Sr, Nd and Pb isotope geochemistry of the Oslo rift igneous province, southeast Norway

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Abstract—Sr, Nd and Pb isotopic compositions are presented for a series of 290 to 250 Ma old basaltic to granitic rocks from the Oslo rift, southeast Norway. A large group of basalts, larvikites and rhomb porphyry lavas cluster within a restricted range of initial isotope ratios: ϵ_{Sr}^i: −3 to −16, ϵ_{Nd}^i: +3.3 to +4.2, $(^{206}Pb/^{204}Pb)_i$: 18.9 to 19.3, $(^{207}Pb/^{204}Pb)_i$: 15.59 to 15.66, $(^{208}Pb/^{204}Pb)_i$: 38.6 to 39.1. The remainder of the rocks trend towards higher initial Sr and lower initial Nd and Pb isotopic ratios.

Data are tested against mantle-crust mixing models. The Oslo rift magmatic rocks originated from a somewhat heterogeneous, mildly depleted source located in the subcrustal lithosphere. The isotopic character of this source has been inherited by the rocks showing uniform isotopic ratios, which have thus not suffered significant crustal contamination. The rest of the mafic to intermediate rocks and the syenites were contaminated in the intermediate to lower crust, which increased slightly their Sr-, but decreased their Nd- and Pb-isotopic ratios. As much as 40–50% contamination is suggested for some of the samples. Strong increases in radiogenic Sr, seen primarily in the granites, are attributed to contamination in the upper crust.

The mildly depleted mantle proposed as the source for the Oslo rift mafic rocks has an isotopic character which can only be explained in terms of a multistage history which included periods of relatively high U/Pb and Th/Pb ratios, resulting from a relatively short depletion history in the subcontinental lithosphere and metasomatic enrichment of the mantle in selected elements.

INTRODUCTION

NUMEROUS QUESTIONS CONCERNING intraplate volcanism remain unanswered in spite of increasing efforts from geoscientists in recent years. Among these are the locations of the mantle source regions for intraplate primary magmas, the trace element and isotopic characteristics of the sources, and the importance of crustal contamination. It has been proposed that both continental alkaline complexes and ocean island basalts originate in a strongly depleted mantle source underlying both the continents and the oceans (*e.g.*, BELL *et al.*, 1982; GRÜENFELDER *et al.*, 1986; TILTON *et al.*, 1986). However, recent studies of magmatic rock complexes in different parts of the world, including western USA and West Germany, suggest that source regions with a history of lower Sm/Nd and higher Rb/Sr than the mid-ocean ridge basalt (MORB) reservoir may exist in the subcontinental lithosphere (*e.g.* DOSSO and MURTHY, 1983; MENZIES *et al.*, 1983; CROWLEY *et al.*, 1985; LOEFFLER and FUTA, 1985; PERRY *et al.*, 1985; WÖRNER *et al.*, 1986). Similar results have also been cited from kimberlites (SMITH, 1983; FRASER *et al.*, 1985). A major problem in the interpretation of geochemical data on intraplate rocks is thus to identify those rocks which have retained the geochemical characteristics of their source regions, and distinguish them from rocks which originated in a depleted mantle reservoir, but have subsequently been contaminated at depth in the crust.

These problems have been pursued in the Oslo rift of southeastern Norway. Previous studies of the Oslo rift rocks, based on trace elements, Rb-Sr systematics, and Sm-Nd data on a limited number of samples, suggest that crustal contamination is important. There is, however, disagreement between different authors as to the nature of the mantle source, and

the extent of crustal contamination. The following hypotheses have been published:

(a) the basaltic rocks in the Oslo rift are derived from a common mantle source (with Th/U ≈ 3.9 and ϵ_{Sr}^i ≈ −3.6, t = 290 Ma) by different degrees of partial melting (SUNDVOLL, 1978a,b);

(b) the strongly alkaline Skien basalts, the mildly alkaline Vestfold basalts, and the Krokskogen tholeiite have different ϵ_{Nd}^i-ϵ_{Sr}^i characteristics ((+1.5, −15), (+3, +20) and (−0.7, +18) respectively), suggesting that three different source regions were involved in their formation, most likely a mantle source with ϵ_{Nd}^i > +4, suffering contamination in the deep crust to form the Skien basalts, and contamination in the shallow crust to form the Krokskogen tholeiite (JACOBSEN and WASSERBURG, 1978);

(c) larvikites in the Larvik batholith (Fig. 1) and their extrusive equivalents formed by fractional crystallization from basaltic melts originating from the same source which gave rise to the basalts (RAADE, 1978; SUNDVOLL, 1978a,b; NEUMANN, 1980);

(d) small amounts of crustal contamination may be important in the formation of the intermediate plutonic and volcanic rocks (larvikites and rhomb porphyry lavas) (JACOBSEN and WASSERBURG, 1978);

(e) a series of syenites relatively poor in LILE (*e.g.*, nordmarkites in the Sande and Nittedal cauldrons) were derived by anatexis from, or were strongly contaminated by, a part of the intermediate or deep crust with Th/U: 4.5–6.5, and $^{87}Sr/^{86}Sr$ ratios of 0.705–0.706 in Permian time (RAADE, 1978; RASMUSSEN *et al.*, 1987);

(f) syenites and granites from Hurdal with strong LILE-enrichment and initial Sr isotope ratios of 0.704–0.716 have been contaminated to varying degrees in the upper crust (TUEN, 1985).

Furthermore, Sm-Nd isotopic data suggest that the upper mantle under southwestern Scandinavia may have had a relatively short history of depletion, beginning about 1700 Ma ago (MEARNS, 1986; MEARNS *et al.*, 1986).

This study presents Sr, Nd and Pb isotopic data and Rb, Sm, Th and U abundances on selected groups of Oslo rift rocks. These groups cover the compositional range found in the rift, and also include rocks for which different modes of origin have been suggested in previous papers.

The objectives for this work were:

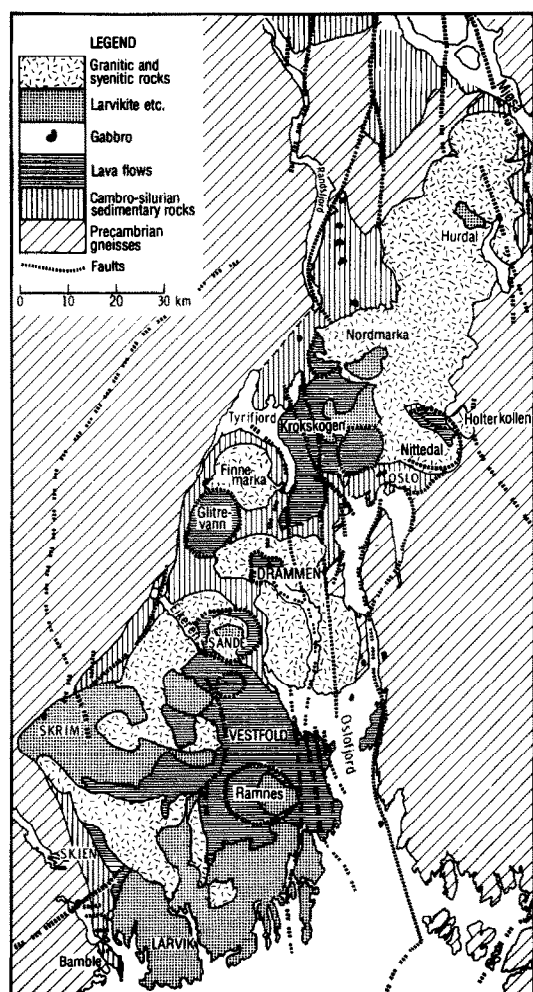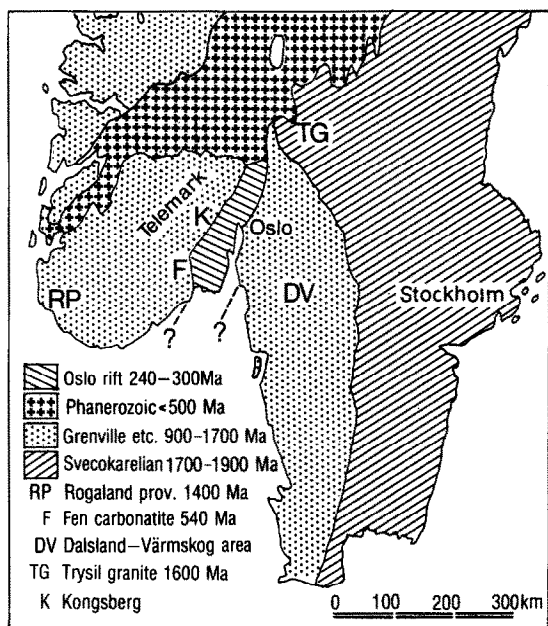* *Present address:* Oljedirektoratet, 4001 Stavanger, Norway.

