79	63.3	0.70	17.1	1.55	3.15	0.22	0.76	2.57	5.70	4.91	0.26	0.23	0.11
38	63.1	0.66	17.58	2.43	0.74	0.16	0.48	1.38	6.08	7.17	0.18	0.05	0.08
171	64.0	0.68	17.5	2.05	0.99	0.19	0.32	0.96	5.26	6.24	0.12	0.41	0.16
88	65.9	0.36	16.0	3.36	0.24	0.19	0.28	1.46	5.82	5.83	0.12	0.03	0.10

From *Imsland* [1984].

Table 2. Sr-Nd-Pb Isotopic Composition

Sample	$^{87}Sr/^{86}Sr$	2σ 10^{7}	$^{143}Nd/^{144}Nd$	2σ 10^{6}	$^{206}Pb/^{204}Pb$	2σ 10^{3}	1s.d. %	$^{207}Pb/^{204}Pb$	2σ 10^{3}	1s.d.	$^{208}Pb/^{204}Pb$	2σ 10^{3}	1s.d. %
167	0.7034895	126	0.512896	10	18.535	53	0.673	15.455	46	0.673	38.190	121	0.672
65	0.7035180	97	0.512848	24	18.635	19	0.340	15.463	15	0.341	38.336	38	0.339
43	0.7035034	101	0.512861	12	18.627	23	0.444	15.473	20	0.450	38.333	49	0.445
85	0.7035354	110	0.512852	31	18.709	10	0.164	15.475	8	0.162	38.473	20	0.157
70	0.7035051	92	0.512872	14	18.689	5	0.198	15.450	8	0.202	38.369	20	0.206
82	0.7035274	134	0.512867	8	18.714	5	0.097	15.460	4	0.094	38.391	10	0.095
92	0.7035069	117	0.512893	6	18.753	9	0.171	15.488	7	0.173	38.513	18	0.172
90	0.7034904	125	0.512855	11	18.711	6	0.113	15.450	5	0.113	38.373	12	0.118
79	0.7035028	97	0.512903	7	18.728	6	0.123	15.484	5	0.126	38.495	14	0.134
38	0.7036004	98	0.512884	6	18.771	5	0.103	15.487	4	0.101	38.507	10	0.099
171	0.7038005	91	0.512918	45	18.844	6	0.122	15.483	5	0.125	38.549	13	0.127
88	0.7034777	107	0.512867	7	18.759	7	0.140	15.458	5	0.134	38.384	14	0.137

based on 10 U.S. Geological Survey and Canmet certified reference materials. During the analytical session one of the standards was reanalyzed for every group of 10 samples. The precision and accuracy for the various elements are listed in Table 3.

The isotopic compositions of Sr, Nd, and Pb were determined by standard chemical separation and mass spectrometry procedures at the Mineralogical-Geological Museum, University of Oslo. Prior to chemical dissolution and separation, the powdered samples were subjected to leaching in cold 0.3 M HCl for 2 hours followed by overnight leaching in 6 M HCl at 80°C. During the analysis period the following results were obtained for international standards: NBS 987, $^{87}Sr/^{86}Sr$ = 0.71021 ±2 (2s error at decimal place), Johnson Matthey, $^{143}Nd/^{144}Nd$ = 0.511112 ±5 and NBS 981, $^{206}Pb/^{204}Pb$ = 16.907 ± 0.03%, $^{207}Pb/^{204}Pb$ = 15.455 ± 0.03%, and $^{208}Pb/^{204}Pb$ = 36.578 ± 0.03%.

4. Results

4.1. Sr-Nd Isotopic Composition

The Sr-Nd isotopic composition of the Jan Mayen samples (Table 2) is mostly restricted to the narrow ranges 0.70348–0.70354 and 0.51285–0.51290, respectively (Figure 4). Two of the trachytic samples with elevated radiogenic Sr fall outside this range. There is no correlation between the Sr-Nd isotopic composition and the major element chemistry of the volcanics.

In the Sr-Nd compositional space the Jan Mayen samples overlap with the C component of *Hanan and Graham* [1996]. This component, which is defined on the basis the three Pb isotopic systems, is common to all subpopulations of mid-ocean ridge basalt (MORB) (Figure 5). The Sr-Nd ratios of the Jan Mayen volcanics fall just outside the range of Icelandic volcanics, at the low $^{143}Nd/^{144}Nd$ and high $^{87}Sr/^{86}Sr$ ends of the Icelandic range. The alkaline off-rift volcanics define the lower right-hand part of the Icelandic range, and the volcanics from the Snæfellsnes zone of western Iceland is most similar to the Jan Mayen volcanics in terms of the Sr-Nd isotopic ratios (Figure 5).

The Sr-Nd isotopic compositions of the Jan Mayen rocks overlap with those of some of the Indian Ocean MORB, whereas Atlantic and especially Pacific MORB have higher Nd ratios and lower Sr ratios [*Hofmann*, 1997]. Along the southernmost part of the Mohns Ridge the alkaline basalts are comparable to the Jan Mayen rocks in terms of Sr-Nd-Pb isotope compositions as well as incompatible trace element concentra-

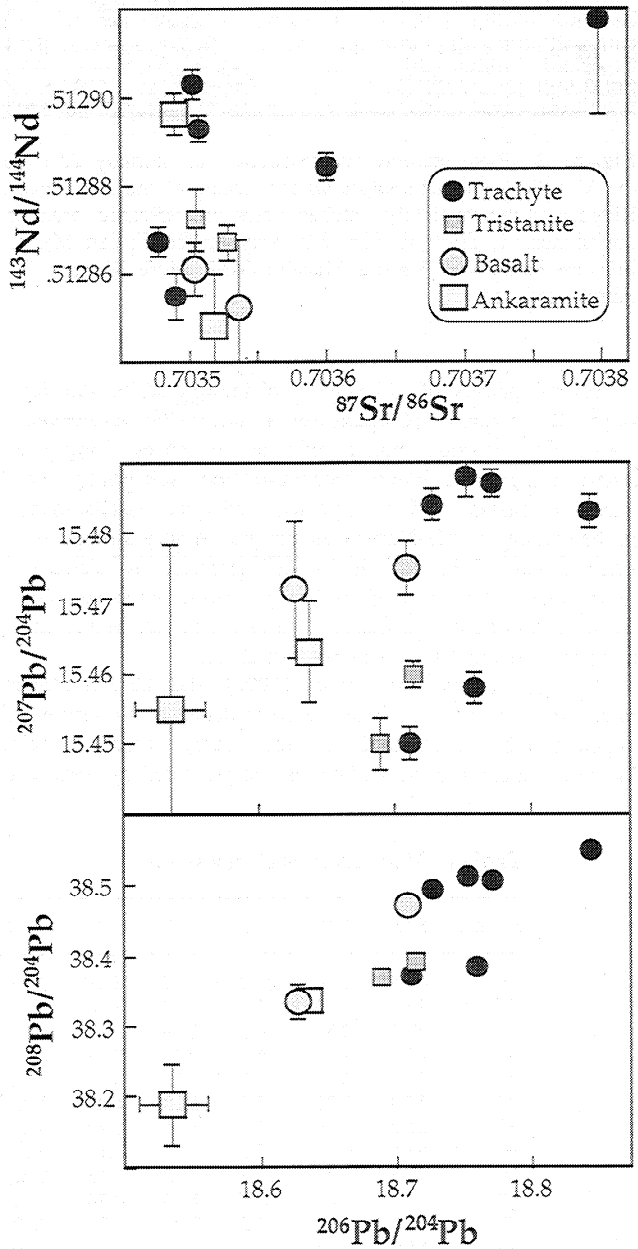


Figure 4. Isotopic composition of the Jan Mayen samples. The 2σ error bars are smaller than the symbols, except where indicated.

tions [*Mertz and Haase*, 1997; *Haase et al.*, 1996; *Neumann and Schilling*, 1984; *Waggoner et al.*, 1981]. The Jan Mayen rocks are located in the upper left-hand portion of the oceanic island array in the $^{143}Nd/^{144}Nd$ versus $^{87}Sr/^{86}Sr$ diagram (Figure 5). The Vesteris seamount in the Greenland basin has an isotopic composition that partly overlaps with the Jan Mayen [*Haase and Devey*, 1994], whereas the 56 Ma Vestbrona formation nephelinites off the Møre coast of Norway have more radiogenic Sr and less radiogenic Nd [*Prestvik et al.*, 1999].

