Rb-Sr and Sm-Nd relationships in dyke and sill intrusions in the Oslo Rift and related areas

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Eighteen dykes and three sills from the Oslo Rift and related areas in SW Sweden have been investigated by the Rb-Sr and Sm-Nd methods. Rb-Sr isochron ages in the range 287 to 248 Ma were obtained for twelve of the dykes. All dyke ages fall within the time-span previously established for the Oslo Rift magmatism: 305-240 Ma.
An early group of tholeiitic dolerites and microsyenitic dykes fall in the period 297-285 Ma. The intrusion pattern of these dykes suggests strike-slip movements during an early phase of rift evolution. Rhomb-porphyry (RP) dykes are generally later (280-270 Ma) than the main period of plateau volcanism (295-275 Ma), and are contemporaneous with the emplacement of monzonitic (larvikite) plutons. The age (249±3 Ma) of a per-alkaline microgranite dyke from the Nittedal caldera is compatible with a derivation of the dyke from late differentiates of the alkali-syenite intrusions. A syenite dyke from Scania, Sweden, yielded an age (261±6 Ma) considerably younger than the dolerites (≈300 Ma), supporting other evidence of a prolonged period of intrusive activity in this area. The Mjøndalen-Etnedal RP dyke shows evidence of at least three intrusion pulses along its strike, of magmas with different Sr isotopic signature.
The Nd and Sr initial ratios of the dykes fall within the field covered by other Oslo Rift igneous rocks, indicating that the mixing model involving two mantle sources and a crustal component is also applicable to the dyke rocks. Two dykes show evidence for in-situ interaction between magma and a selective radiogenic ^{87}Sr contaminant, most likely crustal fluids.

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Introduction

The Permo-Carboniferous Oslo Rift (Fig. 1), situated in the southwestern part of the Fennoscandian Shield, is an exceptional example of a highly magmatic rift initiated by a passive rifting mechanism (Neumann et al. 1992). By volume, the Oslo Rift magmatic suite is dominated by plutonic complexes. A major part of the extrusive rocks has most probably been removed by post-Permian erosion (Ramberg & Larsen 1978, Zeck et al. 1988). Although modest in volume, the most diverse group of magmatic rocks are the dyke and sill intrusions which include several rock types that have no counterparts among the plutonic or volcanic rocks. In spite of their obvious importance in the magmatic evolution of the Oslo Rift, little modern petrological or geochemical work has been dedicated to these intrusions since the pioneer investigations by W.C. Brøgger (Brøgger 1887, 1894, 1898, 1932, 1933b, 1933c, Sæther 1947, Dons 1952, Carstens 1959, Hasan 1971, Huseby 1971, Samuelsson 1971, Kresten et al. 1982). One notable exception is the early complex of sills and dykes that has been studied by Scott & Middleton (1983) and Sundvoll et al. (1992).

The aim of the present study is (a) to combine isotope and other geochronological investigations of selected dykes with field observations into a temporal and spatial pattern for the dyke intrusions; and (b) to compare this pattern with the evolutionary model of the Oslo Rift, as presented in the studies of Sundvoll et al. (1990) and Neumann et al. (1988, 1992).

The dyke and sill intrusions in the Oslo Rift

General

The Oslo Rift (Fig. 1) is made up of two major grabens: (a) the on-land Oslo Graben (OG) comprising the Oslo Region of Palaeozoic rocks and the Precambrian Kongsberg block (Ramberg & Larsen 1978), and

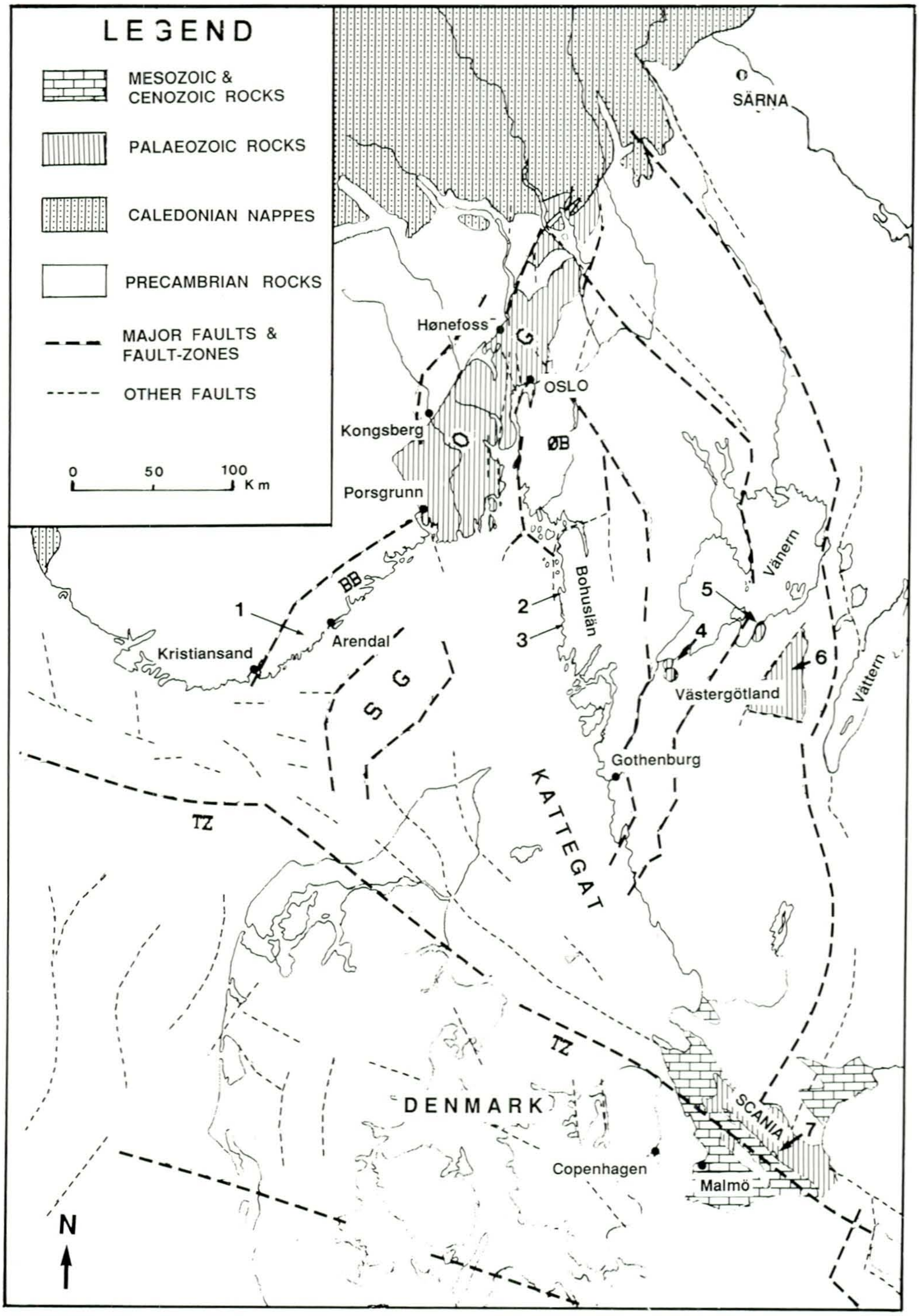

Fig. 1. Geological map of the Oslo Rift, Norway and related areas in SW Sweden. (Bedrock geology in offshore areas and Denmark deleted). Offshore structural elements after Ro et al. (1990a). BB : Bamble block, ØB : Østfold block, OG : Oslo Graben, SG : Skagerrak Graben, TZ : Tornquist zone. 1 : Grimstad dyke, 2 : Raftötången dyke, 3 : Valön dyke, 4 : Hunneberg sill, 5 : Kinnekulle sill, 6: Billingen sill, 7 : Torpa klint dyke.