FIG. 1a. Generalized geologic terrain map of southern Scandinavia (after PATCHETT et al., 1986), showing the setting of the Oslo rift. b. Generalized map of the Oslo rift based on maps by OFTEDAHL (1960), and RAMBERG and LARSEN (1978).

1) to test earlier hypotheses for the origin of the Oslo rift magmatic rocks on the basis of their Sr-Nd-Pb isotopic relations;

2) to evaluate the extent of crustal contamination in these rocks;

3) to establish the isotopic characteristics of the mantle source region(s):

4) to provide the basis for a discussion of the evolution of the lithosphere in southern Scandinavia in Palaezoic time.

GEOLOGY

Magmatism in the Oslo rift started about 300 Ma ago with extrusion of a series of basalts designated B_1 (OFTEDAHL, 1952). These basalts show a general pattern of decreasing thickness and alkalinity from south to north. B_1 in the Skien area in the southern part of the Oslo Region (Fig. 1b), consists of a >1500 m thick sequence of nephelinites, ankaramites and basanites. In the Vestfold area, it comprises mildly silica-undersaturated to -saturated ankaramites, alkali basalts and trachybasalts (170–180 m thick in Vestfold, 800–1500 m east of the Oslofjord), while at Krokskogen (north of Oslo), it is restricted to a single flow of aphyric quartz tholeiite (LARSEN, 1978; SEGALSTAD, 1979; ØVERLI, 1985; SCHOU-JENSEN and NEUMANN, 1987). Younger lavas comprise basalts, rhomb porphyry lavas, ignimbrites and rhyolites. Magmatism ended with the emplacement of large monzonitic (larvikites), syenitic and granitic batholiths, the youngest of which is about 240 Ma old (SUNDVOLL, 1978a; TUEN, 1985).

The samples of this study belong to rock series whose petrography, major element chemistry and mineral chemical variations have been published previously (or described in theses). Trace element data are available for some of the rocks. Samples were selected to be representative of each rock series. Brief sample descriptions are given in the Appendix, together with references to the more detailed descriptions.

ANALYTICAL PROCEDURES

The analyses were carried out in two different laboratories. Rb-Sr and Sm-Nd on the Oslo rift whole rock samples were determined at the Mineralogical-Geological Museum in Oslo, Norway, while U-Th-Pb analyses were obtained at the University of California, Santa Barbara (UCSB).

Sm-Nd and Rb-Sr

The chemistry and mass spectrometry procedures followed in Oslo have been described by MEARNS (1986).

Laboratory total system blanks are typically $\ll 1$ ng for both Nd and Sr and are thus negligible for this study. Blank concentrations were measured by isotope dilution using mixed ^{87}Rb-^{84}Sr and ^{149}Sm-^{148}Nd spikes.

Isotopic ratios were measured on a VG 354 fully automated 5-collector instrument. Laboratory values for standards given by MEARNS (1986) are BCR1 (13 duplicate analyses): $^{147}Sm/^{144}Nd$ = 0.1384 ± 2, $^{143}Nd/^{144}Nd$ = 0.512650 ± 20 and $^{145}Nd/^{144}Nd$ = 0.348395 ± 28 (all 2σ mean). Nd isotopic ratios are normalised to $^{146}Nd/^{144}Nd$ = 0.721900. 20 single analyses of Johnson and Matthey Nd_2O_3, batch no. S819093A: $^{143}ND/^{144}Nd$ = 0.511125 ± 8 and $^{145}Nd/^{144}Nd$ = 0.348412 ± 8 (2σ mean). 30 single analyses of NBS 987: $^{87}Sr/^{86}Sr$: 0.710227 ± 21 (2σ mean).

The decay constant used for ^{147}Sm = 6.54 $*$ 10^{-12} y^{-1}. ϵ_{Nd} and ϵ_{Sr} values are calculated relative to CHUR with present day $^{147}Sm/^{144}Nd$ = 0.1967, $^{143}Nd/^{144}Nd$ = 0.512647, $^{87}Rb/^{86}Sr$ = 0.0827, and $^{87}Sr/$

^{86}Sr = 0.7045 (ALLÈGRE *et al.*, 1983; JACOBSEN and WASSERBURG, 1984), using Rb-Sr ages to correct for *in situ* radiogenic ^{143}Nd.

U-Th-Pb

The chemistry and mass spectrometry procedures followed at UCSB are described by TILTON *et al.* (1986), the only difference being that for the Oslo rift, isotopic data were collected on whole rock samples, not mineral separates.

Blanks for the samples were about 0.2 ng for Pb, and 10–30 pg for U and Th. 23 replicate measurements of NBS standard 981 gave ^{204}Pb/^{204}Pb = 0.05904 ± 8 (2σ mean), ^{207}Pb/^{206}Pb = 0.91464 ± 32 (2σ mean), and ^{208}Pb/^{206}Pb = 2.1667 ± 15 (2σ mean) after applying a fractionation correction of 0.12% per mass unit. The decay constants used are for ^{238}U: 0.155125 × 10^{-9} y^{-1}, for ^{225}U: 0.98485 × 10^{-9} y^{-1}, and ^{232}Th: 0.049475 × 10^{-9} y^{-1}.

RESULTS

The analytical results are given in Tables 1 and 2. Initial isotopic ratios and ε'-values for the Oslo rift rocks are calculated on the basis of Rb-Sr age determinations by SUND-VOLL (1978a), TUEN (1985), and RASMUSSEN *et al.* (1987).

Sr and Nd isotopes

Sr and Nd initial ratios of the Oslo rift rocks vary considerably (Fig. 2, Table 1). None correspond to the character on the strongly depleted MORB reservoir. The most depleted character, *i.e.*, highest ϵ'_{Nd} and lowest ϵ'_{Nd}, is found among the mildly and strongly alkaline basalts (F15, F16, F21, FZ2), the larvikites (except sample 508), and 3 of the 4 analyzed rhomb porphyry lavas. These rocks cluster in an area bounded by ϵ'_{Nd}-values of +3.3 and +4.2 and ϵ'_{Sr}-values of −3 and −16 (Fig. 2). The rest of the mildly alkaline (Vestfold) basalts (FA2, FA3, F8A, F23, FX2), one rhomb porphyry lava (PA7) and the Krokskogen tholeiite analyzed by JACOBSEN and WASSERBURG (1978) define a trend towards considerably lower ϵ'_{Nd}- and somewhat higher ϵ'_{Sr}-values. This trend lies close to the less depleted part of the "mantle array" defined by MORB and ocean island (OIB) or continental flood basalts (*e.g.*, O'NIONS *et al.*, 1977; DEPAOLO and WASSERBURG, 1977, 1979; ALLÈGRE *et al.*, 1983). The mildly alkaline Vestfold basalt analyzed by JACOBSEN and WASSERBURG (1978) falls off the "Vestfold trend" defined by the samples of this study. The strongly alkaline cpx-basalts from Skien, including the sample analyzed by JACOBSEN and WASSERBURG (1978), form a separate group (ϵ'_{Nd}: +0.7–+2.1, ϵ'_{Sr}: −14–−15), whereas the Skien cpx-plag-basalt fall within the field of the most depleted Oslo rift samples. No clear correlation is found between degree of alteration and position in the ϵ'_{ND}-ϵ'_{Sr} diagram. There is also no strong correlation with major element composition.

The syenites and granites show a wide scatter ranging from the general area of the basalt trend (Sande and Nittedal syenites, Hurdal granite ET3: ϵ'_{Sr} = −3 to + 21, ϵ'_{Nd} = +3.0 to −3.3) to high positive ϵ'_{Sr} values (other Hurdal units: ϵ'_{Sr} = +4 to +226, ϵ'_{Nd} = +0.8 to −1.7) (Table 1, Fig. 2). The wide scatter and high ϵ'_{Sr}-values observed among the Hurdal rocks suggest addition of radiogenic strontium. Even small amounts of radiogenic Sr would change the ^{87}Sr/^{86}Sr ratios of the Sr-poor Hurdal silicic rocks significantly.

Pb-isotopes

In the ^{206}Pb/^{204}Pb-^{238}U/^{204}Pb and ^{208}Pb/^{204}Pb-^{232}Th/^{204}Pb diagrams (Fig. 3) some groups of rocks fall close to reference isochrons which slopes correspond to the known ages of these rocks. These are the Larvik larvikites and the rhomb porphyry lavas (except PA7) (relatively high Pb initial ratios of (^{206}Pb/^{204}Pb), ≈ 19.2 and (^{208}Pb/^{204}Pb), ≈ 39.0–39.2), the Sande syenites and the Nittedal syenites (considerably lower initial ratios of ≈ 18.6 and 38.0–38.3 respectively). Loss of uranium does not appear to be a problem in these rocks.