4.2. Pb-Isotopic Composition

The Pb isotopic composition of the Jan Mayen volcanics is also restricted ($^{206}Pb/^{204}Pb$ = 18.54–18.84, $^{207}Pb/^{204}Pb$ = 15.45–15.49, and $^{208}Pb/^{204}Pb$ = 38.19–38.55), with the ankaramites the least radiogenic and the trachytes the most radiogenic (Figure 4). This compositional range is within the range of Icelandic volcanics and generally less radiogenic than most oceanic island volcanics (Figure 5). The Jan Mayen rocks have much less radiogenic Pb than extreme high-m (HIMU) basalts, as well as the C component of *Hanan and Graham* [1996]. A unique feature of volcanic products of the NE Atlantic mantle is that they have lower $^{207}Pb/^{206}Pb$ ratios than most other mantle-derived rocks [*Thirlwall et al.*, 1994]. The volcanics from Jan Mayen and Iceland share this compositional feature with the Reykjanes, Kolbeinsey, and Mohns Ridge segments and the Vestbrona and Vesteris volcanics. As shown in Figure 5, the NE Atlantic rocks fall below the Northern Hemisphere Reference Line, and the Jan Mayen volcanics have $\Delta 7/4$ of –4 to –7 and $\Delta 8/4$ of 14 to 23 (terminology of *Hart* [1984]). The confinement of the Icelandic alkaline off-rift volcanics and the Jan Mayen rocks to one end of the Icelandic compositional range observed in the Sr-Nd system is not present in the Pb systems. Rather, the Jan Mayen and Icelandic alkaline fields occupy a central part of the Icelandic Pb isotopic spectrum.

4.3. Trace Element Composition

The basaltic rocks are characterized by chondrite-normalized La/Lu ratios (La/Lu_N) of 15–19, whereas the tristanites and trachytes have slightly higher ratios of 21–26 (Table 3 and Figure 6). Such high ratios of light to heavy rare earth elements (LREE/HREE) for the basalts indicate that a major proportion of the melting took place within the stability field of garnet peridotite. The relative depletion of the intermediate REE in the trachytes is compatible with clinopyroxene fractionation from parental basaltic melts or with partial remelting of mafic intrusives with clinopyroxene as a residual phase. The spider diagram normalized to primitive mantle (Figure 7) shows that the Jan Mayen basalts overlap with the ocean-island basaltic average composition [*Sun and McDonough*, 1989]. The mantle-normalized trace elements patterns of the evolved Jan Mayen volcanics are excluded from the diagram for clarity. They are generally parallel to the basaltic patterns at higher concentration levels. An important feature of the Jan Mayen volcanics is the high concentrations of Nb and Ta relative to average ocean island basalts. In addition, the Jan Mayen rocks are characterized by high Rb and Ba, low Rb/Ba ratio, and negative K and P anomalies. The negative Pb anomaly of many ocean island basalt appears less pronounced in the Jan Mayen basalts, although the quality of Pb analytical data (see Table 3) does not allow firm conclusions. Both Icelandic and Jan Mayen basalts have μ values ($^{238}U/^{204}Pb$) in the general range of 10–25.

5. Discussion

5.1. Regional Isotopic Variation in the NE Atlantic

A review of the lateral variation of radiogenic isotope ratios within the sublithospheric upper mantle in the vicinity of Jan Mayen is useful for the evaluation of the possibility of anatectic contributions from continental crust and lihosphere. Figure 8 shows the acquired isotopic data from Jan Mayen in the context of along-axis isotopic variation. There is a good coverage of Sr-Nd-Pb isotopic data along the spreading centers from about 60°N to the Jan Mayen Fracture Zone (the Reykjanes Ridge, Iceland, and the Kolbeinsey Ridge) but a scarcity of published isotope geochemical data of the volcanic rocks from the Mohns-Knipovich Ridge. However, *Neumann and Schilling* [1984] report abundant major and trace element data, and *Waggoner et al.* [1981] give the range of the Sr-Nd isotopic values along the Mohns Ridge. *Haase et al.* [1996] and *Mertz and Haase* [1997] have published additional trace element and Sr-Nd-Pb isotopic data from the southern part of the Mohns Ridge and the area near Jan Mayen. The Sr-Nd isotopic ratios of the Knipovich Ridge basalts (north of the area of Figure 8) appear to overlap with the Kolbeinsey Ridge values. Along the southernmost part of the Mohns Ridge, however, all of the isotopic ratios change dramatically toward the values recorded for the Jan Mayen volcanics (Figure 8). This trend is also observed with respect to the trace elements [*Waggoner et al.*, 1981; *Neumann and Schilling*, 1984; *Haase et al.*, 1996].

In terms of the combined variation in the different isotopic systems, the Kolbeinsey Ridge basalts are more different from the Jan Mayen volcanics than either the Icelandic or the Mohns Ridge basalts (Figures 5 and 8). The Kolbeinsey Ridge basalts overlap with the portion of the Icelandic isotopic range that is farthest away from the Jan Mayen compositional range. In particular, the basalts from the southernmost part of the Kolbeinsey ridge overlaps isotopically with the primitive picritic rocks of the nearby Theistareykir volcanic system of northern Iceland [*Elliot et al.*, 1991; *Thirlwall*, 1995; *Mertz and Haase*, 1997].

In contrast to the isotopic variation along the Kolbeinsey Ridge axis, the isotopic compositional range of the northernmost Reykjanes Ridge basalts extends into the central portions of the Icelandic isotopic space. This led *Mertz et al.* [1991] to suggest that the plume-asthenosphere interaction that is evident along the Reykjanes Ridge south of Iceland [e.g., *Schilling*, 1973; *Schilling et al.*, 1983] is less developed or absent north of Iceland.

5.2. Lack of Continental Crustal Contamination

The mid-Tertiary separation of the Jan Mayen Ridge from the east Greenland margin, points to a lower crustal infrastructure of the ridge of Precambrian and Early Phanerozoic ages. Even minor amounts of contamination with such a crust should be readily detectable in terms of isotopic and trace element variations.

The volcanic products recovered from the seafloor in the close vicinity of Jan Mayen (e.g., at the Jan Mayen platform to the north of the fracture zone) and along the southern part of

Table 3. Trace Element Analyses by ICP-MS.

	V	Cr	Co	Ni	Cu	Zn	Ga	Ge	Rb	Sr	Y	Zr	Nb	Mo	Sn	Sb	Cs	Ba
167	283	1565	65	365	75	76	13	1.9	28	343	15	108	43	1	2	0.2	<0.5	440
65	288	798	56	161	44	76	18	1.7	25	644	24	178	55	1.3	<1	0.2	<0.5	541
43	283	366	44	84	61	72	19	1.7	34	768	25	200	66	1.3	2	0.2	<0.5	657
85	257	164	36	47	32	82	20	1.6	50	961	29	269	95	2	1	0.2	0.5	1046
70	140	28	18	<10	21	102	22	1.7	64	1028	38	357	124	1.4	2	0.3	<0.5	1139
82	39	<10	11	10	21	95	21	1.5	87	893	33	459	147	1.8	30	0.3	<0.5	1360
92	13	20	5	96	21	100	19	1.7	97	775	29	537	138	3.7	<1	0.3	0.7	2052
90	24	<10	5.8	<10	20	107	21	1.8	88	741	30	567	154	4	6	0.3	0.6	2059
M_{av}	521	443	86	185	123	176	19	1.5	8	269	13	98	20	1.2	3.3	0.8	0.8	49
s.d.	31	18	4	20	20	22	0.9	0.5	0.8	11	0.7	12	2	0.6	0.6	0.3	0.3	8
M_{ac}	526	430	87	193	134	191	17	1.0	8.5	266	14	108	20	0.9	3.6	0.9	0.6	61