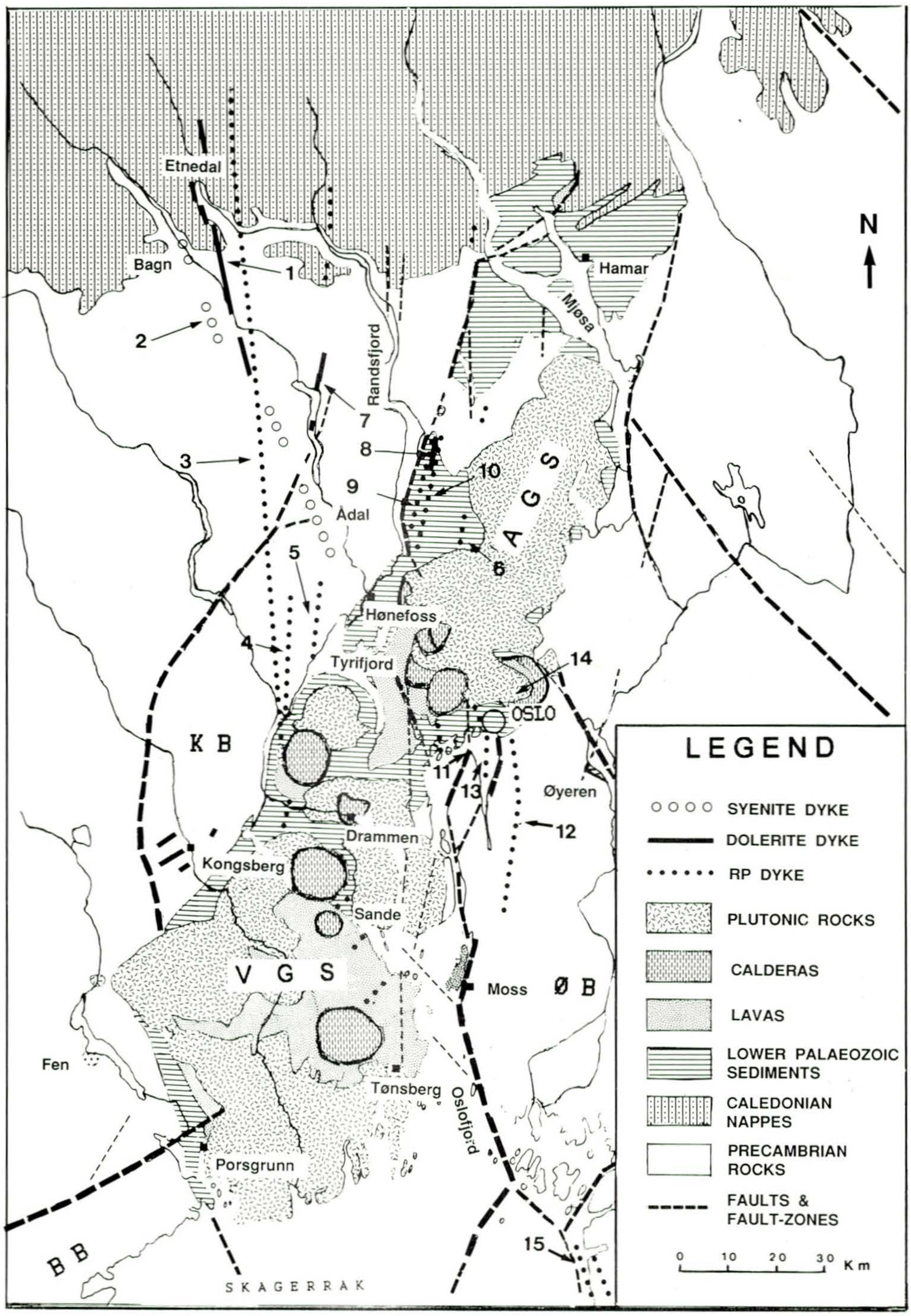

Fig. 2. Geological map of the Oslo Graben showing the major dykes and dyke swarms. AGS : Akershus graben segment, BB : Bamble block, KB : Kongsberg block, ØB : Østfold block, VGS : Vestfold graben segment. 1 : Tonsåsen dyke, 2 : Bagn-Ådal dyke, 3 : Mjøndalen-Etnedal dyke, 4 : Katfoss dyke, 5 : Nakkerud dyke, 6 : Roa dyke, 7: Bjonvika dyke, 8 : Brandbu dyke, 9 : Gran dyke, 10 : Jevnaker dyke, 11 : Nesodden dyke, 12 : Ekeberg dyke, 13: Tyvholmen dyke, 14 : Storhaug dyke, 15 : Raftötången dyke.

(b) the offshore Skagerrak Graben (SG) (Ro et al. 1990b). The SG is structurally linked to the Tornquist zone (Ro et al. 1990a). Ramberg & Larsen (1978) have subdivided the OG (Fig. 2) into a (southern) Vestfold graben segment (VGS) and a (northern) Akerhus graben segment (AGS).

Dykes associated with the Oslo Rift magmatic suite are numerous inside the OG, but also occur in adjacent Precambrian areas (Figs. 1 and 2), in Bohuslän (Samuelsson 1967, 1971, Kresten et al. 1982), Østfold, Ådal-Etnedal (Goldschmidt 1909, Strand 1938, 1954, Isachsen 1942, Dietrichson 1945, Smithson 1963), Kongsberg (Bugge 1917, 1937), and Bamble (Suleng 1919, Barth 1944, Carstens 1959). Sills occur almost exclusively in Lower Palaeozoic sediments inside the OG, but they also occur within the small isolated area of down-faulted Cambrian strata on the western shore of the lake Øyeren (Fig. 2) (Holtedahl 1907), and in Precambrian rocks on some islands (Ny-Hellesund) southwest of Kristiansand (Barth 1944, Halvorsen 1970).

Dykes of similar composition and appearance commonly occur in swarms. Inside the OG, such dyke swarms may be spatially associated with plutons of petrographically similar rock types or with calderas (Sæther 1947, 1962). In association with calderas or ring structures, characteristic ring- and cone-sheet dykes may also be present (Oftedahl 1953). Dykes are also abundant in areas where major structural elements intersect. However, some dyke swarms, like the Kongsberg dolerites (Bugge 1917, Ihlen et al. 1984), appear not to be connected with other magmatic or tectonic features.

The dimensions of the dykes and sills are variable. Individual dykes may have a thickness of a few cm up to 60 m, and a length of up to 160 km. Single sills have thicknesses up to 15 m, and lengths up to 20 km. Lamprophyre dykes are generally thin (<1 m) and short (<100m). Dykes that have counterparts among the plutonic rocks (rhomb-porphyry, quartz-porphyry, alkali-syenitic and perakaline granitic dykes, etc.) are usually wider (>1 m) and longer (>100 m), and generally continuous along strike. Larger, older dykes of basaltic and syenitic compositions (see below) are frequently discontinuous along strike and may be off-set in an en echelon manner. Indications of forceful emplacement have also been noted among some ultrabasic dykes (Kresten et al. 1982).

A large majority of the dykes have strikes falling between NE-SW and NW-SE, the most common (approximate) trends being NNW-SSE, N-S, NNE-SSW and NE-SW (Sæther 1945, 1946, 1947, 1962, Dons 1952, Huseby 1971). However, irregular trends are also observed.

Many dykes, especially those of rhomb-porphyry (RP), syenite and quartz-porphyry types, are composite, generally with a more basic composition along one or both borders (Brøgger 1932, Antun 1964, Oftedahl 1957, Samuelsson 1967, Hasan 1971). A large number of the diabase and lamprophyre dykes are heavily altered, and in most cases this alteration is considered to be auto-metamorphism associated with late- or post-intrusive processes in the dyke (Sæther 1947). Some lamprophyre (kersantite) dykes northeast of Oslo look very fresh (Naterstad 1978).

A few dykes and sills contain xenoliths. Older basaltic sills from the Sande area contain xenoliths of mafic cumulates (Brøgger 1933b). Some mafic dykes from the Oslo area carry inclusions of basement rocks, mostly fragments of gneisses of upper crustal origin (Bäckström 1890). No mantle xenolith has yet been identified. Several lamprophyre dykes are known to contain ocelli, xenocrysts and/or amygdales (Brøgger 1898, Carstens 1958, 1959), and orbicular textures have also been recorded (Bryhni and Dons 1975).

One lamprophyre dyke from the Bamble area deserves special attention as it contains vesicles filled with hydrocarbons, possibly acquired from Lower Palaeozoic (Cambrian) sediments (Dons 1975). A syenite sill at the southern end of lake Mjøsa (Fig. 2), intruded into Cambrian sediments and older syenitic sills, contains topaz and beryl (Goldschmidt 1911).

Field and age relationships

From their field relationships some of the dykes and sills can roughly be divided into three age-groups (Werenskiold 1911, Brøgger 1933b, 1933c, Sæther 1947, 1962, Dons 1952):

I. *The oldest group of dykes and sills.* This group is primarily made up of microsyenitic and camptonitic sills and dykes forming intrusion complexes in the Lower Palaeozoic sediments of the OG (an exception being the area northeast of lake Mjøsa where no sills occur). Both the microsyenites and the camptonites are believed to be derived from hydrous alkali-olivine basaltic magmas (Rock 1977, Scott & Middleton 1983). The age of these complexes are 300 ± 5 Ma (Sundvoll et al. 1992), indicating that they predates the period of most intensive volcanism (plateau-lavas) and graben formation in the Oslo Rift (Sundvoll et al. 1990; Sundvoll et al. 1992).

Several large dykes, some of which are chemically similar to the early syenite sills, and others that are of basaltic compositions, may also belong to this group. A number of syenite dykes occur in the Precambrian area west of the AGS (Fig. 2), one of them unusually long (75 km), and similar dykes are also found in the Oslo area (Brøgger 1887, Isachsen 1944). In this Precambrian area and in the western part of the AGS, there are several large dolerite dykes of tholeiitic affinity and with strikes between NNW-SSE and N-S (Goldschmidt 1909, Brøgger 1933a, 1933b, Strand 1938). Field observations indicate that the dolerites are older than the syenites and that both types are older than the RP dykes (see below). Other large basaltic dykes, but with strikes of about NE-SW, are also developed in the Kongsberg area (Bugge 1917, Ihlen 1984). Some lamprophyres and ultramafic dykes occurring in the Bohuslän area are also considered to have been emplaced earlier than the RP dykes (Kresten et al. 1982).

II. *The rhomb-porphyry dykes.* From field evidence, this group is clearly younger than group I. The RP dykes are petrographically and chemically related to the RP plateau lavas and the larvikite plutons. This episode of dyke intrusion occurred in several areas within and outside the OG and in areas associated with the SG (Figs. 1 and 2). The RP dykes tend to cluster in dyke swarms. It has generally been assumed that the RP dykes represented feeders for the RP lavas of the plateau volcanism stage, and that they are also spatially associated with the major graben faults in the OG (Brøgger 1933c). However, no RP dyke has yet been connected with any of the existing RP lavas, and RP dykes are rarely intersected by synrift faults. The RP dykes are observed to cross-cut both dykes and sills of group I, the B1 basaltic lavas and the RP lavas.