The basalts show the same kind of systematics in the ^{206}Pb/^{204}Pb-^{238}U/^{204}Pb and the ^{206}Pb/^{204}Pb-^{232}Th/^{204}Pb diagrams: the Horten basalts F15, F16, F21 and F23 have the highest Pb isotopic ratios and fall close to reference isochrons with initial ratios similar to those found for the larvikites. The rest of the basalts fall well below the "larvikite isochron" in both systems. Reference isochrons drawn through the samples S41, S47, FZ2, OB8 and OB87 give initial ratios similar to those of the Sande and Nittedal syenites (18.3 and 38). The consistent behavior of the basalts in the U-Pb and Th-Pb isotope plots (Fig. 3) suggests that alteration occurred soon after crystallization, and that subsequent gains or losses of Th, U and Pb have been small.

The Hurdal silicic rocks show considerable scatter in both the U-Pb and the Th-Pb isotopic systems. These rocks thus appear to have been open to U, Th and/or Pb at some stage after formation. Another possibility is that they have been subjected to contamination by a variety of crustal rocks, causing the initial ratios to be variable.

Estimated Pb isotopic initial ratios are shown in Fig. 4. The Hurdal samples are omitted from the figures involving initial Pb isotopic ratios (Figs. 4, 5 and 7) as they may not give reliable initial ratios. In the (^{207}Pb/^{204}Pb)$_i$-(^{206}Pb/^{204}Pb)$_i$ diagram, the rest of the rocks define a wide band parallel to a 290 Ma secondary isochron with μ ≈ 8.2. In the (^{208}Pb/^{204}Pb)$_i$-(^{206}Pb/^{204}Pb)$_i$ system, most of the rocks fall close to ZARTMAN and DOE's (1981) evolution line for the upper crust, with a tail towards the high (^{208}Pb/^{206}Pb)$_i$-low (^{206}Pb/^{204}Pb)$_i$ area believed to be typical of the lower crust (*e.g.*, ZARTMAN and DOE, 1981).

There is, furthermore, a simple correlation between ϵ'_{Nd}-ϵ'_{Sr} and Pb data. The highest initial Pb isotopic ratios are found among those basalts, larvikites and rhomb porphyry lavas which have the highest ϵ'_{Nd}- and lowest ϵ'_{Sr}-values (Tables 1 and 2), that is to say they show the most depleted ϵ_{Nd}-ϵ_{Sr} character.

DISCUSSION

The isotopic data on Oslo rift rocks presented above suggest a complex origin for these rocks, involving mixing between materials from isotopically different source regions. The discussion presented below is aimed at characterizing these source regions with respect to Nd, Sr and Pb isotopes on the basis of available information on the composition of different parts of the mantle and crust, and hypothetical mixing calculations.

Nd and Sr isotopic relations

In order to explain the ϵ_{Nd}-ϵ_{Sr} relations observed among the analyzed Oslo rift rocks it is necessary to call upon at

Table 1. The isotopic compositions of Sr and Nd and concentrations of Rb, Sr, Sm, and Nd in magmatic rocks in the Permian Oslo rift. (Rb-Sr age determinations by Tuen, 1985, and Rasmussen et al., 1987).

Sample	Concentr. (ppm) Rb	Sr	$\frac{^{87}Rb}{^{86}Sr}$	$\frac{^{87}Sr}{^{86}Sr}$	(σ)	Concentr. (ppm) Sm	Nd	$\frac{^{147}Sm}{^{144}Nd}$	$\frac{^{143}Nd}{^{144}Nd}$	(σ)	ε^t_{Sr}	ε^t_{Nd}
Strongly alkaline basalts (B₁), Skien, assumes age 290 Ma												
S01B						12.4	75.1	0.10016	0.512484+7			+0.5
S36B	33.7	825	0.1183	0.704580+16		34.4	213	0.09813	0.512498+4		-13.7	+0.7
S41	24.6	633	0.1124	0.703578+14		8.2	47.0	0.10650	0.512584+4		-14.8	+2.1
S47	82.8	974	0.2461	0.704741+14		8.4	42.4	0.12017	0.512685+5		-6.2	+3.6
Mildly alkaline basalts (B₁), Vestfold, assumed age 290 Ma												
FA2	33.7	825	0.1183	0.704580+16		13.8	73.2	0.11490	0.512595+4		-1.0	+2.0
FA3	35.7	1047	0.0985	0.704514+14		16.4	87.3	0.11415	0.512606+4		-0.7	+2.4
F8A	36.4	911	0.1156	0.705061+10		13.5	74.8	0.10961	0.512552+5		+6.0	+1.4
F15	32.2	1189	0.0783	0.704037+10		17.7	96.1	0.11202	0.512689+6		-6.3	+3.9
F16	42.7	986	0.1254	0.704364+10		16.5	88.8	0.11289	0.512689+5		-4.4	+3.9
F21	98.3	1615	0.1762	0.704736+10		24.8	144.9	0.10428	0.512631+6		-2.1	+3.1
F23	104.9	1649	0.1844	0.704770+10		23.5	136.1	0.10514	0.512616+5		-2.1	+2.8
FX2	44.9	982	0.1321	0.705143+10		11.6	63.5	0.11166	0.512522+9		+6.2	+0.7
FZ2	22.8	656	0.1005	0.704315+10		8.7	45.1	0.11713	0.51267+ 6		-3.7	+3.4
Quartz tholeiite (B₁), Krokskogen, assumed age 290 Ma												
OB8	13.0	372	0.1012	0.70572+ 5							+22.2	
Larvikite, Larvik, age 277 +3 Ma												
2	87.5	720	0.3515	0.705393+10		13.5	82.7	0.09924	0.512655+ 5		-2.5	+3.6
4	97.0	883	0.3176	0.705010+10		12.4	79.4	0.09492	0.512633+ 5		-6.1	+3.4
9	87.5	807	0.3136	0.705202+8		14.9	93.2	0.09703	0.512649+15		-3.1	+3.6
29	119	805	0.4265	0.705306+10		12.9	83.6	0.09373	0.512673+12		-8.0	+4.2
448	91.0	631	0.4174	0.705639+12		19.7	122.1	0.09807	0.512644+ 5		-2.8	+3.5
498	150.4	826	0.5266	0.705619+10		20.7	122.9	0.10244	0.512668+ 4		-9.2	+3.8
506	176	876	0.5819	0.705351+16		20.3	116.2	0.10641	0.512683+ 5		-16.2	+3.9
508	207	228	2.6292	0.714468+16		24.1	145.1	0.10135	0.512660+ 5		-2.5	+2.2
Rhomb porphyry lavas, Krokskogen, assumed age 280 Ma												
PA7	166	919	0.5241	0.706313+10		15.8	95.6	0.10065	0.512586+4		+0.8	+1.4
PA21	133	777	0.4965	0.705823+10		25.4	146.3	0.10583	0.512663+5		-4.6	+3.6
PA25	151	1340	0.3264	0.705079+ 8		21.2	134.1	0.09629	0.512620+5		-5.6	+3.1
PA29	138	1556	0.2558	0.704846+10		20.3	127.7	0.09699	0.512642+9		-5.9	+3.5
Syenite, Sande cauldron, assumed age 270 Ma												
R302	149	51.4	8.4064	0.73798 +9		11.3	69.6	0.09858	0.512628+7		+1.1	+3.0
R309	110	23.3	14.980	0.76278 +9		18.7	87.5	0.13007	0.512621+5		-3.1	+1.8
Syenite, Nittedal cauldron, age 252 + 3 Ma												
R176	88.2	468	0.5459	0.706795+10		15.7	95.1	0.10071	0.512565+12		+9.2	+1.5
R180	81.6	2.7	91.81	1.03480 +1		15.4	130.1	0.07193	0.512555+5		+21.2	+2.2
R182	74.0	10.4	20.70	0.77929 +9		22.8	55.0	0.25236	0.512568+4		+12.6	-3.3
Syenite porphyry, Hurdal, assumed age 240 Ma												
ET5IA	184	184	2.8902	0.71592 +3							+26	
ET5IF	169	236	2.0755	0.71209 +3							+11	
Syenite, Hurdal, age 246 + 5 Ma												
ET8A	106	101	3.0581	0.716252+14		13.8	92.5	0.09065	0.512475+6		+16.6	+0.0
ET8E	101	362	0.8076	0.708105+12		5.7	38.7	0.08985	0.512428+6		+14.6	-0.9
Syenite, Hurdal, age 248 + 4 Ma												
ET9A	216	10	52.847	0.89359+11		13.3	74.4	0.10900	0.512540+10		+42	+0.7
ET9D	192	8	63.765	0.93532+ 7		9.8	56.6	0.10588	0.512524+10		+88	+0.5
ET9E	197	18	30.575	0.81722+ 3		12.1	75.9	0.09731	0.512519+ 8		+73	+0.7
Granite, Hurdal, age 242 + 12 Ma												
ET1D	245	65.3	10.909	0.752060+12		1.9	13.0	0.08912	0.512390+3		+151	-1.7
ET1E	298	37.3	23.375	0.799954+18		0.86	7.5	0.06949	0.512367+2		+226	-1.6
Granite, Hurdal, age 248 + 6 Ma												
ET3C	257	93	7.997	0.73256+ 5		4.2	27.8	0.09169	0.512450+ 8		+51	-0.5
ET3E	218	101	6.245	0.72633+ 6		4.1	26.3	0.09581	0.512462+10		+8.0	-0.4
Granite porphyry, Hurdal, assumed age 240 Ma												
ET5IID	166	50	9.539	0.73842+ 5							+23	
ET5IIE	169	55	8.775	0.73563+ 9							+21	
Granite, Hurdal, age 267 + 3 Ma												
ET10A	167	32	14.969	0.76254+ 8		12.4	76.4	0.09872	0.512479+ 8		+21	-0.1
ET10C	171	35	14.3554	0.76038+11		10.8	63.0	0.10429	0.512424+10		+25	-1.2
ET10E	196	22	25.6787	0.80371+10		10.1	60.6	0.10164	0.512424+12		+28	-1.1