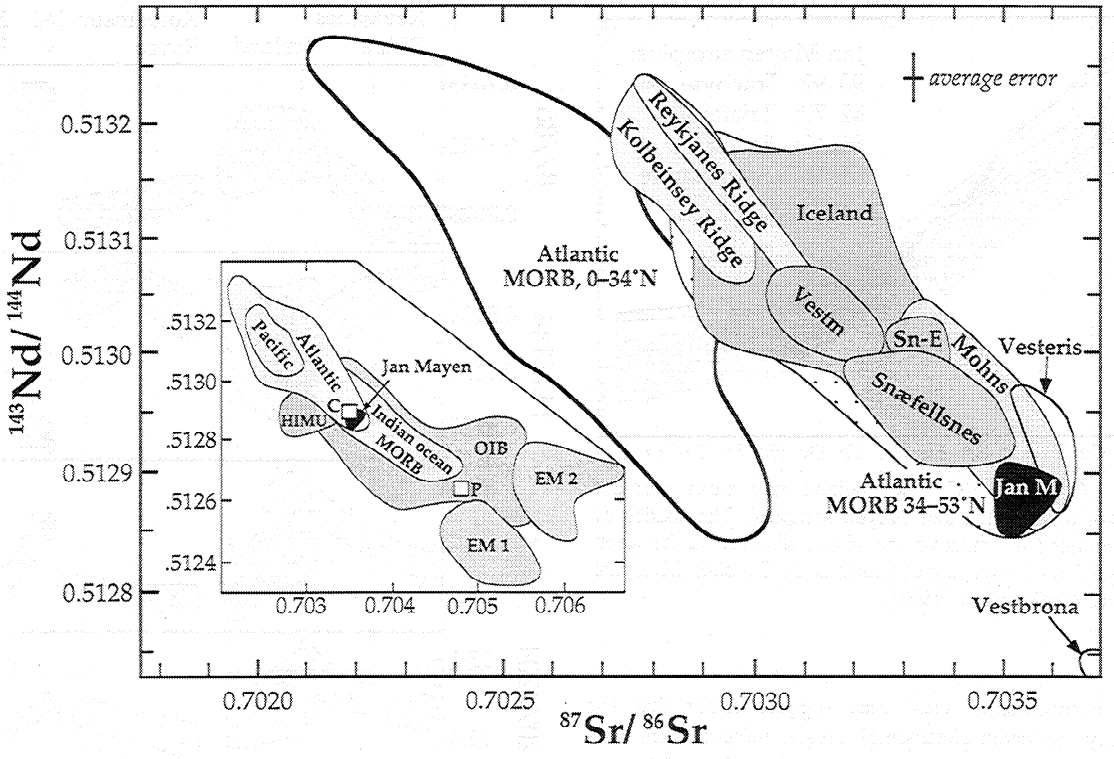
	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf	Ta	Pb	Th	U
167	24	51	5.91	22	4.6	1.32	3.5	0.6	3.1	0.5	1.5	0.2	1.2	0.17	3	3.63	<5	2.7	0.7
65	37	77	9.07	35	7.2	2.12	5.6	0.9	4.7	0.8	2.3	0.32	1.8	0.25	4.5	3.74	<5	3.8	0.9
43	46	101	11.2	45	9	2.48	6.6	1.1	5.4	1	2.6	0.36	2.1	0.28	5.5	4.04	9	4.5	1
85	60	125	14.2	51	10	2.87	7.1	1.2	5.9	1.1	3	0.39	2.4	0.34	6.5	5.53	7	6.6	1.6
70	83	172	18.9	73	14	3.71	9.7	1.5	7.7	1.4	3.8	0.53	3.2	0.44	8.5	8.16	10	8.5	1.5
82	94	188	19.7	67	12	3.17	7.5	1.3	6.5	1.2	3.5	0.52	3.3	0.46	11	8.92	10	13	3
92	104	194	19.8	68	10	2.95	6.1	1	5.4	1	3	0.46	2.9	0.42	12	8.48	14	12	3
90	98	198	19.8	67	11	3.15	6.3	1	5.6	1.1	3.2	0.51	3.3	0.47	13	9.29	14	12	3.1
M_{av}	9.9	26	3.2	19	4.5	1.41	4.0	0.6	2.9	0.5	1.3	0.13	0.8	0.12	3.8	0.85	5.3	0.9	0.3
s.d.	0.5	1.1	0.2	0.9	0.2	0.07	0.26	0.06	0.11	0.02	0.06	0.01	0.2	0.01	0.2	0.07	1.4	0.1	0.02
M_{ac}	9.8	26	3.4	19	4.5	1.39	4	0.5	2.9	0.5	1.1	0.11	0.6	0.12	3.8	0.8	10	0.9	0.2

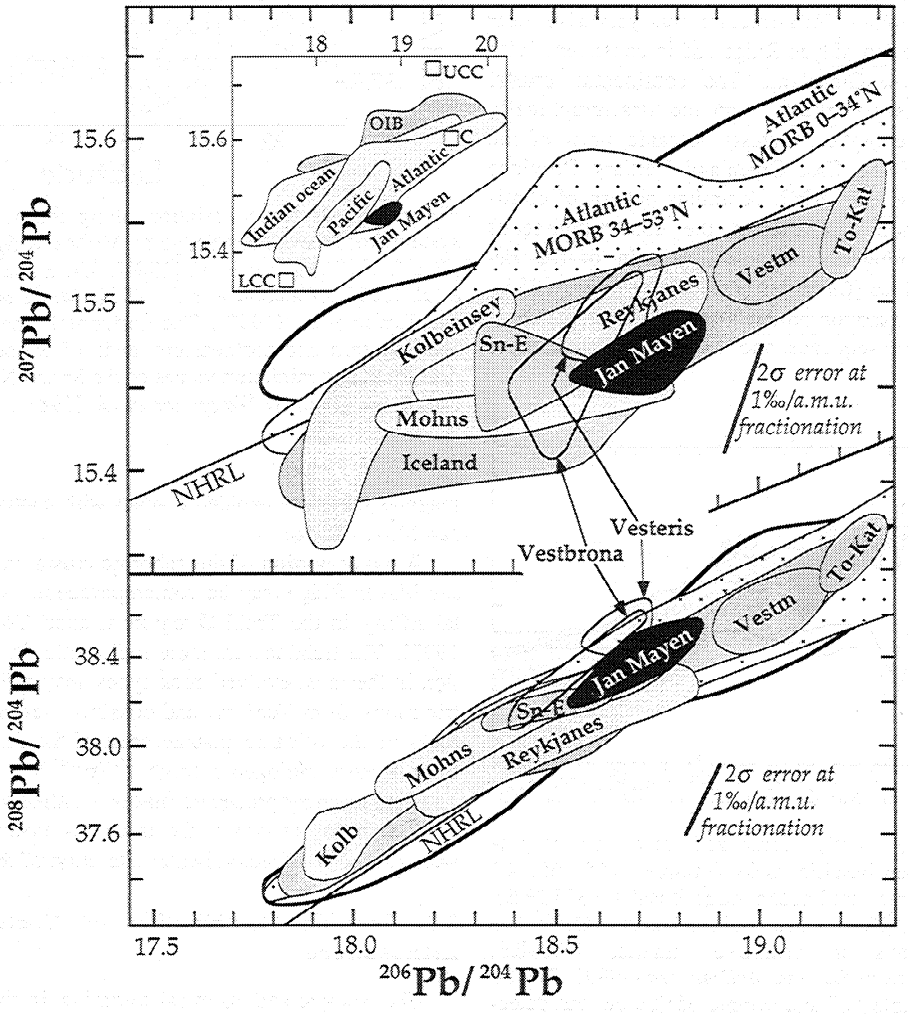
The following analyzed element concentrations were below the detection limit: As (<5 ppm), Ag (0.5), In (0.2), Tl (0.1), and Bi (0.2). M_{av}, s.d.: average values and standard deviations of analyses of the international gabbro standard MRG-1 at in 1996/97 (E.Hoffman. Activation Laboratories). M_{ac}: accepted concentrations for the MRG-1 standard.

the Mohns Ride are indistinguishable from the recent volcanics on the island in major and trace element composition and isotopic ratios. This is strong evidence that the Jan Mayen magmas have escaped significant contamination of a continental crustal source, since the continental crustal infrastructure of the N-S trending Jan Mayen Ridge do not extend north of the fracture zone [*Gudlaugsson et al.*, 1988].

A characteristic feature of the Jan Mayen samples is the isotopic homogeneity. Anatectic melt contributions from the wall rocks of the magmatic plumbing systems would likely affect especially the evolved part of the magma spectrum. Even a small amount of anatectic contribution from a lower continental crust would thereby create a significant isotopic variation range. The lack of geochemical signs of anatectic contribu-

Figure 5. Comparison of the isotopic composition of the Jan Mayen-samples with the compositions of other oceanic basalts, based mostly on work by *Hofmann* [1997] and *Mertz and Haase* [1997]. Icelandic data are from *Elliott et al.* [1991], *Furman et al.* [1991], *Mertz et al.* [1991], *Hemond et al.* [1993], *Hards et al.* [1995], *Thirlwall* [1995], *Mertz and Haase* [1997], and Stecher et al. [1999]. Data from the Vesteris seamount and Vestbrona formation nephelinites are from *Haase and Devey* [1994] and *Prestvik et al.* [1999]. Atlantic, Pacific, and Indian Oceans indicate the approximate compositional range of the mid-ocean ridge basalts (MORB) from these respective oceans. OIB, ocean island basalts; C, common component of various subpopulations of MORB defined on the basis of Pb isotopic compositions from *Hanan and Graham* [1996]; P, primitive mantle component [*Hoffmann*, 1997]; the enriched mantle components HIMU, EM 1, and EM 2 are as defined by *Zindler and Hart* [1986]; UCC and LCC, upper and lower continental crust are components defined by *Zartman and Haines* [1988]; alkaline, off-rift volcanic systems in Iceland: Sn-E, Snæfell (eastern Iceland); Vestm, Vestmannaeyjar; To-Ka, Torfajökull–Katla; NHRL, Northern Hemisphere Reference Line. A remakable feature of the Pb isotopic data obtained by *Elliott et al.* [1991] for the Theistareykir and Reykjanes volcanic systems are the very low $^{207}Pb/^{204}Pb$ ratios, particularily for the Theistareykir system. Based on reanalysis of two of these samples, *Hanan and Schilling* [1997] ascribed the very low $^{207}Pb/^{204}Pb$ ratios to mass fractionation problems during the analyses by *Elliott et al.* [1991]. The Pb-isotopic values of *Elliott et al.* [1991] have been increased accordingly. For the 56 Ma old Vestbrona nephelinites the Sr and Nd ratios shown are initial ratios. The Pb ratios, however, are presently measured ratios.