In the area north of Oslo (Fig. 2) several RP dykes cut larvikite (monzonite) plutons (Sæther 1962), but no RP dyke has been observed to cut later syenitic or (alkali-) granitic plutons. The relationship between the RP dykes and quartz-porphyry dykes or the (older) biotite granites in the OG is not clear, but a RP dyke in the Sande area (Fig. 2) is cut by the Drammen granite. This indicates that the RP dykes may be older than the quartz-porphyry dykes and the granites (Brøgger 1933c).

In the Precambrian areas it seems evident that the RP dykes have utilized pre-existing faults, lineaments and foliations (Ljungner 1927, Selmer-Olsen 1950), and there are also strong indications that in areas with Palaeozoic sediments and lavas, their strike trends are controlled by structures in the Precambrian basement. In the Oslo area, some RP dykes locally form sill-like sheets in the Lower Palaeozoic sediments (Brøgger 1887).

Several large RP dykes exhibit zoning. The zoning is usually across strike, as described from the Bohuslän dykes (Samuelsson 1967, 1971). Dyke zoning or composite dykes are generally believed to be the products of a multiple intrusion mechanism.

III. *The late group of dykes.* This group comprises dykes which are never cut by RP lavas or monzonitic plutons. They also seem to be younger than most subvolcanic and extrusive rocks related to the caldera phase (Sæther 1962), indicating an upper age limit of about 270 Ma. The dykes belonging to this group are very heterogeneous, including rock types such as quartz-porphyry, syenite-porphyry, alkali-microsyenite ('sølvsbergite'), per-alkaline microgranite ('grorudite') and tinguaite. They appear to be spatially associated with the younger plutonic rocks of the Oslo igneous suite, the syenites and the (younger) alkali-granites, and may represent the dyke equivalents of these intrusive complexes. The genetic relations are inferred from petrological, chemical and field evidences (Brøgger 1894, 1898, 1933a, Sæther 1947, 1962).

A wide variety of smaller diabase and lamprophyre dykes have intruded during the whole period of the rift history (Sæther 1947, 1962) and fall outside the age groups.

Dykes and sills in adjacent areas
Contemporaneous dyke and sill intrusions occur in the Västergötland and Scania areas of southern Sweden (Hjelmqvist 1940, Priem et al. 1968, Mulder 1971). In the Västergötland area (Fig. 1) dolerite sills occur in half-grabens or outliers with Lower Palaeozoic sediments (Hunneberg/Halleberg, Kinnekulle, Billingen). The areas containing sills and sediments are spatially close to the major fault zones that subdivide the Precambrian of SW Sweden and SE Norway (Fig. 1). These fault zones are considered to have been reactivated during the Permo-Carboniferous tectonic event that formed the Oslo Rift (Lidmar-Bergstrøm 1973).

In the Scania area (Fig. 1), dolerite and lamprophyre dykes occur. The dolerites are tholeiitic in composition, and the lamprophyres mostly camptonitic (Hjelmqvist 1940). The age of the dolerites has been determined by the K-Ar isochron method to 300 ± 4 Ma (Klingspor 1976). Among the basic dykes of Scania, Sweden, one dyke of syenitic composition has been discovered (Hjelmqvist 1940). Field evidence and paleomagnetic data indicate that the lamprophyre dykes may be somewhat younger than the dolerites (Hjelmqvist 1940, Mulder 1970, Bylund 1974). All dykes in Scania have trends from NW-SE to WNW-ESE, and they are all located within or along the Tornquist zone.

Post-Permian dykes
Some published K-Ar dates (Neumann 1960, Dons 1977) on diabase and dolerite dykes from the Oslo Rift fall in the Mesozoic era. These ages are younger than that of the supposedly latest pluton in the OG (Tryvann granite: 241 ± 5 Ma; Sundvoll & Larsen 1990), indicating dyke intrusions after the emplacement of the latest composite plutons. Furthermore, these plutons are cut by lamprophyre dykes (Sæther 1962), none of which have been dated. However, all K-Ar ages hitherto obtained on Oslo Rift magmatic rocks are discordant, argon loss being a likely interpretation. Thus, the the published K-Ar ages are too young, and the timing of the termination of the magmatic activity is still uncertain.

Within the rift zone, in the eastern Skagerrak (north of Jutland), Flodén (1973) has reported a possible occurrence of small magmatic bodies intruded into Mesozoic sediments. Otherwise, little evidence of post-Permian magmatism (or tectonism) has been demonstrated.

Geochronology and other isotopic data

Analytical methods
Strontium and neodymium isotopic analysis, including radiometric age determinations, were carried out on samples from selected dykes covering the different age groups. Six additional sample sites are located in Sweden (Fig. 1): a RP dyke (2) and an ultramafic dyke (3) in the Bohuslän area, three dolerite sills (4, 5, 6) in the Västergötland area (Hunneberg, Kinnekulle and Billingen) and a syenite dyke (7) in the Scania area. For purposes of comparison reasons, a gabbro sample from the Dignes neck (southern shore of lake Tyrifjord, Fig. 2) and a silica-undersaturated lava from the B1 basalt sequence in the Porsgrunn area (Fig. 2) were also analysed. As experience had

shown that the whole-rock isochron method is usually ineffective on dyke rocks, the mineral isochron method or the phenocryst-whole rock-matrix method was applied to a limited number of the samples.

The analytical work was carried out during 1983-86 at the laboratory of isotope geology at the Mineralogical-Geological Museum, University of Oslo. Mineral separations were accomplished by a combination of magnetic and heavy liquid procedures. Phenocrysts and matrix were separated manually by hand-picking. Whole-rock samples and mineral fractions were analysed for Sr isotopes, and a limited number also for Nd isotopes. The analytical procedures and instrument performances were identical to those reported by Sundvoll & Larsen (1990) and Mearns (1986).

Isochron calculations followed the procedure of York (1969), using the values 1.42 x 10^{-11} a^{-1} and 6.54 x 10^{-12} $a^{-1}$for the decay constants of, respectively ^{87}Rb and ^{147}Sm. (Steiger & Jager 1977). The _ notation follows DePaolo & Wasserburg (1976a) using UR values for Rb-Sr reported by DePaolo & Wasserburg (1976b) and CHUR values for Sm-Nd reported by Jacobsen & Wasserburg (1984). Errors quoted are at 2 sigma level.

Results

The results of the isotopic analysis are presented in Tables 1 and 2, and the calculated isochron ages and $\in_{Sr}$ & $\in_{Nd}$ values in Table 3.

The T-1 sample of the dolerite dyke at Tonsåsen (Fig. 2; Goldschmidt 1909) gave a mineral age of 297±9 Ma. Additional whole rock samples from the same dyke (T-1b and T-2, Table 1) also fitted the mineral isochron. However, the apatite fraction from the T-1 sample did not fit the isochron. The isochron yielded a ^{87}Sr/^{86}Sr initial ratio of .70672±5 (Table 3), and the apatite .70493±6 (Table 1). The Bjonvika and Brandbu dolerite dykes (Fig. 2; Brøgger 1933b) were not dated, nor were the dolerite sills from Västergötland, Sweden; only

Table 1.Rb-Sr elemental and isotopic data. Rb-Sr concentrations determined by XRF spectroscopy except those marked #, which were determined by isotope dilution technique. wr = whole rock, mx = matrix,fen = phenocryst, fs = feldspar, afs = alkali-feldspar, plg = plagioclase, cpx = clinopyroxene, px = pyroxene, ap = apatite, bio = biotite.