Table 2. The isotopic composition of Pb and concentrations of Pb, U and Th in magmatic rocks from the Permian Oslo rift. (Rb-Sr age determinations by Tuen, 1985, and Rasmussen et

Sample	Concentrations (ppm)			Atomic ratios				
	Pb	U	Th	$\frac{206Pb}{204Pb}$	$\frac{207Pb}{204Pb}$	$\frac{208Pb}{204Pb}$	$\frac{238U}{204Pb}$	$\frac{232Th}{238U}$
Strongly alkaline basalts (B_1), Skien, assumed age 290 Ma								
S01B	4.75	1.92	6.49	20.554	15.727	40.204	27.2	3.49
S36B	3.39	2.35	8.66	20.723	15.733	40.939	47.1	3.80
S41	4.42	1.17	2.95	19.400	15.634	38.687	17.0	2.61
S47	5.76	0.723	2.59	18.615	15.635	38.456	8.0	3.69
Mildly alkaline basalts (B_1), Vestfold, assumed age 290 Ma								
FA2	6.55	2.79	5.83	18.963	15.598	39.305	27.6	2.16
FA3	6.57	1.29	6.92	18.902	15.619	39.591	12.7	5.57
FA8A	9.56	1.29	7.09	18.661	15.610	39.506	8.7	5.70
F15	6.38	2.34	8.67	20.350	15.652	40.245	24.5	3.82
F16	5.88	2.11	7.83	20.388	15.707	40.413	24.0	3.84
F21	9.17	2.89	13.08	20.104	15.706	40.439	21.0	4.69
F23	7.89	3.60	12.69	20.605	15.701	40.548	30.7	3.64
FX2	7.25	1.46	6.18	18.654	15.619	39.052	13.0	4.36
FZ2	4.57	0.810	3.45	18.859	15.644	38.774	11.4	4.41
Quartz tholeiite (B_1), Krokskogen, assumed age 290 Ma								
O88	15.03	0.539	2.11	18.393	15.625	38.187	2.27	4.04
O887	5.24	0.469	2.00	18.506	15.582	38.434	5.69	4.41
Larvikite, Larvik, age 277 ± 3 Ma								
2	8.65	2.98	11.57	20.285	15.692	40.195	23.0	4.01
4	7.98	4.46	16.08	20.962	15.714	41.002	38.0	3.73
9	7.76	2.92	10.43	20.043	15.698	40.117	25.0	3.69
29	9.09	4.78	18.73	20.609	15.698	40.791	35.5	4.05
448	8.98	4.82	17.24	20.616	15.683	40.544	36.1	3.70
498	8.97	6.12	23.90	21.093	15.711	41.390	46.7	4.03
506	8.79	4.90	20.34	20.597	15.679	40.906	37.7	4.29
508	9.78	7.39	30.51	21.508	15.725	42.102	52.5	4.26
Rhomb porphyry lavas, Krokskogen, assumed age 280 Ma								
PA 7	9.38	3.48	26.80	19.680	15.649	41.029	24.8	7.97
PA25	12.35	7.28	26.40	20.841	15.724	41.060	40.1	3.75
PA29	12.21	7.13	25.68	20.893	15.697	40.903	39.6	3.72
Syenite, Sande cauldron, assumed age 270 Ma								
A2	13.60	2.21	6.78	19.075	15.632	38.643	10.5	3.17
A4	15.04	2.01	9.87	19.059	15.664	38.809	8.61	5.08
A40	13.01	2.70	10.24	19.293	15.624	38.925	13.4	3.93
R302	6.65	1.16	5.56	19.427	15.643	39.134	11.4	4.94
R309	7.57	2.15	5.90	19.385	15.649	38.948	18.4	2.83
Syenite, Nittedal cauldron, age 252 ± 3 Ma								
R176	14.25	2.24	9.00	18.980	15.602	38.866	10.14	4.15
R180	5.93	1.56	9.43	19.377	15.618	39.627	17.22	6.24
R182	4.39	1.31	8.39	19.635	15.647	40.290	19.77	6.62
R183	9.12	1.82	11.05	19.117	15.607	39.516	12.98	6.28
Syenite porphyry, Hurdal, assumed age 240 Ma								
ET5IA	9.53	4.93	17.72	19.560	15.623	39.286	33.8	3.71
ET5IF	14.15	13.16	18.29	19.771	15.642	39.836	61.4	1.44
Syenite, Hurdal, age 246 ± 5 Ma								
ET8A	10.64	2.27	13.83	19.384	15.621	39.544	14.0	6.30
ET8E	17.41	1.55	6.93	19.078	15.620	38.894	5.73	4.63
Granite, Hurdal, age 242 ± 12 Ma								
ET1A	9.53	4.93	17.72	19.560	15.623	39.286	33.8	3.71
ET1D	18.80	24.4	39.94	23.013	15.803	40.427	90.1	1.69
Granite porphyry, Hurdal, assumed age 240 Ma								
ET5IID	6.16	11.22	41.33	22.412	15.772	45.253	133	3.81
ET5IIE	8.32	9.48	43.01	20.989	15.712	42.770	80.2	4.69

least three "reservoirs" with distinct isotopic characteristics: one (M) lies on, or close to, the "mantle array" in the ($+\epsilon_{Nd}$, $-\epsilon_{Sr}$) quadrangle; the others lie in the ($-\epsilon_{Nd}$, $+\epsilon_{Sr}$) field and have similar ϵ_{Nd}, but quite different ϵ_{Sr}. Mixing in various proportions between melts or materials with these isotopic characteristics can produce the whole range of ϵ_{Nd}-ϵ_{Sr} relations observed in the Oslo rift rocks.

The ϵ_{Nd}-ϵ_{Sr} relations defined by the "mantle array" have been interpreted as the result of mixing between melts originating in the strongly depleted MORB-source (SDM) (ϵ_{Nd} > 10, ϵ_{Sr} < -30) and melts from an undepleted source deeper in the mantle ($\epsilon_{Nd} \approx 0$, $\epsilon_{Sr} \approx 0$) (e.g., DePAOLO and WAS-

SERBURG, 1979; DePAOLO, 1980; ALLÈGRE et al., 1983). However, models involving mixing of depleted with "enriched" mantle sources (e.g., McCULLOCH et al., 1983) or multicomponent models (e.g., ZINDLER et al., 1982; ZINDLER and HART, 1986) provide more likely explanations for the observed trend.