average error
Reykjanes Ridge
Kolbeinsey Ridge
Iceland
Atlantic MORB, 0–34°N
Vestm
Sn-E
Mohns
Vesteris
Snæfellsnes
Atlantic MORB 34–53°N
Jan M
Vestbrona
Pacific
Atlantic
Jan Mayen
Indian ocean
MORB
HIMU
OIB
EM 2
EM 1
P
C
0.5132
0.5131
0.5130
0.5129
0.5128
.5132
.5130
.5128
.5126
.5124
0.703
0.704
0.705
0.706
0.7020
0.7025
0.7030
0.7035
143Nd/144Nd
87Sr/86Sr


18
19
20
UCC
LCC
OIB
C
Indian ocean
Pacific
Atlantic
Jan Mayen
15.6
15.4
Atlantic MORB 0–34°N
Atlantic MORB 34–53°N
To-Kat
Vestm
Reykjanes
Kolbeinsey
Sn-E
Jan Mayen
Mohns
Iceland
NHRL
2σ error at 1‰/a.m.u. fractionation
Vesteris
Vestbrona
15.5
38.4
38.0
37.6
Kolb
17.5
18.0
18.5
19.0
207Pb/204Pb
208Pb/204Pb
206Pb/204Pb

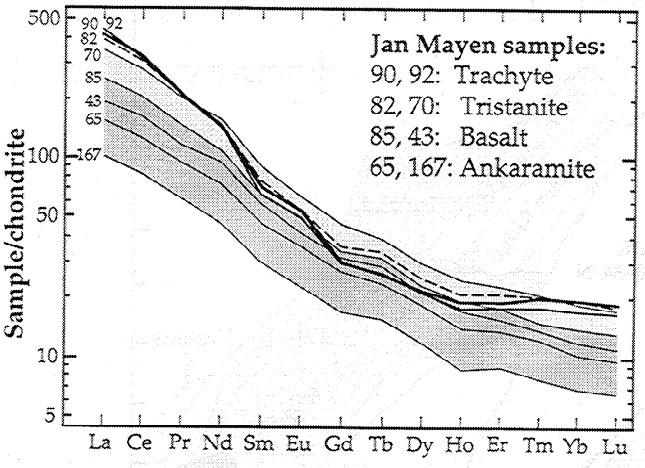


Figure 6. Chondrite (C1) normalized rare earth element abundances of eight of the Jan Mayen samples. The shades of gray are introduced to improve the visual distinction between the samples. The element concentrations in C1 chondrites are from *Sun and McDonough* [1989].

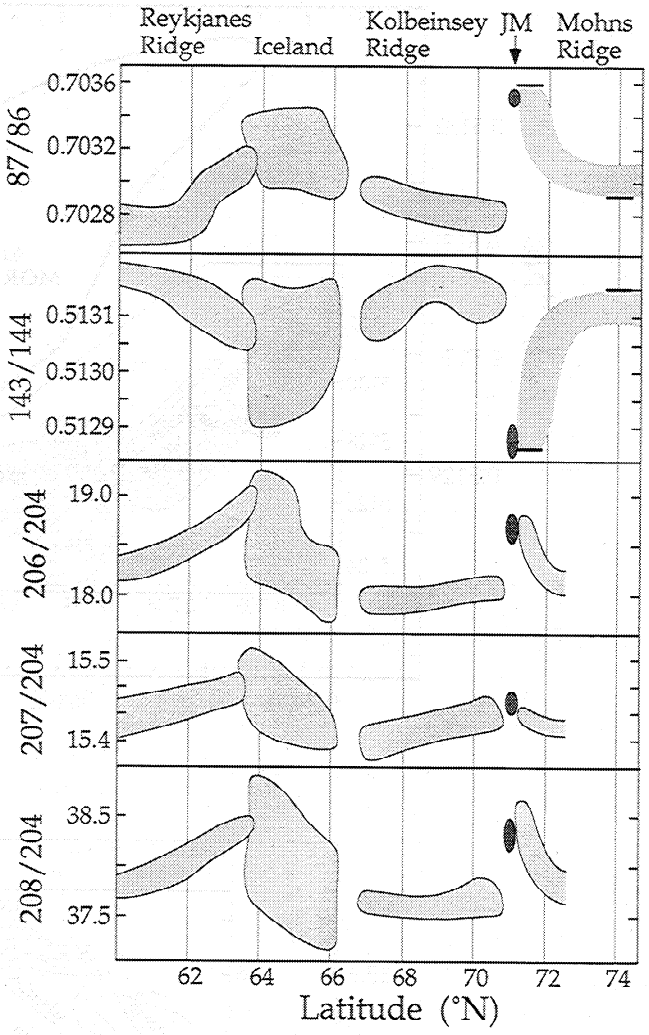


Figure 8. Isotopic variation along the north Atlanic ridge system from Reykjanes Ridge to Mohns Ridge. Data are compiled from *Waggoner et al.* [1981], *Mertz et al.* [1991], *Elliott et al.* [1991], *Hemond et al.* [1993], *Mertz and Haase* [1997], and *Taylor et al.* [1997]. The horizontal line segments at the southwestern and northeastern ends of Mohns Ridge are the maximum and minimum values of the Sr and Nd isotopic variation range given by *Waggoner et al.* [1981].

tions from a continental crust may suggest either that the geophysically indicated continental crustal infrastructure does not extend to the northernmost parts of the Jan Mayen Ridge or that the recent Jan Mayen volcanics may have escaped contamination from such a crust. The latter scenario is likely if the Tertiary to recent magmatic infrastructure was pervasive near the northern end of the Jan Mayen Ridge and is consistent with observations from east Greenland. The continental crustal contamination decreases markedly from the stratigraphically lowest (earliest) to the highest (latest) volcanic units of the breakup volcanics of the East Greenland Tertiary Province [*Holm*, 1988; *Fitton et al.*, 1998]. A similar pattern of continental crustal contamination affected the contemporaneous volcanics on the conjugate continental margin of the Hebridean volcanic province [*Carter et al.*, 1978; *Dickin*, 1981]. The recent Jan Mayen eruption products are the latest members in an extensive volcanic sequence, and it is possible that these magmas therefore avoided contact with continental crust of the Jan Mayen Ridge.

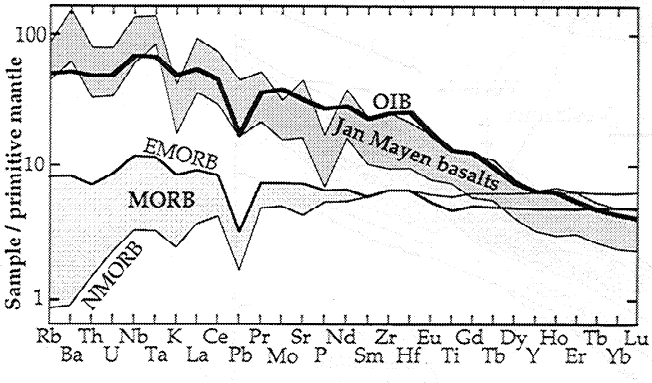


Figure 7. Primitive mantle normalized tracc element patterns of the Jan Mayen basaltic rocks (samples 165, 65, 43 and 85), average normal mid-ocean ridge basalts (NMORB), enriched MORB (EMORB) and ocean island basalts (OIB). The element concentrations in primitive mantle, NMORB, EMORB and OIB are from *Sun and McDonough* [1989]. The Pb concentrations of sample 167 and sample 65 (below the detection level of 5 ppm) are arbitrarily set to 3 ppm.

A major portion of the gabbroic crustal infrastructure of the Jan Mayen Ridge may be contemporaneous with the continental rifting in the Traill Ø region at about 36 Ma [*Price et al.*, 1997]. The trend toward more radiogenic Pb isotope composition in the most evolved rock types may reflect anatectic contributions from Tertiary, and possibly seawater-altered, mafic rocks in the volcanic plateau crust of the Jan Mayen Ridge or from a more radiogenic (high $^{206}Pb/^{204}Pb$) continental crust. The acid leaching procedure makes it unlikely that the elevated $^{87}Sr/^{86}Sr$ ratios of two of the trachytes (samples 38 and 171) were caused by direct seawater alteration of the trachytes.