Sample	ppm Rb	ppm Sr	^{87}Rb/^{86}Sr	^{87}Sr/^{86}Sr
Tonsåsen				
T-1a wr	33.1	615.2	.1558'	.70742±7
T-1b wr	32.9	536.0	.1776'	.70752±6
T-2 wr	33.5	612.4	.1581'	.70754±8
T-1a fs1	116.8	317.8	1.0636'	.71137±8
T-1a ap	1.1	1045.5	.0031'	.70493±6
T-1a fs2	65.1	1142.5	.1648'	.70733±8
T-1a fs3	49.8	1123.3	.1284'	.70727±4
T-1a px1	6.3	138.9	.1314'	.70731±7
T-1a px2	7.0	159.3	.1267'	.70730±10
T-1a fs4	52.4	921.5	.1646'	.70738±4
T-1a fs5	123.6	220.0	1.6272'	.71343±10
Bjonvika				
BV-1	36.7	617.7	.17189	.70512±5
Brandbu				
RH-1	2.9	695.3	.01206	.70508±5
Valön (Bohuslän)				
BG-3	42.1	697.4	.17460	.70483±4
Hunneberg (Västergötland)				
HV-2	23.1	443.7	.15062	.70725±5
Billingen (Västergötland)				
BL-2	8.7	349.5	.07200	.70443±5
Kinnekulle (Västergötland)				
SK-1	208.2	507.2	1.18803	.71118±5
Nesoddtangen				
NT-1 ap	3.5	878.5	.0115'	.70537±5
NT-1 fs1	135.0	358.4	1.0901'	.70975±9
NT-1 wr	106.4	387.0	.7954'	.70871±9
NT-1 fs2	96.8	428.6	.6536'	.70803±6
Bagn-Ådal				
SP-1 wr	233.9	211.1	3.2117'	.72741±8
SP-1 afs	487.0	104.1	13.6051'	.76560±8
SP-1 fs1	239.9	791.6	.8776'	.71892±7
SP-1 fs3	95.4	193.2	1.4301'	.72114±9
SP-1 px1	37.9	41.4	2.6524'	.72619±7
SP-1 px2	49.7	72.3	1.9891'	.72332±6
SP-1 fs2	224.3	289.1	2.2483'	.72432±9
Torpa klint (Scania)				
TK-1 wr	159.8	307.3	1.5056'	.71300±10
TK-1 fs1	116.7	344.0	.9819'	.71095±10
TK-1 fs2	121.3	129.4	2.7133'	.71733±7
TK-1 bio	207.8	92.0	6.5507'	.73172±10
Grimstad				
GG-1 wr	134.9	492.3	.7930'	.70767±5
GG-1 mx	159.7	346.6	1.3336'	.70972±8
GG-1 fen	57.4	857.6	.1935'	.70521±5
Raftötången (Bohuslän)				
BG-1 mx	100.1	550.5	.5260'	.70631±9
BG-1 wr	100.5	580.3	.5009'	.70621±4
BG-1 fen	69.0	846.8	.2356'	.70528±6
BR-2 wr	132.0	449.4	.8500'	.70764±5
BR-2 fs1	45.3	978.2	.1340'	.70481±5
BR-2 fs2	116.7	574.3	.5879'	.70660±4
Mjøndalen-Etnedal				
GB-1	105.8	650.6	.4706	.70919±7
GB-1b	35.1	354.1	.2868	.70847±8
GB-2	93.9	418.9	.6486	.70970±6
GB-3	94.6	396.4	.6902	.70772±5
GB-4	71.8	314.6	.6605	.71001±8
GB-5	116.1	408.9	.8213	.70829±7
GB-7	148.3	366.9	1.1694	.70933±9
GB-9	154.5	356.8	1.2535	.70989±9
GB-10	146.2	369.1	1.1463	.70914±9
GB-16	125.5	391.4	.9277	.70863±9
GB-18	59.5	470.9	.3657	.70774±9
GB-19	151.9	376.4	1.1679	.70925±5
GB-21	119.4	423.8	.8152	.70832±6
GB-22a	77.1	478.3	.4667	.71139±9
GB-22b	73.2	439.8	.4817	.71157±8
GB-23	72.4	441.2	.4751	.71151±9
GB-24	169.7	431.7	1.1377	.70925±9
GB-25	160.7	407.7	1.1403	.70925±4
GB-26	132.3	446.8	.8565	.70809±9
GB-31	60.0	363.4	.4777	.71472±7
Mjøndalen-Etnedal dyke (minerals, Huken sample)				
GB-6 wr	158.9	479.2	.9596'	.71360±7
GB-6 afs	476.2	147.0	9.4099'	.74681±8
GB-6 plg	272.2	724.7	1.0874'	.71422±8
GB-6 bio	281.0	31.7	25.8870'	.81098±10
GB-6 px1	7.8	35.2	.6366'	.70807±9
GB-6 px2	12.1	56.7	.6166'	.71060±10
Mjøndalen-Etnedal dyke (minerals, Åmot sample)				
GB-13 wr	100.4	197.6	1.4700'	.71031±7

Table 1 (cont.)

GB-13 afs	206.9	43.9	13.6951'	.75798±6
GB-13 fs2	33.8	385.2	.2538'	.70542±9
GB-13 fs1	75.7	691.6	.3165'	.70578±8
Katfoss				
GB-8 wr	166.1	428.5	1.1214	.70829±6
GB-12 wr	169.3	447.5	1.0945	.70823±8
GB-15 wr	175.9	415.5	1.2252	.70880±7
GB-14 wr	175.0	423.9	1.1943'	.70871±5
GB-14 fen	73.4	832.7	.2549'	.70503±2
GB-14 mx	232.8	210.7	3.1990'	.71674±7
Nakkerud				
NA-1	78.1	669.1	.3377	.70779±7
NA-2	67.1	527.1	.3682	.70564±7
NA-3	91.0	538.9	.4887	.70613±8
Tyvholmen				
TG-1 wr	161.2	567.0	.8225'	.70706±6
TG-1 mx	175.1	398.3	1.2720'	.70883±4
TG-1 fen	62.0	1307.6	.1371'	.70446±8
HG-1 wr	189.3	496.5	1.1030	.70800±7
Ekeberg				
EB-1	152.7	535.5	.8250	.70696±9
EB-2	160.8	478.7	.9718	.70769±9
EB-3	154.9	531.5	.8432	.70702±7
EB-4	161.0	496.7	.9381	.70735±6
EB-7	158.3	549.1	.8338	.70699±9
Ekeberg (minerals)				
EB-5 wr	153.7	487.7	.9117'	.70728±3
EB-6 wr	156.1	520.9	.8670	.70717±3
EB-5 mx	175.5	299.4	1.6963'	.71034±5
EB-5 fen	89.9	1131.0	.2299'	.70467±5
Roa				
RG-1 wr	194.3	780.6	.7199'	.70668±7
RG-1 mx	240.7	378.3	1.8429'	.71107±6
RG-1 fen	58.1	1659.8	.1013'	.70431±6
Jevnaker				
RG-2	158.9	341.5	1.34642	.70922±3
Gran				
RG-3	166.0	639.8	.75060	.70692±3
Storhaug				
GR-1 wr	190.6	8.5	66.0567'	.93894±8
GR-1 afs	384.0	4.5	269.6369'	1.66733±10
GR-1 px	17.5	4.8	10.6312'	.74598±7
GR-1 fs2	195.5	7.4	79.1155'	.98879±4
GR-1 fs1	224.3	4.2	161.4667'	1.28063±10
GR-1 fs3	165.9	21.6	22.3506'	.78896±10
Porsgrunn B_1 lava				
OB-69	63.0	844.7	.2157	.70419±5
Dignes gabbro				
D-2	56.9	1091.1	.15082	.70398±3

whole-rock samples were measured for these intrusions.

A microsyenite dyke of a composition similar to sills of the early complex of dykes and sills termed 'mænaite' (Sundvoll et al. 1992), situated at the northern tip of the master fault along the eastern shore of the Oslofjord (Nesoddtangen), yielded an age of 290±11 Ma and a $^{87}Sr/^{86}Sr$ initial ratio of .70533±10.

The large porphyric syenite ('mænaite') dyke occuring in the Precambrian area northwest of Hønefoss (Fig. 2), with a strike c. NNW-SSE (Isachsen 1944, Strand 1954, Smithson 1963), yielded a mineral age (excluding the K-feldspar and the whole rock fractions) of 285±7 Ma and an initial $^{87}Sr/^{86}Sr$ ratio of .71532±20. The sample used (SP-1) was not completely fresh, and closer inspection revealed that the groundmass K-feldspar was partly epidotised. However, the plagioclase phenocrysts were fresh (fractions fs1, fs2 and fs3, Table 1). Because of the relatively large amount of epidotised K-feldspar in the rock, the whole-rock sample also fell off the mineral isochron.

The syenite dyke from Scania (from the small Precambrian horst at Torpa klint; Hjelmqvist 1940) gave an age of 261±6 Ma and an initial $^{87}Sr/^{86}Sr$ ratio of .70733±22.

The 8 selected RP dyke samples (Figs. 1 & 2) yielded mineral isochron ages between 281±11 and 271±10 Ma, and initial $^{87}Sr/^{86}Sr$ ratios between 70379±9 and 70994±10. Sample GG-1 from the Grimstad dyke, Bamble, described by Suleng (1919) yielded an isochron age of 281±11 Ma and the Raftötången dyke, Bohuslän (Samuelsson 1971), 275±12 Ma. In this case, two samples (BG-1 and BR-2, Table 1) and their phenocryst and matrix separates were used. The EB-5 sample from the Ekeberg dyke (Oslo; Brøgger 1933c) yielded an isochron of 272±7 Ma. Additional whole-rock samples taken from a cross-cutting section of this dyke, did not fit on the phenocryst-whole rock-matrix isochron, except for the adjacent sample EB-6. The TG-1 sample from the Tyvholmen dyke, Oslo (Brøgger 1933c) yielded an isochron of 271±10 Ma. However, the sample HG-1, taken from an assumed extension of this dyke within Oslo city (Brøgger 1887), did not fall on this isochron.

The two mineral isochrons, (samples GB-6 Huken and GB-13 Åmot), representing the Mjøndalen-Etnedal dyke (Brøgger 1933c), gave the same age (275±3 Ma; 275±4 Ma), but different initial ratios, .70994±10 and. 70449±12, respectively (Fig. 4). However, the clinopyroxene fractions from sample GB-6, did not fall on the mineral isochron. (This phenomenon and the whole-rock data are discussed separately below). Sample GB-14 from the Katfoss dyke, Modum (Brøgger 1933c) gave an isochron of 276±6 Ma. The other samples from this dyke also fit the isochron. The Nakkerud dyke from the same area (Brøgger 1933c) was not dated, but two whole-rock samples (NA-2 and NA-3, Table 1) suggest an age of ≈286 Ma. The RG-1 sample from the Roa dyke (Hadeland; Brøgger 1933c) gave an age of 273±7 Ma.