The clustering of basalts, larvikites and rhomb porphyry lavas from different parts of the rift within a limited range of ϵ_{Nd}-ϵ_{Sr} values, suggests that they reflect the isotopic characteristics of a specific mildly depleted source, rather than accidental mixing between melts from two different source regions. The suggestion of a mildly depleted source (or sources) for continental magmatism is also supported by the fact that $^{143}Nd/^{144}Nd$ ratios above 0.51305 (corresponding to a present day $\epsilon_{Nd} \approx 8$) appears to be totally absent in continental volcanic provinces (WÖRNER et al., 1986; HART et al., 1987). MEARNS (1986) has, furthermore, presented evidence that Scandinavia may be divided into geographic regions (e.g., central Sweden, W. Norway and S. Norway), within each of which the Proterozoic mafic magmatic rocks define an ϵ_{Nd}-time trend considerably less depleted than DePAOLO's (1981) "depleted mantle trend" (Fig. 5). Mearns' evolutionary trend for S. Norway is also in general agreement with isotopic data on a series of rocks from the 540 Ma old Fen carbonatite complex (ANDERSEN, 1987). According to Andersen, his data suggest that the magmatic system at Fen was dominated by a component derived from a moderately depleted volume of the upper mantle ($\epsilon_{Sr} \le -16$, $\epsilon_{Nd} \ge +4$, for $t = 540$ Ma). As shown in Fig. 5, the most depleted group of Oslo rift basalts and larvikites fall on, or close to, the evolutionary trend for S. Norway.

From the above considerations it is concluded that the mantle source (M) involved in the formation of the Oslo rift rocks had a mildly depleted isotopic character similar to that of the most depleted Oslo rift basalts, larvikites and rhomb porphyry lavas (M: $\epsilon_{Nd} \approx +3.3$ to $+4.2$, $\epsilon_{Sr} \approx -3$ to -16) (Fig. 2). The same general isotopic characteristics as those found in the "uncontaminated" Oslo rift rocks are found in basalts in the Eifel volcanic field, West Germany, and in some oceanic islands (WÖRNER et al., 1986; WRIGHT and WHITE, 1987).

The existence of a ϵ_{Nd}-time trend for S. Norway, implies that the mildly depleted mantle source has retained its position relative to the crust over a long period of time. It must therefore be located in the lower lithosphere.

The reservoirs in the ($-\epsilon_{Nd}$, $+\epsilon_{Sr}$) quadrant are believed to represent different parts of the crust.

High positive ϵ_{Sr} is usually regarded as typical of the upper crust (e.g., HAMILTON et al., 1979; DePAOLO, 1980, 1981; ALLÈGRE et al., 1983). An average of granitic gneisses, granites and amphibolites in the Precambrian southern Telemark area, southwest of the Oslo Region (Fig. 1) has been used as a model for the pre-Permian upper crust in southeast Norway. This gives $\epsilon_{Nd} = -5.9$, Nd = 76 ppm, $\epsilon_{Sr} = +748$, Sr = 120 ppm for $t = 290$ Ma (referred to as ST below) (ANDERSEN, 1987). Mixing by assimilation of upper crustal rocks in basaltic magmas derived from a mildly depleted mantle source is indicated in Fig. 2 by the hypothetical mixing trend B-ST.

Contamination in the intermediate to lower part of the crust during the Oslo rifting event, is highly likely. The crust
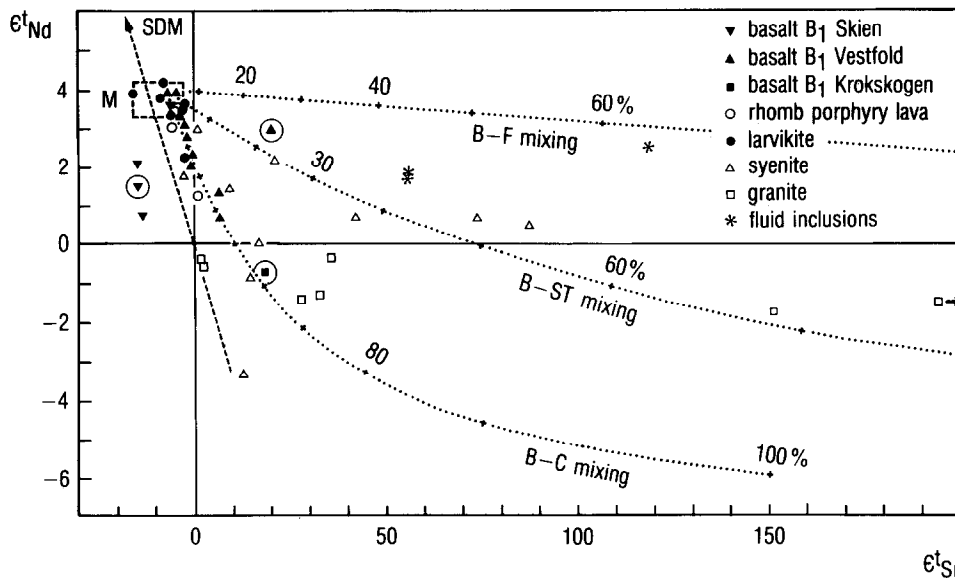
FIG. 2. Initial ϵ_{Nd}-ϵ_{Sr} relations among the analyzed Oslo rift rocks. Circled points: data by JACOBSEN and WASSERBURG (1978). Dashed line: "mantle array" (*e.g.*, O'NIONS *et al.*, 1977; DEPAOLO and WASSERBURG, 1977, 1979; ALLÈGRE *et al.*, 1983). Also shown are mixing relations involving various reservoirs which may be involved in the formation of these rocks. The degree of crustal contamination is marked with intervals of 10%. SDM: the strongly depleted source of MORB ($\epsilon_{Nd} > +10$, $\epsilon_{Sr} < -30$) (DEPAOLO, 1981; ALLÈGRE *et al.*, 1983); M (dashed box): a mildly depleted, somewhat heterogeneous source; ST: a model for the pre-Permian upper crust in southeast Norway, based on the age-corrected average of Precambrian granitic gneisses, granites and amphibo lites in southern Telemark (T. ANDERSEN, pers. commun., 1986) ($\epsilon_{Sr} = +748$, Sr = 119 ppm, $\epsilon_{Nd} = -5.9$, Nd = 76 ppm); F: a model for a Permian upper crustal fluid, based on data for ST and data by NORMAN and MEARNS (pers. commun., 1987) on fluid inclusions in the Drammen granite (Fig. 1) ($\epsilon_{Sr} = +748$, Sr = 120 ppm, $\epsilon_{Nd} = -5.9$, Nd = 7 ppm); C: a possible composition of the intermediate to lower crust, differing from ST only with respect to ϵ_{Nd}.

under the Oslo rift is about 33 km deep (TRYTI and SPELLEVOLL, 1977). A positive gravity anomaly along the rift axis is interpreted as indicating the presence of large masses of dense cumulates and residues after anatectic melting in the intermediate to deep crust under the rift (RAMBERG, 1976; NEUMANN *et al.*, 1986; WESSEL and HUSEBYE, 1987). These data are supported by fluid inclusion studies of olivine-clinopyroxenite xenoliths in a basalt flow at Krokskogen which give a minimum pressure of formation of 5.5 kbar (NEUMANN *et al.*, 1988). Finally, the major and trace element relations among the basaltic and monzonic rocks may best be explained as the result of crystallization at depths of 7–10 kbar where the stability field of pyroxene is significantly expanded relative to that of plagioclase (NEUMANN, 1980; NEUMANN *et al.*, 1985). If large volumes of hot magma are stored at depth in the crust over long periods of time, and additional heat is released through crystallization, then assimilation of, and anatexis in, the side rock can hardly be avoided. We propose that the reservoir characterized by low positive ϵ_{Sr} and negative ϵ_{Nd} values was located in the intermediate to lower crust.

Isotopic studies of metamorphic and igneous basement rocks and crustal xenoliths show large isotopic heterogeneities within the crust, with a clear tendency for the lower crust to be depleted in Rb relative to the upper crust (*e.g.*, DEPAOLO, 1980, 1981; ALLÈGRE *et al.*, 1983; DOWNES, 1984; ESPERANCA *et al.*, 1985). Available Sr isotopic data on the Sveconorwegian province of SW Scandinavia, including 900 to 1600 Ma old suborogenic and postorogenic granites, and amphibolite to granulite grade metamorphic rocks, have been compiled by SMALLEY (1983). These data reveal a SW Scan-

dinavian crust with Sr isotopic ratios ranging from about 0.703 to 0.72 or more, 900 to 1000 Ma ago. The subsequent evolution depends on the local Rb/Sr ratios. Little is known about the Nd isotopic character of the SW Scandinavian crust. However, DEPAOLO (1981) has proposed that ϵ_{Nd} decreases with increasing age of crustal formation. The ϵ_{Nd}^t value of about -6 (for $t = 290$ Ma) estimated for the southern Telemark composite is consistent with the accepted time of crustal accretion in south Norway, that is 1700–2000 Ma ago. Such a value may also be generally representative for deeper parts of the crust. Contamination of mildly depleted basaltic magmas in the intermediate to low crust is visualized by the hypothetical mixing trend B-C in Fig. 2.