5.3. Possible Contribution of Continental Mantle Lithosphere

The isotopic and chemical variation in the Jan Mayen area and along Mohns Ridge is most likely a result of mixing of

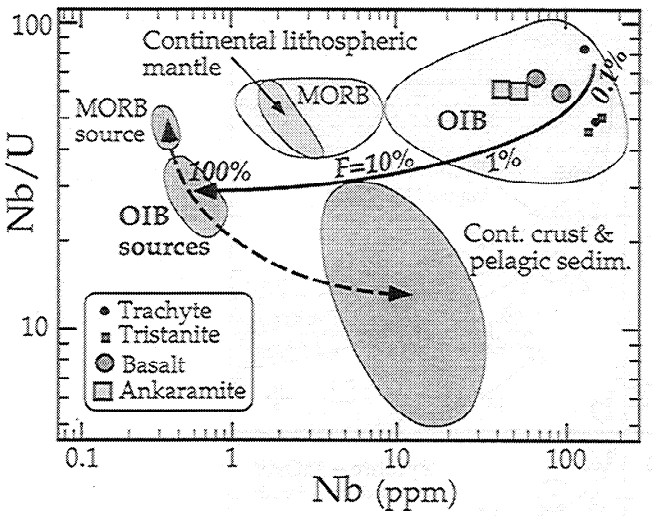


Figure 9. Logarithmic variation diagram of Nb/U versus Nb for the Jan Mayen rocks along with the fields of mantle sources for mid-ocean ridge basalts (MORB) and ocean island basalts (OIB) as well as the fields for continental lithospheric mantle, continental crust and pelagic sediments, MORB, and OIB. The dashed and curved double arrow indicates a range of magma sources with MORB mantle and average continental crust as end-members, and the curved arrow is the approximate melting curve of an average OIB mantle source with indicated F values (partial melt fraction) of 0.1, 1, 10, and 100%. Both the fields and the approximate melting curve are adopted from *Sims and DePaolo* [1997].

low-degree melts from a garnet peridotite source (dominant near Jan Mayen) and higher-degree melts of largely spinel peridotites in the upwelling asthenosphere beneath the ridge. A continental lithospheric mantle inherited from the east Greenland margin is one possible source for the low-degree melts.

Sims and DePaolo [1997] used diagrams with an incompatible element ratio versus an incompatible element to investigate the extent to which petrogenetic processes, e.g., partial melting, change such element ratios. Based on the trace element compositions of various ocean island basalts (OIB), they calculated the composition of their mantle sources in terms of these elements and a set of reasonable, but slightly variable assumptions on source mineralogy (garnet and spinel lherzolite sources). The Jan Mayen basaltic rocks plot well inside the calculated OIB field in such diagrams, e.g., in Figure 9. The OIB sources are compositionally different from common continental lithospheric mantle defined by the range of median and mean values of spinel lherzolite and harzburgite xenoliths from continental basalts [*McDonough*, 1990; *Sims and DePaolo*, 1997]. Although the incompatible element ratio diagrams (e.g., Figure 9) cannot exclude anatectic contributions from an inherited continental mantle lithosphere, they show that Jan Mayen basalts could represent very small degrees of partial melting of ordinary OIB lherzolite sources.

5.4. Lithospheric Control on Melt Separation

In spite of the negative K anomaly in Figure 7 and lower K/Nb, K/U, and K/Th ratios than most OIB and the alkaline off-rift volcanics in Iceland, the basalts from the Jan Mayen area, including the Jan Mayen Bank and the Jan Mayen Platform, have high K_2O/Na_2O ratios [*Neumann and Schilling*, 1984; *Haase et al.*, 1996, this study]. The K_2O/Na_2O ratios of the Jan Mayen basalts (0.5–0.8) exceed those of the alkali basalts in the Icelandic off-rift zones (mostly 0.2–0.3) and the Vesteris seamount (0.5–0.6), as well as the Vestbrona nephelinites (0.4–0.5). High K/Na ratios in combination with high concentrations of Rb and Ba and low Rb/Ba and K/Nb ratios point to the presence of a potassic residual phase, e.g., phlogopite. A heterogeneous mantle with enriched portions (irregular and deformed lumps or veins, millimeter to meter size), where enriched material melts before refractory material, is suggested for the Jan Mayen area [*Haase et al.*, 1996]. A major portion of such a heterogeneous mantle, however, is most likely peridotitic.

The steepness of the chondrite-normalized REE pattern of the ankaramitic and basaltic Jan Mayen samples (Figure 6) shows that the melts separated from garnet-bearing residues at considerable depth and after low degree of partial melting [e.g., *Ellam*, 1992]. A similar conclusion was reached for the Jan Mayen Platform and Jan Mayen Bank by *Neumann and Schilling* [1984] and *Haase et al.* [1996]. If the mantle source is enriched, the estimates of melt separation depths based on LREE/HREE ratios for the Jan Mayen basalts may be somewhat higher than the actual separation depths.

The Ce/Y ratios of basaltic rocks from Jan Mayen and the offshore Jan Mayen Bank [*Haase et al.*, 1996] range from 3.0 to 4.3. Using the model of *Ellam* [1992] and *Parsons and McKenzie* [1978] for the age-thickness relations of the oceanic lithosphere, the average Ce/Y value of 3.8 would correspond to a melt separation depth of 90 km. A similar depth is obtained by the model of *Haase* [1996] based on the SiO_2 content at about 9% MgO. The *Parsons and McKenzie* [1978] model predicts that the age of oceanic lithosphere with a thickness of 90 km would be about 53 Ma. A simple age–thickness relation for the Jan Mayen Ridge lithosphere is unlikely because it was probably inherited from the east Greenland continental margin. Nevertheless, a truncation of the partial melting column at a depth near 90 km under Jan Mayen seems reasonable. A thermal and mechanical boundary layer of 90 km thickness does not necessarily correspond exactly to the continental lithosphere.

The sample from the Jan Mayen Platform about 70 km ENE of Nordkapp has a Ce/Y ratio of 2.2, corresponding to a thermal boundary layer thickness of only 32 km, according to the models of *Ellam* [1992] and *Parsons and McKenzie* [1978]. Correspondingly, the recent alkaline basalts in the Icelandic off-rift zones have average Ce/Y ratios of about 2.5 (Snæfellsjökull), 1.5 (Snæfell), and 1.3 (Vestmannaeyjar) [*Hardarson and Fitton*, 1991; *Hards et al.*, 1995; *Furman et al.*, 1991].

A polybaric melting model based on the REE ratios and Ti concentrations combined with a primitive (chondritic) mantle source [*Fram and Lesher*, 1993] can produce the Jan Mayen basalts by about 5% melting between 2.5 and 2.0 GPa (from 80 to 60 km depth). A similar REE-based polybaric model with a slightly depleted mantle source [*Tegner et al.*, 1998] gives unrealistically low melt fractions.

5.5. Partial Melting Processes and the High-Nb Source Composition

In order to put further constraints on the mantle source and melting process, the results of various simple equilibrium and fractional melting models are compared with the composition of the alkaline volcanics of Jan Mayen, the Vestbrona forma-

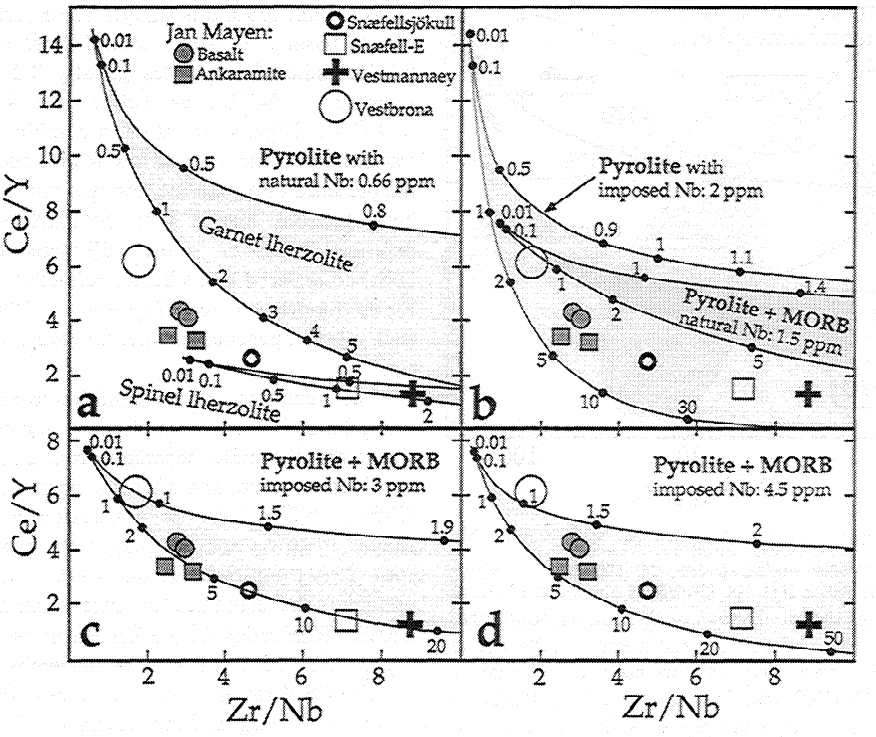


Figure 10. Graphical presentation of the results from partial melting modelling based on partitioning coefficients, source compositions and melting modes listed in Table 4. The melting sources comprise pyrolite and equal amounts of pyrolite and NMORB, with natural or imposed concentrations of Nb as indicated. The partitioning coefficients are chosen as median values of the ranges given by *Green* [1994], except for the Nb values which are in the lower half of the ranges. Trace element concentations for pyrolite are from *McDonough and Sun* [1995] and for NMORB from *Sun and McDonough* [1989]. Source mineralogies are approximately according to *McKenzie and O'Nions* [1991] and *Irifune* [1993], and the melting modes are from *Gudfinnsson and Presnall* [1996]. For each composition and mineralogy the upper and lower curves represent fractional and equilibrium melting, respectively. Numbers along the curves are melt fractions in percent. Average values for Icelandic alkaline volcanics and Vestbrona nephelinites are from the references listed in Figure 5. The simplified melting models involving pyrolite–MORB mixtures are used only to illustrate the trace element constraints. The alkaline basaltic composition of the NE Atlantic may require metasomatically enriched mantle sources (e.g., with phlohopite), and the overall source composition is unconstrained.