The GR-1 sample from the Storhaug 'grorudite' dyke (Fig. 2) yielded an age of 249±3 Ma and an initial ^{87}Sr/^{86}Sr ratio of .70856±92. This dyke belongs to a swarm of N-S trending, peralkaline, microgranite dykes from the Nittedal caldera, northeast of Oslo, which cut all rocks (except lamprophyre dykes) exposed inside the caldera (Naterstad 1978),

Discussion

Age-pattern and relation to rift development

The ages obtained on the dyke samples from the Oslo Rift all fall within the time span 305-240 Ma (Sundvoll & Larsen 1990, Sundvoll et al. 1992) established for the rift-related lavas and plutonic rocks (Fig. 3). The ages of the dykes also fit the general concept of age groups suggested by field evidence, although the group III dykes and the group of diabases and lamprophyres are represented by only one sample each.

The Tonsåsen, Bjonvika and Brandbu dykes (Fig. 2) have comparable mineralogy and whole-rock chemistry (Brøgger 1933a) indicating a tholeiitic affinity of the original magma. When using the apatite value in the Tonsåsen dyke, the ^{87}Sr/^{86}Sr initial ratios are also comparable and suggest a common origin. This is supported by the Nd isotopes (Table 2), which fit a 305±82 Ma Sm-Nd wole-rock isochron with a ^{143}Nd/^{144}Nd initial ratio of. 51240±7 (MSWD= .19). These dykes are therefore considered comagmatic and coeval. The age of this dyke-swarm (297±9 Ma) is not significantly different from the mean age of the early complex of sills and dykes (≈ 300 Ma), presumably emplaced under a tectonic regime of compression at shallow (<2 km) levels (Sundvoll et al. 1992). However, the fact that only tholeiitic dykes are known, suggesting a tensional stress regime, may signify that this dyke swarm was emplaced slightly later than the early complex of sills and dykes.

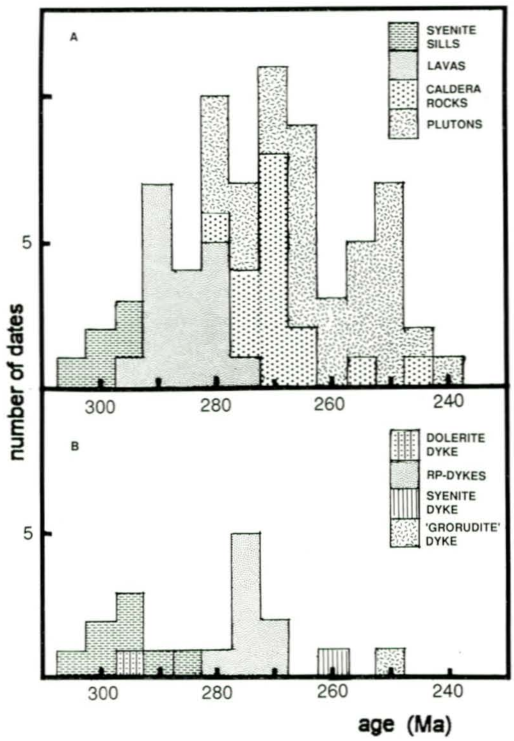

Fig. 3. Histogram showing distribution of ages from (A) Oslo Rift lavas and plutonic rocks, (B) dykes and sills. Data from Table 3, Sundvoll et al. (1990) and Sundvoll et al. (1992). The early syenite sills are shown in both histograms.

The discordant K-Ar ages of 275-265 Ma (Ihlen et al. 1984) of the dolerite dykes at Kongsberg (Fig. 2) indicate that this swarm was intruded somewhat before 275 Ma and possibly during the same period of dolerite dyke intrusions as those discussed above. However, the different strike trends of the Kongsberg dyke swarm may signify that this swarm was actually emplaced during a different overall stress regime (NW-SE tension) than the northern dyke swarm (E-W tension). This change may have occurred about the time the AGS started forming at about 280-270 Ma (Sundvoll & Larsen 1990).

The isochron ages obtained on the Bagn-Ådal dyke (285±7 Ma) and the Nesoddtangen dyke (290±11 Ma) suggest that dykes similar to those of the older complex of dykes and sills also intruded during an interval following the emplacement of this complex (Sundvoll et al. 1992). However, the

Table 2. Sm-Nd elemental and isotopic data.

Sample	ppm Sm	ppm Nd	^{147}Sm/^{144}Nd	^{143}Nd/^{143}Nd
Tonsåsen				
T-1a	11.67	53.01	.13408	.512665±5
Bjonvika				
BV-1	10.09	53.24	.11542	.512618±5
Brandbu				
RH-1	8.84	46.63	.11549	.512629±5
Valön (Bohuslän)				
BG-3	17.80	89.71	.12056	.512462±5
Hunneberg (Västergötland)				
HV-2	6.80	30.12	.13745	.512387±5
Billingen (Västergötland)				
BL-2	4.38	17.00	.1570	.512666±5
Kinnekulle (Västergötland)				
SK-1	10.57	47.39	.13581	.512404±5
Bagn-Ådal				
SP-1	18.90	106.18	.10841	.512542±5
Grimstad				
GG-1	17.17	103.00	.10152	.512589±5
Mjøndalen-Etnedal				
GB-3	13.03	73.37	.10817	.512635±5
GB-4	8.15	41.76	.11881	.512670±5
GB-6	8.40	42.02	.12168	.512662±5
GB-13	17.80	96.16	.11272	.512641±5
GB-24	17.97	96.82	.11298	.512642±5
Katfoss				
GB-14	17.39	105.13	.10069	.512639±5
Tyvholmen				
TG-1	20.85	121.35	.10463	.512678±5
Roa				
RG-1	16.1	97.8	.10025	.512661±5
Jevnaker				
RG-2	25.13	138.70	.11032	.512649±5
Gran				
RG-3	27.42	154.42	.10813	.512676±5
Ekeberg				
EB-5	21.52	125.10	.51269	.512694±5
Porsgrunn B_1 lava				
OB-69	7.86	58.36	.10171	.512558±5
Dignes gabbro				
D-2	18.38	99.04	.11305	.512755±5

ages also indicate that most of these dykes were intruded prior to emplacement of the plutons, that is >275 Ma (Sundvoll & Larsen 1990). The field relationship between the Nesoddtangen dyke and the northern tip of the Oslofjord master fault (Swensson 1990) indicate that faulting took place both prior to and after the emplacement of the dyke (290±11 Ma). Faulting and magmatism may, thus, have started concurrently.

The RP dyke ages (281-271 Ma), including those from the Bamble (Grimstad) and Bohuslän (Raftötången) areas, imply that these dykes are temporally disconnected from the eruption of the RP lavas of the plateau volcanism stage, dated to 295-280 Ma in the south and 295-275 Ma in the central part of the OG (Sundvoll et al. 1990). Thus, Brøgger's (1933b) original concept that the large RP dykes represented feeder-dykes for the RP lavas, is in dispute. On the other hand, the RP dykes now appear to be associated with the emplacement of the monzonitic (larvikite) plutons which took place at about 280-275 Ma in the VGS and about 275-265 Ma in the AGS (Sundvoll & Larsen 1990).

The age of the Storhaug 'grorudite' dyke (249±3 Ma) is not significantly younger than the age of the youngest pluton (252±3 Ma; Sundvoll & Larsen 1990) it intersects, and fits the prevalent view that the 'grorudite' dykes are associated with late differentiates of the alkali-syenitic (nordmarkite) magmas that formed peralkaline granitic intrusions (Sæther 1962). Thus, these dykes are conceivably chemically and petrograpically related to equivalent plutonic rocks.

The syenite dyke from Scania gave an age of 261±6 Ma, which is considerably younger than the dolerite dykes in that area (300±4 Ma; Klingspor 1976). This age provides evidence for an extended period (300-260 Ma) of magmatic activity in the area, which is also further supported by the suggestion that the lamprophyre dykes of this area are somewhat younger than the dolerites (Hjelmqvist 1940). Ro et al. (1990a) have shown that the SG is structurally linked to the Tornquist zone. The genetic and evolutionary relationship between the Tornquist zone and the Oslo Rift is further strengthened by the fact that magmatic activity in the Tornquist zone also shows a prolonged duration which coincides with the main period of development of the OG.

As noted above, dolerite and microsyenite ('mænaite') dyke swarms intruded early in the evolution of the Oslo Rift commonly exhibit a discontinuous pattern along strike. Similar observations have also been noted among the lamprophyres and ultrabasic dykes in the Bohuslän area (Ljungner 1927, Kresten et al. 1982). It is inferred that such a pattern is the result of dyke intrusion in a transtensional tectonic environment. The accompanying common en échelon offsets also support this conclusion. Strike-slip or shear movements along graben master faults have earlier been suggested by several authors (Cloos 1928, Størmer 1935) from structural analyses of secondary faults. The evidence presented above supports the notion that such movements are important tectonic elements in the early phase of rift development (Sundvoll & Larsen 1993).