Evidence of hydrothermal activity is abundant in the Hurdal intrusive complex, and may also be responsible for some of the alteration observed in the basaltic rocks (see description above). Contamination of basalt due to hydrothermal activity dominated by crustal fluids is indicated by the line B-F, where F has the same isotopic composition as ST, and 120 ppm Sr, but only 7 ppm Nd. Contamination of a granite (Sr $\leq$ 100 ppm, Nd: 50–100 ppm) through hydrothermal alteration would lead to about one order of magnitude stronger increase in ϵ_{Sr} per percent contamination than that which is shown by the line B-F in Fig. 2. Data on fluid inclusions in the Drammen granite (NORMAN and MEARNS, pers. commun., 1987), corrected to Permian age, are also shown in Fig. 2 for comparison.

Most of the Oslo rift rocks fall in an area of the ϵ_{Nd}^t-ϵ_{Sr}^t diagram (Fig. 2) which is compatible with contamination of mantle derived magmas by crustal rocks with moderately
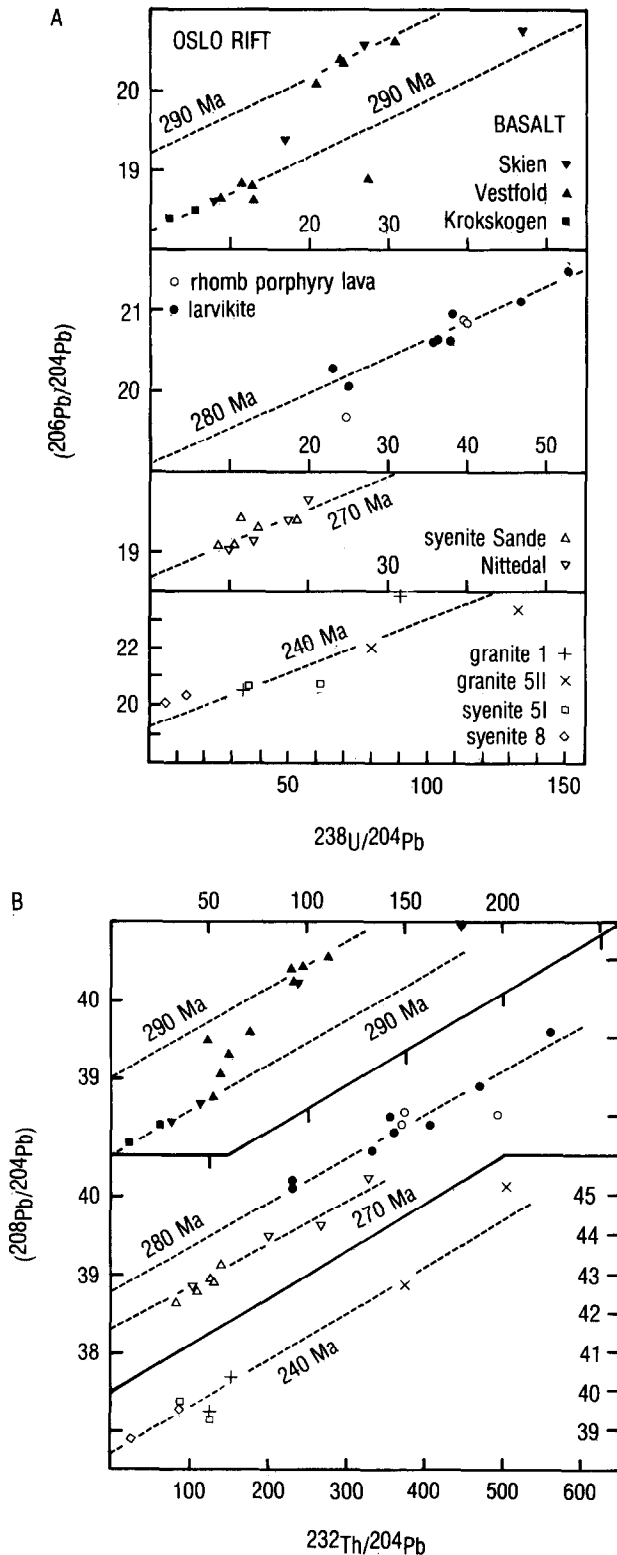
These high numbers are a consequence of the model which assumes assimilation of Sr-poor crustal rocks, or mixing with Sr-poor anatectic melts. Low Sr-concentrations will occur if the anatectic melts are extracted from rocks with plagioclase in the residue.

The strong variations in ϵ_{Sr} with small variations in ϵ_{Nd} exhibited by the Hurdal syenites and granites require contamination in the upper crust. Hydrothermal fluids may be important as contaminating agents, but this would require that the rocks were "undepleted" to "mildly enriched" before the hydrothermal activity started.

A mixing model involving contamination of magma from a SDM type source leads to the conclusion that *all* the analyzed Oslo rift rocks have been strongly contaminated in the crust.

Pb isotopic relations

The contamination model outlined above can also be tested on the Pb isotopic system (Fig. 6). The samples believed to be uncontaminated in the ϵ_{Nd}-ϵ_{Sr} system, are used to define M in the Pb isotopic system (shown as a dashed box in Fig. 6). Available lead isotopic data on Fen rocks are believed to be influenced by upper crustal contamination (ANDERSEN and TAYLOR, 1987), and can therefore not be used to model the mantle under southern Norway with respect to Pb isotopes. ZARTMAN and DOE's (1981) Plumbotectonics I model,

FIG. 3. Pb-U (a) and Pb-Th (b) isotopic relations among Oslo rift magmatic rocks. Dashed lines show reference isochrons based on Rb/Sr age determinations fitted to these plots.

high ϵ_{Sr} in Permian time. The B-C model suggests about 40% contamination for the most highly contaminated Vestfold basalts (F8A and FX2), and possibly as much as 60% for the Krokskogen tholeiite and some of the syenites and granites.
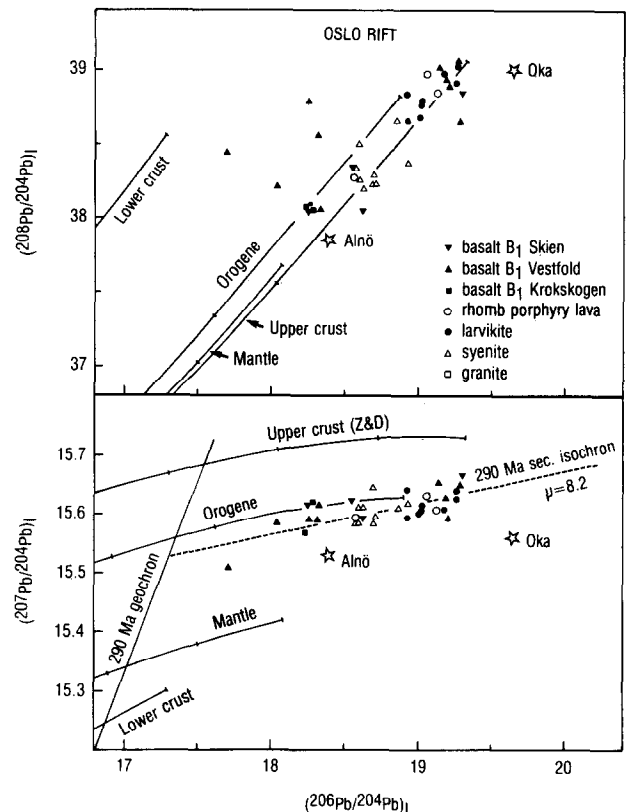
FIG. 4. Initial lead isotope relations among Oslo rift rocks. Evolution trends for the mantle, orogene, and lower and upper crust, as given by ZARTMAN and DOE (1981) are shown for comparison. Also shown are calcite from the 550 Ma old Alnø carbonatite, central Sweden (G. R. TILTON, unpubl. data), and the 120 Ma old Oka carbonatite, Quebec (GRÜNENFELDER *et al.*, 1986).
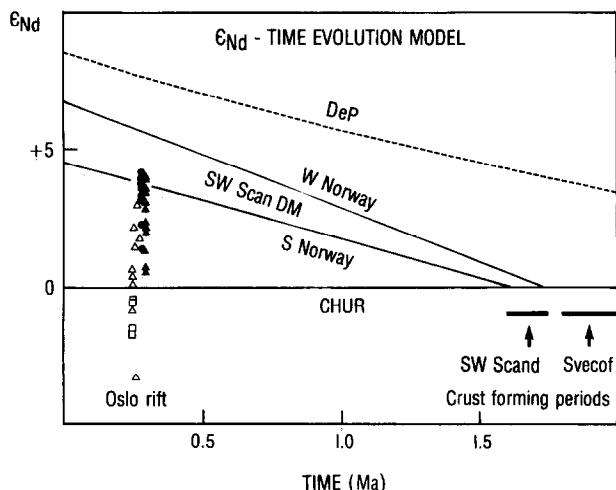
FIG. 5. ϵ_{Nd}-time relations among Oslo rift rocks, seen in relation to proposed evolution trends for different parts of the SW Scandinavian upper mantle (W. Norway and S. Norway) (MEARNS et al., 1986; MEARNS, pers. commun., 1987), CHUR (ALLÈGRE et al., 1983; JACOBSEN and WASSERBURG, 1984), and the depleted mantle model (DeP) of DePAOLO (1981).

interpolating between data for 0 and 400 Ma, is used to show SDM about 300 Ma ago.