tion, and the Icelandic off-rift zones in Figure 10. The Ce/Y and Zr/Nb ratios are insensitive to moderate degrees of low-pressure fractionation of basaltic melts. Alkaline volcanics from the NE Atlantic, including Jan Mayen, Vestbrona, and Iceland, are generally characterized by higher Nb contents and lower Zr/Nb ratios than almost any other oceanic volcanics. It seems impossible to generate such melt compositions from average primitive or depleted mantle peridotite compositions. The partitioning coefficients used in the model calculations (Table 4) are median values compiled by *Green* [1994]. To ensure that the generated melt compositions represent approximately minimum Zr/Nb ratios, the coefficients for Nb were deliberately chosen on the low side of the median values of *Green* [1994]. Even with these low partitioning coefficients for Nb, the melts produced from an average pyrolite source [*McDonough and Sun*, 1995] cannot match the Jan Mayen basaltic rocks (Figure 10a). Modeling using modal and nonmodal melting (mantle mineralogy and melting modes in Table 4) gives very similar results at moderately low melt fractions. Only the nonmodal melting models are shown in Figure 10. The Jan Mayen basaltic compositions fall below the equilibrium melting curve of a garnet peridotite (pyrolite composition [*McDonough and Sun*, 1995]) and clearly below 0.5% melting of a spinel peridotite (Figure 10a). This situation becomes even worse for a more depleted composition (e.g., the primitive mantle of *Hofmann* [1988]).

The situation does not improve appreciably by melting a mixture of 50% pyrolite and 50% mid-ocean ridge basalt (average NMORB, Figure 10b). A source with elevated Nb content is needed. In Figure 10b a pyrolitic source containing 2 ppm Nb, instead of the 0.66 ppm Nb quoted by *McDonough and Sun* [1995], gives an acceptable result. In this model the Jan Mayen basalts could be separated from a Nb-enriched pyrolite residue after 1–5% partial melting, whereas the Vestbrona nephelinites would require even smaller degrees of partial melting.

Figures 10c and 10d show the results of melting an equal mixture of pyrolite and NMORB with added Nb. Whereas the unspiked pyrolite–MORB mixture has 1.5 ppm Nb, the Nb concentration in the mixture was increased to 3 ppm (Figure 10c) and 4.5 ppm (Figure 10d). In the latter model the Jan Mayen basalts could be generated by a combination of 2–5% fractional and equilibrium melting of the pyrolite–MORB mixture. Garnet would clearly be a residual phase in such a composition. The alkaline melts of Snæfellsjökull, Snæfell,

Table 4. Parameters Used in Partial Melting Models.

	Ce	Y	Zr	Nb
Partitioning coefficient				
Olivine (ol)	0.00008	0.004	0.0007	0.00002
Orthopyroxene (cpx)	0.01	0.09	0.03	0.005
Clinopyroxene (opx)	0.07	0.4	0.13	0.01
Garnet (ga)	0.03	2.7	0.5	0.009
Spinel (sp)	0.003	0.003	0.06	0.06
Source composition, ppm				
Pyrolite (py, Figure 12a)	1.68	4.3	10.5	0.66
Pyrolite (Figure 12b)	1.68	4.3	10.5	2
py + NMORB (Figure 12b)	4.6	16.2	42.3	1.5
py + NMORB (Figure 12c)	4.6	16.2	42.3	3.0
py + NMORB (Figure 12d)	4.6	16.2	42.3	4.5

	ol	opx	cpx	ga	sp	melt
Source mineralogy, %						
ga. lherzolite (Fig. 12a–12b)	60	18	8	14		
sp. lherzolite (Fig. 12a)	60	24	12		4	
py+MORB (Fig. 12b–12d)	30	9	34	27		
Melting modes (negative numbers: production/precipitation), %						
sp-bearing (only Fig. 12a)	–12	–3	89		11	–85
ga-bearing (Fig. 12a–12d)	6	–48	71	23		–52

and Vestmannaeyjar could be formed by mixing the garnet-residual Jan Mayen melts with partial melts from spinel peridotites (e.g., the pyrolite composition in Figure 10a).

The most likely origin of a Nb- and Ta-enriched source component in the North Atlantic upper mantle is recycled oceanic lithosphere processed by fluid phase and/or melt extraction of trace elements in a former subduction zone. Such extraction processes produce island arc magmas (and continental crustal material) with strong relative depletions in Nb and Ta, caused by the selective retention of these elements in Ti oxides and amphibole in the descending oceanic lithosphere [e.g., *Hofmann,* 1997]. A mixture containing only minor amounts of recycled oceanic crustal material is required if Nb and Ta are strongly enriched in this component.

5.6. Jan Mayen and NE Atlantic Mantle Sources

Whereas the central stem of the Icelandic mantle plume is defined both geophysically [*Tryggvason et al.,* 1983; *Shen et al.*, 1998; *Wolfe et al.,* 1997] and geochemically [*Schilling,* 1973; *Schilling et al.,* 1983; *Hart et al.*, 1973], there is no indication of an active plume stem causing dynamic uplift near Jan Mayen. Figure 8 demonstrates the strong compositional similarity in terms of radiogenic isotope ratios of the volcanics at the southwestern end of the Mohns Ridge and at Jan Mayen and the gradual change of compositions along Mohns Ridge away from Jan Mayen. These trends are similar to those resulting from the inferred mantle source mixing between the ascending Iceland plume and ambient asthenosphere along the Reykjanes Ridge [*Schilling,* 1973; *Schilling et al.,* 1983]. Although the Mohns Ridge compositional trends seem to require a mixing between a distinct Jan Mayen mantle source and the ambient asthenospheric upwelling along the ridge, they do not require an active plume column centered near Jan Mayen.

The Jan Mayen source composition is further characterized by $^3He/^4He$-ratios (R/R_{atm}) of 6.3–6.8 [*Kurz et al.*, 1982]. The Iceland plume is characterized by variable, and partly very high, He isotopic ratios ranging from 6.9 to 26.2 [*Kurz et al.*, 1985; *Sigmarsson et al.*, 1992]. Based on the five analyses reported by *Poreda et al.* [1986], the He isotopic variation along Mohns Ridge appears to be confined to the restricted range of 7.1 to 8.2. Whereas the Reykjanes Ridge basalts are characterized by He isotopic ratios increasing to about 16 near Iceland, the Kolbeinsey Ridge has lower values of 10-12 [*Poreda et al.*, 1986].

The Iceland mantle source is characterized by a distinct compositional heterogeneity, involving at least two or three different end-members [*Elliott et al.*, 1991; *Hemond et al.*, 1993; *Hards et al.*, 1995; *Fitton et al.*, 1997]. Whereas the source of the alkaline volcanics in the peripheral off-rift volcanic zones is geochemically undepleted and fusible, the tholeiitic, and in particular the picritic, rocks in the axial rift zones represent more refractory components. During dynamic melting in the rising mantle column beneath Iceland, low-degree melts of the "alkaline" source component form first. These melts are then diluted to variable degrees by melts from progressively more refractory sources. The proportions of low-degree melt fractions are highest in the peripheral off-rift zones where a relatively thick mechanical boundary layer truncates the melting column at considerable depths.

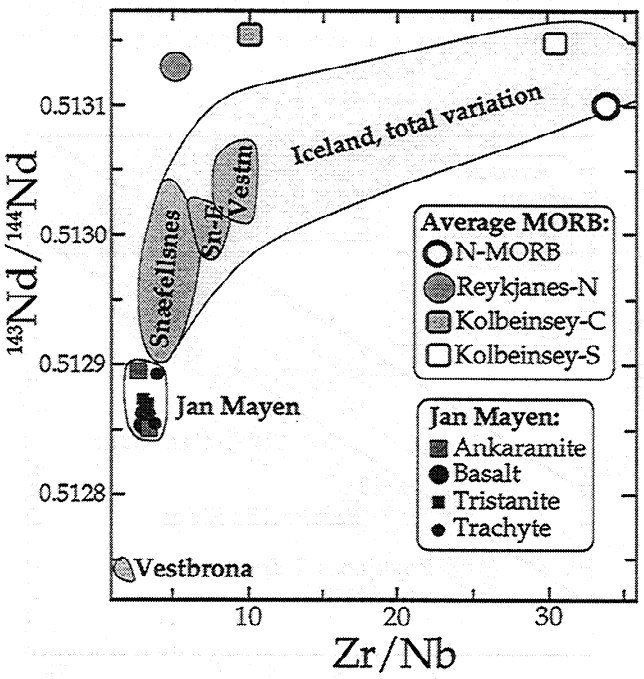


Figure 11. Plot of $^{143}Nd/^{144}Nd$ versus Zr/Nb for groups of Icelandic volcanics and Jan Mayen. The Nd-isotopic ratios of the Vestbrona formation are initial ratios at 56 Ma. The field of Iceland volcanics (total variation) is from *Hardarson and Fitton* [1997], and other fields and average MORB compositions are from *Hofmann* [1988], *Sun and McDonough* [1989], *Furman et al.* [1991], *Hardarson and Fitton* [1991], *Nicholson and Latin* [1992], *Hemond et al.* [1993], *Devey et al.* [1994], *Hards et al.* [1995], *Fitton et al.* [1997], and *Prestvik et al.* [1999]. Reykjanes-N, Reyjkanes ridge north of 61°N; Kolbeinsey-C and S, central and southern part of the Kolbeinsey ridge.