Multiple dyke intrusions

Two of the larger RP dykes, the Ekeberg dyke situated southeast of Oslo (Fig. 2), and the Mjøndalen-Etnedal dyke situated in the northward continuation of the VGS (Figs. 2 and 5), were sampled to test the isotopic homogeneity across and along strike. The results from the Ekeberg dyke, also investigated by Walder (1985), will be presented in a separate publication. However, the relevant basic conclusion from that study is that the 1-2 m border-zone of this 25 m thick dyke invariably displays higher $^{87}Sr/^{86}Sr$ isotopic ratios than the central parts of the dyke implying contamination by the wall-rock (Lesher 1990). In order to obtain representative results, the sampling of the RP dykes discussed in this paper, were performed accordingly.

The Rb-Sr isotopic system of the large (160 km) Mjøndalen-Etnedal dyke displays several interesting properties that are not consistent with a simple intrusion history (Figs. 4 and 5). The two dated samples, GB-6 and GB-13, gave separate isochrons with different initial $^{87}Sr/^{86}Sr$ ratios (Table 3, Fig. 4). Most of the other whole-rock isotopic data fell on, or close to these two isochrons. Some samples (exemplified by GB-4) seem to fit a 275 Ma model isochron line with initial ratios of ≈.7072 (Fig. 5). Three samples fall outside this pattern, one (GB-31) is from the northernmost end of the dyke, and the other two (GB-17 & 18) from the area between GB-3 and GB-6 (Fig. 6). On the map (Fig. 6) the isotopic data from the Mjøndalen-Etnedal dyke demonstrate a close correlation with sample localities. This regular pattern strongly suggests a multiple intrusion mechanism with at least three separate pulses of RP magma. At the northern end of the dyke (Fig. 6), which is rather thin (<3 m) compared with the rest of the dyke (between 10 and 60 m), the intruding magma has evidently been strongly contaminated, as sample GB-31, although taken from the centre of the dyke, displays a very high $^{87}Sr/^{86}Sr$ ratio of ≈.7134 (Table 1, Fig. 4).

A closer inspection of the Mjøndalen-Etnedal samples also confirms differences in petrographic appearance between the three varieties (represented by the samples GB-13, GB-4 and GB-6, Fig. 6). In the northern-

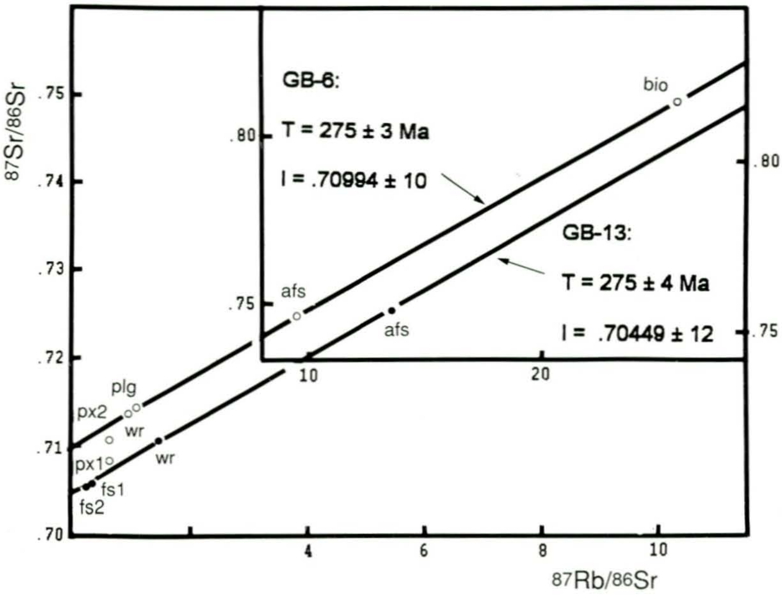

Fig. 4. Rb-Sr mineral isochrons of samples GB-6 and GB-13 from the Mjøndalen-Etnedal RP dyke. (Scale on right y-axis refers to the GB-13 sample in the expanded area).

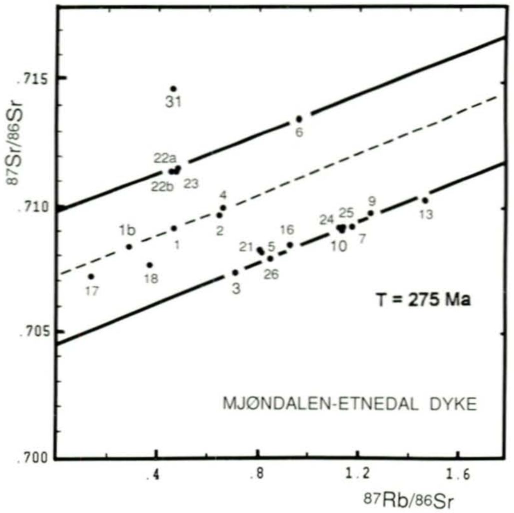

Fig. 5. Rb-Sr isotope systematics of whole-rock samples from the Mjøndalen-Etnedal RP dyke.

most segment the dyke rock is more phenocryst-rich than that in the southernmost segment, and far more phenocryst-rich than in that of the central segment. The dyke rock of the central and southern segments exhibits relatively large, rounded phenocrysts, whereas that of the northern segment displays rhomb-shaped phenocrysts.

Sr and Nd isotopic variation

The relationship among the radiogenic isotopes in the magmatic rocks of the Oslo Rift have been studied by Neumann et al. (1988), Anthony et al. (1989) and Neumann et al. (1990). These studies concluded that the primary magmas of the Oslo Rift igneous province may have originated in two different source regions in the mantle lithosphere. The mantle source of the majority of the magmatic rocks (here called Oslo mantle source: OMS) is characterised by $\epsilon_{Sr} \leq -5$, $\epsilon_{Nd} \geq 4$ and $^{206}Pb/^{204}Pb > 19.2$ (Neumann et al. 1988). Strongly silica-undersaturated basalts from the Skien area (here called the Skien mantle source, SMS), show $\epsilon_{Sr} < -10$, $2 > \epsilon_{Nd} > 1$ and $^{206}Pb/^{204}Pb > 20.5$ (Anthony et al. 1989). The OMS is comparable to the PREMA (prevalent mantle) and the SMS is similar to the HIMU (high-μ) sources of Zindler & Hart (1986). However, most samples hitherto analysed yielded higher ϵ_{Sr} and lower ϵ_{Nd} values than the OMS source,

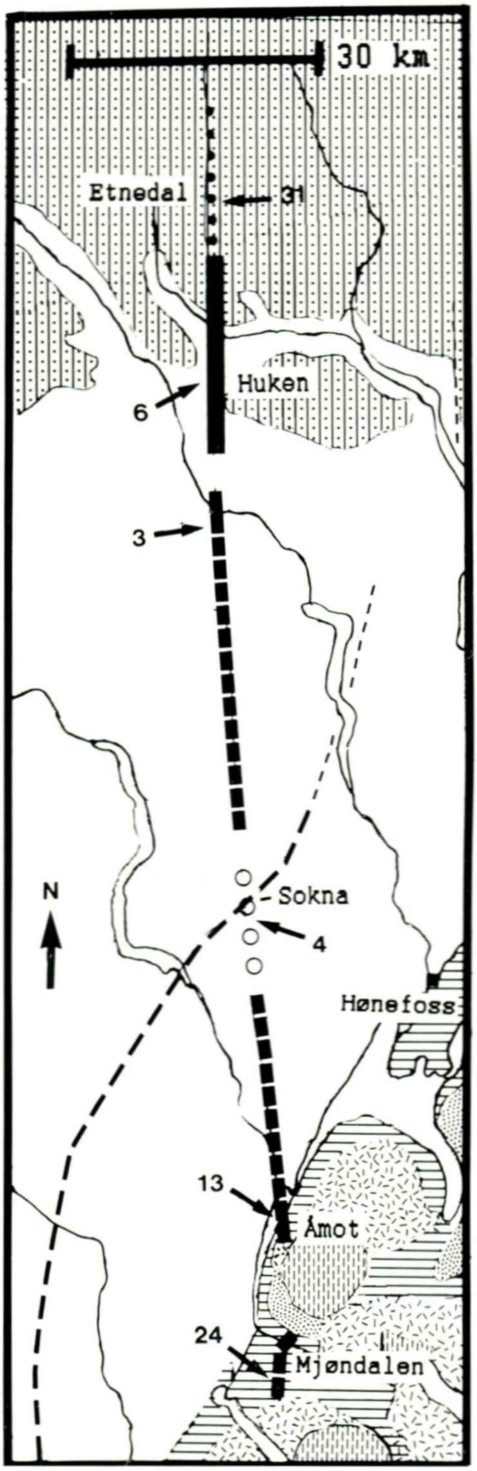

Fig. 6. Geological sketch-map of the Mjøndalen-Etnedal RP dyke indicating the different intrusions. (Country rock legend as in Fig. 2).

Table 3. Tb-Sr age determinations, $^{87}Sr/^{86}Sr$ initial ratios, $\in_{Sr}$ and $\in_{Nd}$ values based on tables 1 and 2. MSDW = $\sqrt{<\sum X^2/(N-2)>}$ where X = $(^{87}Sr/^{86}Sr)_{measured}$ $(^{87}Sr/^{86}Sr)_{isochron}$, N= number of samples. Assumed ages are based on Sundvoll & Larsen (1990) and Priem et al. (1975).