Information on the lead isotopic composition of the upper crust in southwest Scandinavia is available through studies of galena in Permian vein deposits within the Oslo Region and in the Precambrian basement west of the Oslo rift (A. BJØRLYKKE, pers. commun., 1986), and the composite of Precambrian granitic gneisses, granites and amphibolites in southern Telemark (ST) (ANDERSEN and TAYLOR, 1987) (also used in the discussion of Sr-Nd isotopes). The lower range of these data, used as a model for the Pre-Permian upper crust, is shown as a dotted area in Fig. 6. Bjørlykke's results for vein deposits inside the rift cover the same range in Pb isotopic ratios as are found for the Oslo rift rocks of the present study.

Studies of three Precambrian rock complexes have bearing on the lead systematics of the intermediate to deep parts of the crust: that is the 1598 Ma old Trysil granite (TG in Fig. 1) (BJØRLYKKE and THORPE, 1982), 1400 Ma old granulite facies gneisses in the Rogaland Province (RP) WEIS and DE-MAIFFE, 1983), and 1010 Ma old sulphide-bearing quartz veins and wall-rock in the Dalsland–Värmskog area of southwest Sweden (DV) (JOHANSSON, 1985) (Fig. 1). The range of estimated initial Pb isotopic ratios indicated by these three complexes is shown as a hatched area in Fig. 6. These data suggest that evolution of lower parts of the crust in southern Scandinavia since Precambrian time has been governed by low U/Pb and Th/Pb (not shown) ratios.

In order that the above data on the Precambrian reservoir in the intermediate to lower crust may be used in mixing models for the Oslo rift, it is necessary to estimate its Pb isotopic composition in Permian time. Pb isotopic ratios at $t = 290$ Ma will lie somewhere along a secondary isochron defined by three difference and μ-values. This secondary isochron is marked P in Fig. 6. It is interesting to note that none of the analyzed Oslo rift rocks fall to the left of this

line, and that the basalts FX2 and FZ2 with the lowest ϵ_{Nd} values among the basalts, fall close to it.

Pb-Nd and Pb-Sr isotopic relation

Figure 7 shows the consequences of crustal contamination on basalts derived from the mildly depleted mantle source M. Trends have been calculated for the Pb-Nd and Pb-Sr systems, using the compositions of the various mixing members discussed above. The Pb contents of the crustal reservoirs in question are not known, but data on the Rogaland gneisses, which show 8–42 ppm Pb (WEIS and DEMAIFFE, 1983), indicate a wide range of possible values. Mixing trends for 6, 20 and 50 ppm Pb in the crustal component are therefore shown in Fig. 7.

CONCLUSIONS

The observed variations in initial isotopic ratios among the Permo-Carboniferous Oslo rift magmatic rocks can be interpreted in terms of mixing models, using available information on the isotopic evolution of the crust and upper mantle under southern Scandinavia. The mixing models (illustrated in Figs. 2, 6 and 7) and discussion presented above, imply that:

a) The observed isotopic variations among the Oslo rift rocks may be explained in terms of crustal contamination of magmas derived from a mildly depleted, somewhat heterogeneous mantle source region.
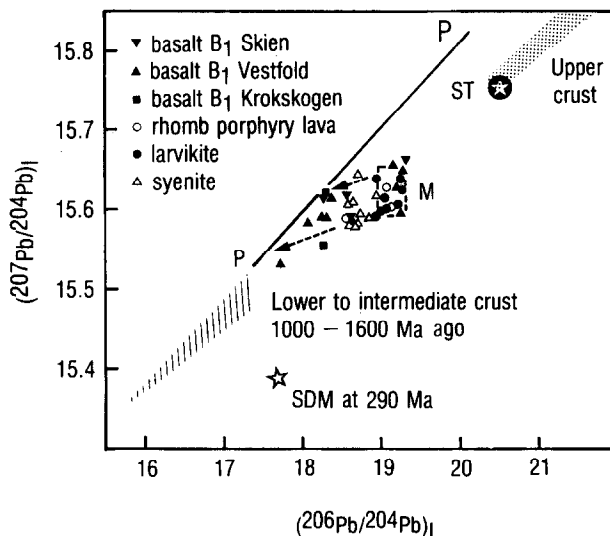

FIG. 6. Illustration of proposed mixing model for the Oslo rift rocks in term of $(^{207}Pb/^{204}Pb)_i$–$(^{206}Pb/^{204}Pb)_i$ relations. M: a mildly depleted mantle source under SE Norway; SDM: the strongly depleted mantle as given by ZARTMAN and DOE's (1981) Plumbotectonics Model I, interpolating between data for 0 and 400 Ma; hatched area: the lower to intermediate crust 1000 to 1600 Ma ago as given by data on the Trysil granite (BJØRLYKKE and THORPE, 1982), Rogaland Province granulites (WEIS and DEMAIFFE, 1983) and the Dalsland-Varmskog area (JOHANSSON, 1985); dotted area: the upper crust as given by data on galena vein deposits in the Kongsberg area (A. BJØRLYKKE, pers. commun., 1986) and the southern Telemark crustal composite (ST) (T. ANDERSEN, pers. commun., 1986). The line P-P is used to model the Pb isotope relations in the intermediate to lower crust at 290 Ma. Dashed arrows indicate mixing trends. See discussion in text for further information.
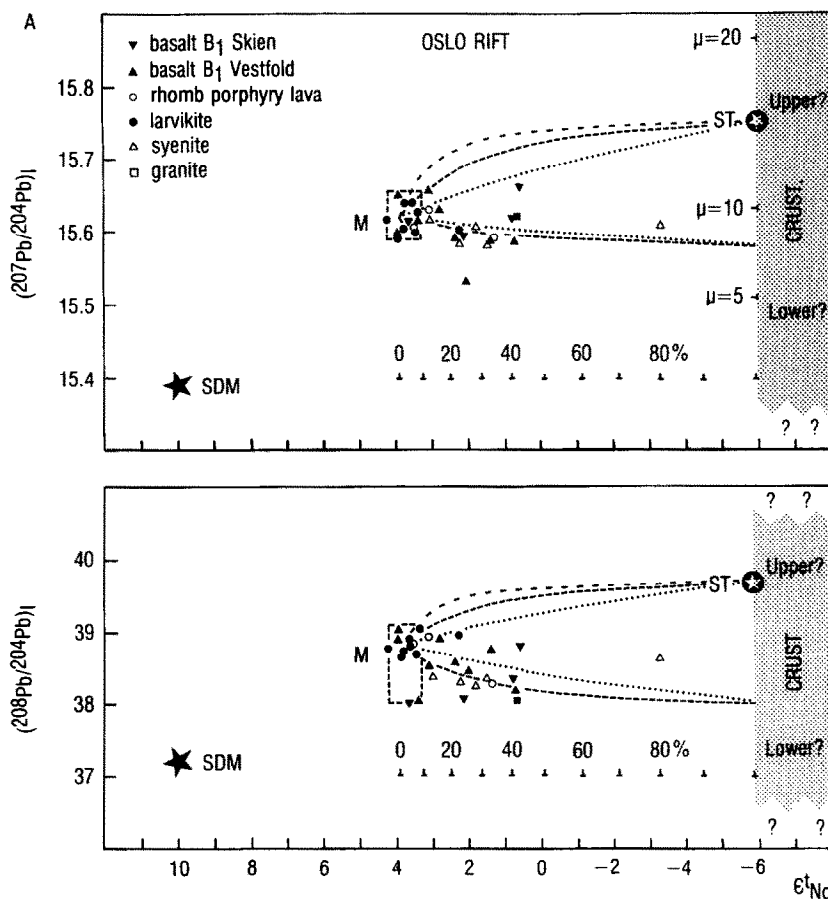
FIG. 7. An illustration of the mixing model in terms of Pb-Nd (a) and Pb-Sr (b) relations. Mixing trends are given for 6 (dotted), 20 (dashed) and 50 ppm Pb (open-spaced dashes) in the crustal contaminant. Expected isotopic variations in the crust under the Oslo rift, as indicated by available data, are indicated by the dotted areas. Numbers indicate percent comtamination in different parts of the crust. For further explanation of the mixing model and symbols, see Figs. 2 and 6, and the text.