The end members of the heterogeneous Iceland mantle source have certain common isotopic characteristics which are otherwise rather uncommon in the global suite of oceanic basalts. The most notable of these compositional features is the low $^{207}Pb/^{204}Pb$ ratios at a given $^{206}Pb/^{204}Pb$ ratio [Thirlwall, 1995, 1997]. This characteristics is also shared by the volcanics of Jan Mayen and southwestern Mohns Ridge, as well as by the Vesteris seamount and the early Tertiary Vestbrona formation (Figure 5). In terms of the Sr-Nd and partly the Pb isotopic systems, there are also obvious differences between MORB from 0°N to 34°N compared to MORB from 34°N to 53°N and Iceland, Reykjanes Ridge, Kolbeinsey Ridge, Mohns Ridge, and Jan Mayen as the other compositional group (Figure 5). Such large-scale isotopic distinctness of the NE Atlantic mantle may have been produced by supply of material to the uppermost mantle through the ancestral Iceland plume conduit, or it may be an inherited feature of the preexisting subcontinental mantle prior to the early Tertiary rifting and volcanism.

The different end-members of the heterogeneous Iceland mantle source can be resolved within this large-scale NE Atlantic compositional spectrum. In terms of various isotopic, major element, and trace element compositions the alkaline off-rift volcanics in Iceland converge toward the compositionally slightly more enriched Jan Mayen basalts and the more extreme Vestbrona nephelinites. This is clearly seen in the $^{143}Nd/^{144}Nd$ versus $^{87}Sr/^{86}Sr$ diagram (Figure 5) as well as in a $^{143}Nd/^{144}Nd$ versus Zr/Nb diagram (Figure 11). Within Iceland the Snæfellsnes volcanic zone in western Iceland contains the highest proportion of the most fusible component, although this component appears to be even more prominent in the Jan Mayen volcanics. Furthermore, in terms of the He isotopes, the Icelandic compositional array approaches the low value of 6.5 for the analyzed Jan Mayen basalt but ends at about 7.5 ($^3He/^4He$ as R/R_{atm}) for the Snæfellsnes volcanics [*Kurz et al.*, 1982; *Sigmarsson et al.*, 1992]. In terms of the Pb isotopes the picture is slightly more complex with the Jan Mayen and Vestbrona compositions in between the compositional fields of Snæfell volcanic zone in eastern Iceland and the Vestmannaeyjar system (Figure 5).

In order to discriminate between Tertiary and recent basalts formed from the Iceland plume and other basalts in the NE Atlantic area, *Fitton et al.* [1997] introduced a logarithmic Nb/Y versus Zr/Y diagram and a ΔNb parameter (= 1.74 + log(Nb/Y) – 1.92 log(Zr/Y)). In this diagram the Jan Mayen and Vestbrona volcanics plot near the extreme upper end of the Iceland array, next to the Snæfellsnes volcanics (Figure 12). It is noteworthy that the basalts from the northernmost part of the Reykjanes Ridge (north of 61°N) and the southern part of the Mohns Ridge fall inside the Icelandic array, contrary to almost all other normal MORB. Whereas the basalts from the southern part of the Kolbeinsey Ridge plot near the lower limit of the Iceland array, those from the central and northern part of the ridge plot well inside the array.

A discussion of the interaction between various melt sources in the NE Atlantic must also invoke the ambient upper MORB source asthenosphere in addition to the enriched (fusible) and refractory components of the Iceland plume [e.g., *Fitton et al.*, 1997]. Based on the He-Sr-Nd isotopic data, the enriched, low-melting component of the NE Atlantic mantle appears to record a history of even stronger degassing than the common MORB asthenosphere. This is consistent with an origin of the enriched component as recycled oceanic crust. The alkaline nature of the basaltic melts formed by the melting of this component, however, may appear at odds with a simple MORB-recycling model. For the Hawaiian volcanoes, *Hauri* [1996] identified positive correlations between SiO_2, $^3He/^4He$ and $^{187}Os/^{188}Os$ and between FeO and $^{143}Nd/^{144}Nd$, combined with negative correlations between SiO_2 and FeO. These correlations may result from the mixing of dacitic melt fractions from quartz eclogite with picritic to tholeiitic melt fractions from peridotite. *Hauri* [1996] suggested that discrete blobs of recycled eclogitic material became entrained in the rising Hawaiian plume. Recycled eclogitic material more intimately mixed and homogenized with a large fraction of peridotite, however, produces near-solidus melts of nepheline-normative compositions, in accordance with the experimental melting studies of *Falloon and Green* [1988], *Kogiso et al.* [1998], and *Robinson et al.* [1998].

The enriched NE Atlantic mantle source sampled by the Jan Mayen magmas bears some similarities to the Dupal-type mantle [*Hart*, 1984] in the southern hemisphere in Sr-Nd isotopic ratios and some trace element concentrations. However, the low $^{207}Pb/^{206}Pb$ and high $^{208}Pb/^{206}Pb$ ratios of the enriched NE Atlantic mantle is distinctly non-Dupal-like. The likely mechanism of formation of a mantle domain with negative Δ7/4 and positive Δ8/4 (terminology of *Hart* [1984]) involves a relatively recent increase of the μ value ($^{238}U/^{204}Pb$) in a mantle source with a long history with a low μ [*Thirlwall*, 1995, 1997]. This could be accomplished by the mixing between a low-μ mantle and a relatively recent high-μ component of 250–750 Ma recycled oceanic crust.

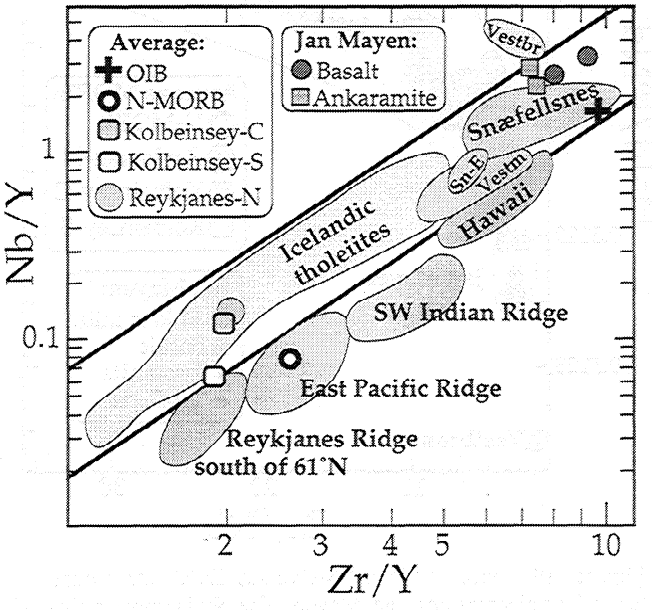


Figure 12. Nb/Y and Zr/Y variation in basaltic rocks from Jan Mayen (JM), Vestbrona (nephelinites), the active volcanic zones of Iceland, various mid-ocean ridge segments, and Hawaii [*Fitton et al.*, 1997]. Variation fields and average compositions from references listed in Figure 11 and from *Dosso et al.* [1993]. Note the similarity between the JM basalts and alkali basalts from the Snæfellsnes volcanic zone. The Iceland array is defined by the two solid lines and the ΔNb-parameter of *Fitton et al*, [1997] equals zero along the lower line.

5.7. Possible Role of the Iceland Plume

The refractory mantle source of the Icelandic tholeiites and picrites seems to differ from MORB-asthenosphere, in having higher $^{3}He/^{4}He$ and lower $^{207}Pb/^{206}Pb$. It is likely that this undegassed, but refractory, plume component represent material supply from the lower mantle [cf. *Shen et al.*, 1998] and that it constitutes the dominant proportion of the rising plume column. The geochemical influence of the present Iceland plume seems to be quite variable, even as close to Iceland as along the southern part of the Kolbeinsey Ridge (Figure 8) [*Mertz et al.*, 1991; *Taylor et al.*, 1997]. In contrast, the early Tertiary ancestral plume head spread laterally in the upper mantle, covering a roughly circular area with a diameter close to 2000 km [*Thirlwall et al.*, 1994; *Fitton et al.*, 1997; *Saunders et al.*, 1997; *Marty et al.*, 1998].