Rock unit	Age (Ma)	$(^{87}Sr/^{86}Sr)_I$	MSDW	N	ϵ_{Sr}	ϵ_{Nd}
Dolerite dykes and sills						
Tonsåsen	297 ± 9	0.70672 ± 5	1.25	9/10#	36.5	2.8
Bjonvika	(300)			1	3.4	2.7
Brandbu	(300)			1	12.1	2.8
Hunneberg d)	(300)			1	34.9	-2.8
Billingen d)	(300)			1	-.4	1.9
Kinnekulle d)	(300)			1	27.9	-2.4
Ultramafic dyke						
Valön b)	(300)			1	-.9	-0.8
Syenite (mænaite) dykes						
Nesoddtangen	290 ± 11	0.70533 ± 10	1.04	4	16.6	-
Bagn-Ådal	285 ± 7	0.71532 ± 20	1.98	5/7#	158.4	1.2
RP dykes						
Grimstad	281 ± 11	0.70446 ± 12	1.62	3	4.1	2.2
Raftötången b)	275 ± 12	0.70429 ± 9	0.69	6	1.7	1.9
Gjuvet (GB-3) a)	(275)			1	11.9	2.9
Sokna (GB-4) a)	(275)			1	46.2	3.2
Huken (GB-6) a)	275 ± 3	0.70994 ± 10	2.18	4/6#	81.8	3.0
Åmot (GB-13) a)	275 ± 4	0.70449 ± 12	0.91	4	4.7	2.8
Mjøndalen (GB-24) a)	(275)			1	8.9	2.8
Katfoss	276 ± 6	0.70402 ± 6	1.36	6	-2.2	3.2
Nakkerud	(275)			3	≈0.4	-
Tyvholmen	271 ± 10	0.70391 ± 16	0.30	3/4#	-4.2	3.8
Ekeberg	272 ± 7	0.70379 ± 9	1.09	4	-6.0	4.2
Roa	273 ± 7	0.70391 ± 11	0.14	3	-3.9	3.7
Jevnaker	(273)			1	-2.6	3.4
Gran	(273)			1	-2.5	3.7
Syenite dyke						
Torpa klint c)	261 ± 6	0.70733 ± 22	0.49	4	44.6	-
'Grorudite' dyke						
Storhaug	249 ± 3	0.70856 ± 92	1.68	6	61.8	.3
Porsgrunn B_1 lava						
OB-69	(295)			1	-12.1	1.8
Dignes gabbro						
D-2	(266)			1	-11.0	5.0

a) - Samples from the Mjøndalen-Etnedal dyke.
b) - Bohuslän, Sweden
c) - Scania, Sweden
d) - Västergötland, Sweden
\# = 5/6 means 5 of 6 analysed samples are used to define the isochron.

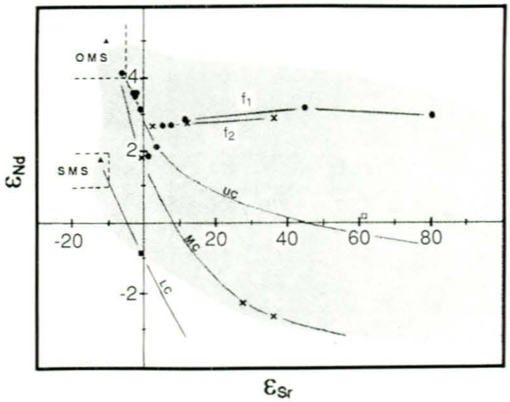

Fig. 7. Sr and Nd isotopic relations among the Oslo rift dykes. Shaded area: area covered by Oslo Rift igneous rocks. OMS: Oslo mantle source, SMS: secondary mantle source. f1 & f2: in-situ fluid interaction mixing trends. UC: mixing trend between OMS and a southern Scandinavian upper crustal sources (Neumann et al. 1988), MC: mixing trend between OMS and a middle crustal sources (Neumann et al. 1988), LC: mixing trend between SMS and a lower crustal source. Filled circles - RP dykes; crosses - dolerite dykes and sills; filled square - ultramafic dyke; filled triangles - gabbro and basalt; open square - per-alkaline granite dyke

indicating possible mixing between this source and crustal components. An important mixing trend, termed the 'Vestfold' (basalts) trend, has been proposed between the OMS and a mid-crustal contaminant component of perhaps ϵ_{Nd} -6 and ϵ_{Sr} 150, (Neumann et al. 1988, Neumann et al. 1990).

Calculated ϵ_{Sr} and ϵ_{Nd} values, as plotted in a ϵ_{Nd} versus ϵ_{Sr} diagram, Fig. 7, show that all the analysed dykes fall within the field represented by other Oslo magmatic rocks (Neumann et al. 1988). The sample from the Dignes gabbro neck that was believed to represent a relatively uncontaminated OMS (Neumann et al. 1985), gave an ϵ_{Nd} of 5 and an ϵ_{Sr} of -11.0, which is in accordance with the model (Fig. 7). The silica-undersaturated basalt sample OB-69 is petrographically similar to those analysed by Anthony et al. (1989), and it yielded an ϵ_{Nd} of 1.8 and an ϵ_{Sr} of -12.1. It is here taken to represent the SMS source.

The dolerite dykes from the Ådal-Valdres area have nearly identical ϵ_{Nd} values of 2.8 (Table 3), but very different and positive ϵ_{Sr} values. A possible explanation for this may be a differential contamination of radiogenic Sr in a magma with an $\epsilon_{Nd} \approx 3$ and $\epsilon_{Sr} \approx 0$ by crustal fluids during or shortly after emplacement, similar to what has been observed in other dykes (Patchett et al. 1979); or it could be explained as an incomplete mixing as envisaged by Lesher (1990). The uncontaminated magma source would fit a mixing-line between the OMS and a mid-crustal component (see below). In-situ contamination is clearly indicated by the Sr-isotope disequilibrium between the apatite fraction and the other minerals in the Tonsåsen dyke (Table 1). As apatite was most probably an early crystallising mineral, it may have gained the Sr isotopic signature of the original magma, whereas the later minerals aquired an input of radiogenic ^{87}Sr from interacting, most likely crustal fluids.

The dolerite sills from Hunneberg and Kinnekulle (Västergötland) fall on a mixing trend similar to the 'Vestfold' trend. The dolerite sill from Billingen, on the other hand, has a higher Nd (1.9), and thus seems more pristine. The difference in ϵ_{Nd} between these samples is also reflected in their chemistry. The Kinnekulle sample (from the border-zone?) is a quartz-basaltic andesite and the Hunneberg sample a quartz-tholeiite, whereas the Billingen sample is an olivine-tholeiite.

The ultramafic dyke from Valön (Bohuslän) may belong either to a mixing-trend beween OMS and a crustal component with a ϵ_{Sr} value of 0 - 50, (a lower crustal source), or it could represent mixing between a more0 ϵ_{Sr} negative primary magma, like the SMS, and a middle or lower crustal component. Petrographically and chemically this rock is a picrite (Kresten et al. 1982), and because of its very primitive composition we believe the second hypothesis to be the most probable. Anthony et al. (1989) have speculated that the SMS in the Porsgrunn area may represent a depleted mantle modified by the 550 Ma Fen magmatism, which is situated close by. However, the possible identification of a similar mantle source in the Bohuslän area would suggest a much wider extent for the SMS source.

The RP dykes can be divided into two groups according to their Sr and Nd isotopic behaviour (Fig. 7):

(1) The samples from the AGS, which have ε_{Nd} 3.5 to 4.2 and ε_{Sr} -2.4 to -6. These samples fit a mixing trend between the OMS and the Precambrian upper crustal average in South Norway (Andersen 1987), and contamination appears to have been moderate. (2) The dyke samples from VGS, and the Bamble and Bohuslän areas, which all have ε_{Nd} < 3.5 and ε_{Sr} >-2.4. The Grimstad dyke and the Katfoss dyke fit on the same mixing line as those of the first group. The Mjøndalen-Etnedal samples, however, have higher ε_{Sr} values, indicating possible in-situ contamination. This is supported by the behaviour of the minerals of sample GB-6. The pyroxene fractions (px1 & px2, Table 1) are not in equilibrium with the other minerals and fall below the isochron (Fig. 3). Although no detailed mineral probing of this sample has been undertaken, it is strongly suggested that early crystallising pyroxene was not in equilibrium with the rest melt, signifying interaction of the magma with a radiogenic ^{87}Sr contaminant, possibly fluids, during crystallisation. The Raftötången dyke from the Bohuslän area falls to the left of the mixing line which may indicate mixing with a less radiogenic ^{87}Sr component.

The fact that dykes in the same area not only yield overlapping ages, but also display very similar magma source isotopic signatures, is strong evidence that the dykes within each area constitute co-magmatic swarms.

The observation that many Oslo Rift igneous rock samples exhibit large positive ε_{Sr} values and still retain positive ε_{Nd} values make simple mixing models difficult to apply, at least in the sense of identifying the crustal component. This is demonstrated in the case of the Bagn-Ådal syenite dyke and the Storhaug peralkaline microgranite dyke (Fig. 7). In cases where no post-magmatic alteration is implied, it is suggested that in-situ or upper crustal interactions of the magmas with host-rock contaminants resulted in selective addition of radiogenic Sr by mechanisms such as those envisaged by Huppert & Sparks (1985) and Lesher (1990). Such phenomena can obscure other isotopic effects and make petrogenetic interpretation difficult and imprecise. Fluid inclusion and trace element studies should be added to petrogenetic investigations of these rocks.