b) This mantle source (M in Figs. 2–7) had the following isotopic character 290 Ma ago: $\epsilon_{Nd} \approx +3.3$ to $+4.2$, $\epsilon_{Sr} \approx -3$ to -16, $(^{206}Pb/^{204}Pb)_I \approx 19.2$, $(^{207}Pb/^{204}Pb)_I \approx 15.63$, $(^{208}Pb/^{204}Pb)_I \approx 38.9$, and was located in the subcrustal lithosphere.

c) A group of basalts, larvikites and rhomb porphyries has not been significantly contaminated.

d) The rest of the basalts were contaminated in the intermediate to lower crust (negative ϵ_{Nd}, moderately high positive ϵ_{Sr}, $^{207}Pb/^{204}Pb \approx 15.5$–$15.6$, $^{208}Pb/^{204}Pb \approx 38$–$39$ in Permian time).

e) The crustal model used in the mixing calculations suggest 0–40% contamination among the Vestfold basalts and possibly as much as 60% contamination of the Krokskogen quartz tholeiite.

f) Some of the syenites and granites show similar isotopic characteristics to the contaminated basalts, implying contamination in the lower to intermediate crust.

g) Other syenites and granites, particularly in the Hurdal area, show a strong dispersion in ϵ_{Sr} values which implies that they have either suffered additional contamination in the upper crust or post solidification alteration.

A contamination model (based on lead data) similar to that favoured for the Oslo rift was proposed by DOE et al. (1969) for a series of basalts in the southern Rocky Mountains.

In addition, crustal contamination has been postulated to explain isotopic relations in syenitic rocks of the Monteregian Hills and White Mountain igneous provinces of Quebec and New Hampshire (CHEN et al., 1984; EBY, 1984) and some of the Little Rock, Arkansas, syenitic bodies (TILTON et al., 1986).

MEARNS' (1986) ϵ_{Nd}-time relations may be explained by a relatively short history of depletion in the sub-Scandinavian mantle (1500–2000 Ma). However, such a simple evolutionary history cannot explain the high lead isotopic ratios suggested for the mantle under southern Norway. In particular, high U/Pb ratios must have existed in the magma sources for a considerable length of time in order to generate the high $^{207}Pb/^{204}Pb$ ratios observed in many of the rock samples. It is therefore necessary to postulate a multistage history for the source with periods of relatively high U/Pb and Th/Pb ratios. One possible mechanism for generating such conditions in the mantle is through metasomatic enrichment in lithophile elements. The Fen carbonatite complex south of the Oslo rift (Fig. 1), has yielded evidence for metasomatic enrichment in light REE in the mantle under southern Norway (ANDERSEN, 1987).

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APPENDIX
SAMPLE DESCRIPTIONS

The four *Skien basalts* are nephelinites to basanites (SEGALSTAD, 1979) with mg-numbers (Mg/(Mg + Fe$_t$) = 0.67–0.54. The dominant phenocrysts are clinopyroxene ± minor amounts of olivine in S01B, S36 and S41; plagioclase (+ clinopyroxene) in S47. The pyroxene-rich flows have Cr-rich diopside as fractured megacrysts and as cores of phenocrysts mantled by Al-Ti-rich augite. The Cr-diopside cores are considered to represent xenocrysts originating in the mantle or deep crust. The groundmass is very fine grained, but augite, magnetite, apatite, melanite, nepheline, chalcopyrite and calcite have been identified, together with the secondary minerals chlorite, epidote, serpentinite and bowlingite.

The mildly alkaline *Vestfold basalts to trachybasalts* (ØVERLI, 1985) are from a profile close to the town of Horten. The samples are listed in Tables 1 and 2 according to stratigraphic position (FA2 near the bottom, FZ2 near the top). Mg-numbers range from 0.51 to 0.33.

The rocks are aphyric (F15, F16), have phenocrysts of augite + pseudomorphs after olivine (FA2, FA3, F8A), augite + plagioclase + pseudomorphs after olivine (FX2, FZ2), or aggregates of plagioclase (F21, F23). Augite, feldspar, magnetite, ± ilmenite, pseudomorphs after olivine, and apatite. Secondary biotite, sericite, clinozoisite, chlorite and Fe-Ti-oxides have been identified in the fine grained to aphanitic groundmass. Miarolitic cavities filled by calcite, chlorite, serpentine, ± quartz make up 2–3% of the rocks. F23 and F16 are relatively strongly, the other samples moderately altered.

The two *Krokskogen quartz tholeiite* samples (OB8, OB87) are from the same aphyric flow. The rocks are vey fine grained and moderately altered.

The selected samples of (monzonitic) *Larvik larvikites* (NEUMANN, 1980) are coarse grained, very fresh rocks consisting of anorthoclase + augite + magnetite$_{ss}$ + ilmenite$_{ss}$ ± olivine ± nepheline ± quartz + apatite ± zircon.

The *rhomb porphyry lavas* are the extrusive equivalents to the larvikites. They have phenocrysts of anorthoclase (often zoned), mantled by alkali feldspar and microphenocrysts of Fe-Ti-oxides + apatite ± pseudomorphs after olivine. Also the groundmass is dominated by feldspar. In sample PA21, groundmass feldspar is mildly sericitized, in PA7, PA25 and PA29 both phenocrysts and groundmass feldspar are sericitized; sample PA29, which is the most strongly altered, also has lots of calcite in the groundmass.

From the *Sande cauldron intrusive complex* (ANDERSEN, 1984) four samples of alkali syenite (nordmarkite) (A2, A4, R302, R309) and one of syenite porphyry from the ring-dyke (A40) were analyzed. The medium to coarse grained, miarolitic, heterogeneous alkali syenite consists of alkali feldspar, quartz (0–10%), sodic pyroxene, sodic amphibole, magnetite and ilmenite, with accessory apatite, sphene, and zircon. Sample R40 is an alkali feldspar-quartz porphyric alkali syenite with aphanitic groundmass. The feldspar is mildly sericitized.

Alkali syenite in the Nittedal cauldron (RASMUSSEN et al., 1987) is coarse grained, granular, and has a similar mineral content to the Sande alkali syenites. Feldspar is again mildly sericitized.

A number of samples were selected for analysis from the *Hurdal intrusive complex* (TUEN, 1985), each number here denotes a specific intrusive unit (e.g., ET8, ET9). ET1, a fine to medium grained granite, consists almost exclusively of albite, orthoclase and quartz, with minor amounts of Fe-Ti-oxides and chlorite. The feldspar is moderately sericitized. ET3 is a coarse grained granite consisting of microperthitic feldspar and quartz, with accessory biotite, sphene, Fe-Ti-oxides, apatite, zircon and fluorite. In sample ET3C, the feldspar is mildly sericitized, in ET3E feldspar and biotite are partly altered to sericite and chlorite. ET5I is a drill core unit, a porphyritic syenite from about 520 m depth. The rock has phenocrysts of alkali feldspar and microphenocrysts of biotite and oxides in a fine to medium grained groundmass of feldspar, quartz, Fe-Ti-oxides, biotite and apatite; abundant calcite, sericite and chlorite reflect extensive alteration. A porphyritic granite ET5II (from 350 m depth in the same drill core as ET5I) has coarse grained aggregates of alkali feldspar and quartz in a fine grained groundmass of feldspar, quartz, Fe-Ti-oxides, apatite, muscovite and calcite. The feldspar is somewhat sericitized, and the rock is cut by veinlets (≤1 mm wide) of quartz, oxides, muscovite and calcite. ET8 is a medium to coarse grained syenite dominated by alkali feldspar (85%), with some interstitial quartz, Fe-Ti-oxides, primary and secondary biotite, sodic pyroxene and amphibole, sphene, apatite and zircon. The feldspar is mildly sericitized, pyriboles show signs of alteration to biotite and chlorite. ET9 is a coarse grained alkali syenite consisting of alkali feldspar, quartz, sodic amphibole, sodic pyroxene, Fe-Ti-oxides, apatite and zircon. In samples ET9A and ET9D the feldspar is mildly sericitized. ET9E shows strong alteration of feldspar to sericite and pyriboles to aggregates of chlorite + quartz + Fe-oxides. ET10 is a coarse grained granite which, besides microperthitic feldspar and quartz, contains sodic amphibole, Fe-Ti-oxides, zircon, sphene, apatite and fluorite (primary). The feldspar is somewhat sericitized, and the amphibole locally partly chloritized. Veinlets of quartz and through-setting trails of fluid inclusions are common in all these rocks. These features result from hydrothermal activity which is also believed to be responsible for most of the observed alterations.