The enriched NE Atlantic mantle source, preferentially sampled by low-degree melts in the Icelandic alkaline volcanic zones, Jan Mayen, Vesteris seamount, and the Vestbrona area, has most likely been confined to the upper mantle, at least since 56 Ma, which is the age of the Vestbrona volcanics. The physical nature (blobs, veins, streaks) of this enriched material is unknown. It may occur intimately mixed and deformed along with more refractory material on a millimeter to meter scale. The mixture may have formed in situ within the upper mantle, e.g., by metasomatic vein formation by low-degree melts, or it may have been transferred from the lower to the upper mantle by the ancestral Iceland plume. The mechanism of emplacement by the ancestral Iceland plume appears most likely due to the widespread occurrence of this mantle source in the NE Atlantic area.

5.8. Model

In our simplified model (Figure 13) we assume that the chemical and isotopic composition of the Iceland plume has been essentially constant from its initiation until today [e.g., *Thirlwall et al.*, 1994; *Saunders et al.*, 1997]. The influence of the stationary present Iceland plume is probably confined to the Icelandic rift zones and the nearby spreading ridge segments. Off-ridge volcanism in the Jan Mayen, Vesteris, and Vestbrona areas, however, may sample the low-degree melting component of plume head material of the ancestral Iceland plume emplaced in the upper mantle.

The geochemical variation in the volcanic rocks along the Reykjanes, Kolbeinsey, and Mohns Ridges is variable and largely linked to the total degree of partial melting in the area. The degree of partial melting of a rising mantle column at a given location is controlled by a combination of the temperature (or depth of solidus) and the lithospheric thickness. The latter features are illustrated for the Jan Mayen area in the bottom cartoon in Figure 13.

The radiogenic isotope ratios (especially the low $^{207}Pb/^{206}Pb$) indicate that within a radius of about 1000 km from Iceland the magma generation is mainly from material characteristic of the ancestral or stationary Iceland plume, even along the spreading ridges. However, the geochemical features of the Kolbeinsey Ridge (e.g., Figure 8) may result from a relatively greater portion of the magma generated by the melting of plume-heated MORB-type asthenosphere.

Our proposed model may be tested by further geochemical studies of the various volcanic units in the NE Atlantic. Additional isotopic systems, e.g., the Re-Os system, may provide complementary and more refined insight. As an alternative to our model, the enriched, low-melting component of the Icelandic and Jan Mayen alkaline volcanics could have been incorporated into the upper mantle of the Eurasia-Laurentia border region prior to the initiation of the Iceland plume and the opening of the NE Atlantic. If such an early enrichment took place, this material would have been entrained in the rising Iceland plume at a relatively shallow level. The Oslo Rift basal-

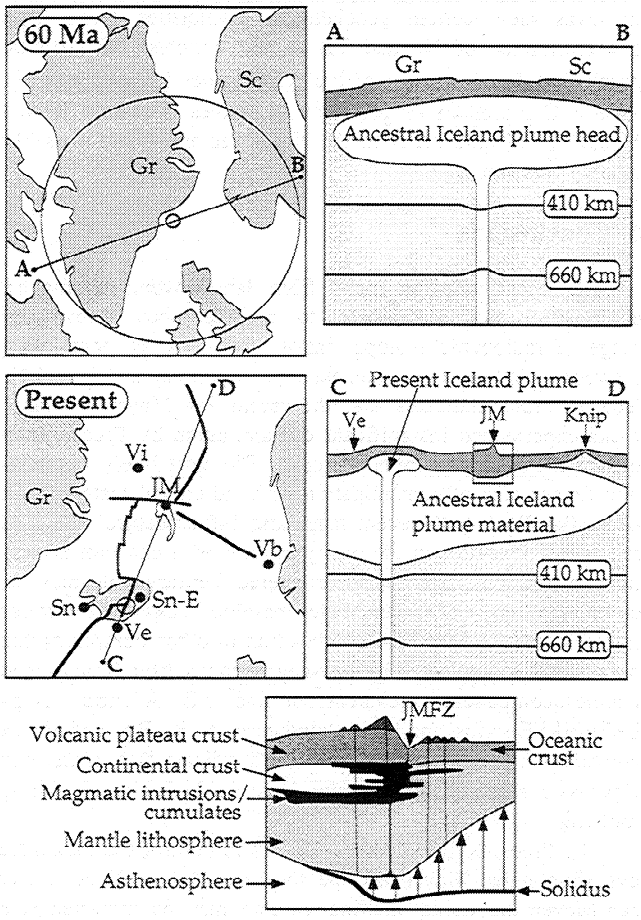


Figure 13. Schematic and and simplified model for the evolution of the NE Atlantic mantle. Gr, Greenland; Sc, Scandinavia; Knip, Knipovich spreading ridge; JM, Jan Mayen; JMFZ, JM Fracture Zone; Vi, Vesteris Seamount; Vb, Vestbrona area; alkaline off-rift volcanic systems in Iceland: Sn, Snæfellsnes peninsula; Sn-E, Snæfell; Ve, Vestmannaeyar. The thick solid lines mark spreading axes and fracture zones. The Jan Mayen Ridge is shown by light shading. The inner and outer circles (60 Ma) represent the approximate plume stem location and the plume head extension of the ancestral Iceland plume [e.g., *Thirlwall et al.*, 1994; *Marty et al.*, 1998]. Note that *Lawver and Müller* [1994] provided a detailed hotspot track with a plume axis location under central Greenland at about 60 Ma. The vertical sections show schematically the variations in lithospheric thickness, with lithospheric doming effects and topography greatly exaggerated. The 410-km and 660-km seismic discontinuities are indicated with the effect of higher temperatures close to the plume stems. Melting at Ve, JM, and Knip is controlled by the relative lithospheric thickness. The enlarged vertical section for the Jan Mayen area illustrates schematically how the melting of rising mantle (upward pointing arrows) is aborted at the base of the lithosphere.

tic lavas show certain geochemical similarities (e.g., high concentrations of Nb and Ta) to the enriched NE Atlantic basalts but do not have negative Δ7/4 values [*Neumann et al.*, 1988]. Comprehensive geochemical studies of mantle-derived Mesozoic volcanic rocks in the North Sea area could possibly resolve this issue.

6. Conclusions

The recent volcanic rocks from Jan Mayen, ranging in composition from ankaramites to trachytes show a restricted range of radiogenic isotope ratios. The lack of correlation between major and trace element concentrations and Sr and Nd isotope ratios indicates that the recent Jan Mayen volcanic rocks experienced insignificant contamination by Precambrian or Lower Paleozoic continental crust. The most likely explanation for the lack of contamination with old crustal material is a pervasive Tertiary to recent magmatic infrastructure. Elevated radiogenic Pb ratios in the trachytes are consistent with anatectic contributions from seawater-altered Tertiary volcanics or continental crust. The Jan Mayen basaltic rocks have similar trace element and isotopic composition to other oceanic plume basalts and is dominated by low-degree melts from an enriched mantle component prevalent in the NE Atlantic. High LREE/HREE ratios and high abundances of K, Rb, and Ba in combination with low K/Nb and Rb/Ba indicate that garnet and a potassic phase like phlogopite were residual minerals during melting.

The lithospheric thickness appears to control the magmatic evolution at Jan Mayen and the southern Mohns Ridge. Under Jan Mayen the rising melting column may be truncated at a depth of nearly 90 km, resulting in final separation of low-degree melt fractions from enriched garnet-bearing sources. Northeast of the Jan Mayen Fracture Zone and along the Mohns Ridge the melt separation occurs at progressively shallower levels, resulting in the dilution of the first melt fractions from enriched and garnet-bearing sources with tholeiitic melts from more refractory spinel peridotite. The increasing thickness of the thermal boundary layer along the southernmost part of the Mohns Ridge toward Jan Mayen may be a result of thermal effects from the superposition of 36 Ma and older oceanic and continental lithosphere southwest of the Jan Mayen Fracture Zone with nearly zero-age lithosphere along the Mohns Ridge. The Jan Mayen Platform area northeast of the fracture zone has not developed a well-defined spreading axis, possibly due to a relatively thick lithosphere.

The Sr-Nd-He isotopic composition and various major and trace element concentrations of Icelandic alkaline off-rift volcanics show a clear trend toward the Jan Mayen alkaline basalts. The Jan Mayen magma may originate as low-degree partial melts of enriched material emplaced in the NE Atlantic upper mantle by the ancestral Iceland plume about 60 Ma. The characteristic and rather unique isotopic composition, in particular, $^{207}Pb/^{206}Pb$-ratios below the NHRL and $^{208}Pb/^{206}Pb$ ratios above the NHRL, common to volcanic rocks of the Jan Mayen area, Iceland and Tertiary lava sequences in the NE Atlantic region strengthens the idea that the Jan Mayen and southern Mohns Ridge magmas were generated from enriched material in the ancestral Iceland plume head. The enriched component of the NE Atlantic mantle with negative Δ7/4 and positive Δ8/4 is most likely a young HIMU component, possibly originating as recycled oceanic lithosphere of Paleozoic age.

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