Conclusions

Rb-Sr isochron ages obtained on the Oslo Rift dykes all fall within the previously established time span of the rift-related magmatism: 305-240 Ma.

The dykes show clear relationships between composition, age and geographic location. The oldest group, emplaced about 300-285 Ma ago, consists of tholeiitic dolerites and microsyenites from the Valdres-Ådal and Hadeland areas, and microsyenites from the Oslo area. A second group consists of c. 280-270 Ma old RP dykes occurring in widely different parts of the rift: Bamble area, Bohuslän (SW Sweden), AGS and the Mjøndalen-Ådal-Etnedal area. The third group is represented by a peralkaline microgranite dyke from the Nittedal caldera that has yielded an age of about 250 Ma, compatible with a possible association with the late alkali-syenite (nordmarkite) intrusions in the area.

The pattern of intrusion among the first group of dykes indicates that strike-slip movements occurred during the earliest phase of the rift evolution. The RP dykes of the second group are temporally associated with their plutonic counterparts. This fact indicates that they are not associated with the plateau RP lava eruptions as previously thought. The dykes of the third group, with chemical and petrographic relations to plutonic intrusions, are both spatially and temporally connected with the emplacement of their plutonic equivalents (larvikites).

RP dykes show large isotopic heterogeneities with respect to the Rb-Sr system. The Mjøndalen-Etnedal RP dyke shows at least three separate intrusion pulses along its strike, all with different initial ^{87}Sr/^{86}Sr ratios. Along-strike multiple intrusion has not previously been noted in the dykes of the Oslo Region.
The Sr - Nd isotopic relationship of the investigated dykes falls within the range covered by the other Oslo Rift magmatic rocks.

The dolerite dykes from the first group have variable ϵ_{Sr} values that may indicate in-situ interaction of the magma with crustal fluids. The dolerites from Västergötland and Scania in Sweden, however, fit a mixing-line between the OMS and a mid-crustal contaminant component.

The RP dykes can be split into two groups: one with $\epsilon_{Nd} > 3.5$, $\epsilon_{Sr} <-2.4$, and one with $\epsilon_{Nd} < 3.5$ and $\epsilon_{Sr} >-2.4$. The first group fits a mixing trend between the OMS and an upper crustal contaminant source; the second group, in addition, shows possible in-situ interaction with crustal fluids.

In-situ interaction between the intruding magma and a radiogenic ^{87}Sr contaminant, most likely crustal fluids, is suggested in the case of the Tonsåsen dolerite and the Mjøndalen-Etnedal RP dyke.

RP dykes from the same area have similar Nd and Sr isotopic behaviour and form true cogenetic swarms.

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References

Andersen, T. 1987: Mantle and crustal components in a carbonatite complex, and the evolution of carbonatite magmas: REE and isotopic evidence from the Fen complex,S.E. Norway. *Chem. Geol. 65,* 147-166.

Antun, P. 1964: Zur Genese des gemischten Gänge im Oslogebiet. *Nor. Geol. Tidsskr. 44,* 43-60.

Anthony,E.Y., Segalstad, T.V. & Neumann, E.-R. 1989: Anunusual mantle source region for nephelinites from the Oslo Rift, Norway. *Geochim. Cosmochim. Acta 53,* 1067-1076.

Barth, T.F.W. 1944: Lamprofyrer av to forskjellige aldre i kystmigmatitten vest for Kristiansand. (In Norwegian, English summary). *Nor. Geol. Tidsskr. 23,* 175-185.

Bäckström, H. 1890: Über fremde Gesteineinschlüsse in einigen skandinavischen Diabasen. *Medd. Stockholms Högskola 108,* 39 pp.

Brøgger, W.C. 1887: Geologisk kart over øerne ved Kristiania. (In Norwegian). *Nyt Mag. f. Naturv. 31,* 162-195.

Brøgger, W.C. 1894: Die Eruptivgesteine des Kristianiagebietes I. Die Gesteine des Grorudit-Tinguait-Serie. *Skr. Vidensk. Selsk. I. Mat.-naturv. Kl. 1894, No. 4,* 206 pp.

Brøgger, W.C. 1898: Die Eruptivgesteinedes Kristianiagebietes. III. Das Ganggefolge des Laurdalites. *Skr. Vidensk. Selsk. I. Mat.-naturv. Kl. 1897, No. 6,* 377 pp.

Brøgger, W.C. 1932: Die Eruptivgesteine des Oslogebietes VI. Über verschiedene Ganggesteine des Oslogebietes. *Skr. Norske Vidensk.-Akad. i Oslo. I. Mat.-naturv. Kl. 1932, No. 7,* 88 pp.

Brøgger, W.C. 1933a: Die Eruptivgesteinedes Oslogebietes VII. Die chemische Zusammensetzung der Eruptivgesteine des Oslogebietes. Skr. *Norske Vidensk.-Akad. i Oslo. Mat.-naturv. Kl. 1933, No. 1,* 147 pp.

Brøgger, W.C. 1933b: Essexitrekkens erupsjoner. (In Norwegian, German summary). *Nor. geol. unders. 138,* 103 pp.

Brøgger, W.C. 1933c: Om rombeporfygangene og de dem ledsagende forkastninger i Oslofeltet. (In Norwegian, German summary). *Nor. geol. unders. 139,* 51 pp.

Bryhni, I. & Dons, J.A. 1975: Orbicular lamprophyre from Vestby, southeast Norway. *Lithos 8,* 113-122.

Bugge, A. 1937: Flesberg and Eiker. Beskrivelse til de geologiske gradavdelingskarter, F. 35 Ø og F. 35 V. (In Norwegian, English summary). *Nor. geol. unders. 143,* 118 pp.

Bugge, C. 1917: Kongsbergfeltets geologi. (In Norwegian, English summary). *Nor. geol. unders. 82,* 272 pp.

Bylund, G. 1974: Palaeomagnetism of dykes along the southern margin of the Baltic Shield. *Geol. Fören. Stoch. Förh. 96,* 231-235.

Carstens, H. 1958: The origin of feldspar inclusions in the lamprophyres off Kristiansand, south Norway. *Nor. Geol. Tidsskr. 38,* 245-252.

Carstens, H. 1959: Comagmatic lamprophyres and diabases on the south coast of Norway. *Contrib. Min. Petrol. 6,* 299-319.

Cloos, H. 1928: Bau und Bewegung derGebirge in Nordamerika, Skandinavien und Mitteleuropa. $s3*Fortschr. Geol. Paläntol. 7,* 241-327.

DePaolo, D.J. & Wasserburg, G.J. 1976a: Nd isotopic variations and petrogenetic models. *Geophys. Res. Lett., 3,* 249-252.

De Paolo, D.J. & Wasserburg, G.J. 1976b: Inference about magmasource and mantle structure from variations of ^{143}Nd/^{144}Nd. *Geophys. Res. Lett. 3,* 743-746.

Dietrichson, B. 1945: Geologiske undersøkelser i Espedalen. Gradteig Vinstra og tilgrensende høifjell. (In Norwegian, English summary). *Nor. geol. unders. 163,* 45 pp.

Dons, J.A. 1952: Studies on the Igneous Rock Complex of the Oslo Region. XI. Compound volcanic neck, igneous dykes, and fault zones in the Ullern-Husebyåsen area, Oslo. *Skr. Norske Vitensk.-Akad. i Oslo I. Mat.-Naturv. Kl. 1952, No. 2.* 96 pp.

Dons, J.A. 1975: Olje-diabas fra Dyvika. (In Norwegian). *Esso Perspektiv 4,* 16-17.

Dons, J.A. 1977: Diabas fra Stig, 219 m.y. (In Norwegian). *Nytt fra Oslofeltgruppen 4,* 29-31.

Flodén, T. 1973: Notes on the bedrock of the eastern Skagerrak. *Stockh. Contrib. Geol. 24* 79-102.

Goldschmidt, V.M: 1909. Geologiske iagttagelser fra Tonsaasen i Valdres. (In Norwegian, German summary). *Nor. geol. unders., 53,* 2-20.

Goldschmidt, V.M. 1911: Die Kontaktmetamorphose im Kristianiagebiet. *Skr. Vidensk.-selsk. I. Mat.-naturv. Kl. 1911, No. 1,* 483 pp.

Halvorsen, E. 1970: Paleomagnetism and age of the younger diabases in the Ny-Hellesund area, S. Norway. *Nor. Geol. Tidsskr. 50.* 157-166.

Hasan, Zia-ul, 1971: Studies on the Igneous Rock Complex of the Oslo Region. XXII. Petrology and geochemistry of composite mica syenite porphyry dikes of the Oslo Region. *Skr. Norske Vitensk.-Akad. i Oslo, I. Mat.-Naturv. Kl. Ny serie, No. 30,* 17-80.

Hjelmqvist, S. 1940: Some post-Silurian dykes in Scania and problems suggested by them. *Sver. geol. unders. Ser. C. No. 430, Årsbok 33, No. 10,* 3-32.

Holtedahl, O. 1907: Alunskiferfeltet ved Øieren. (In Norwegan). *Nor. geol. unders. 45,* 1 1-19.

Huppert, H.E. & Sparks, R.S.J. 1985: Cooling and contamination of mafic and ultramafic magmas during ascent through continental crust. *Earth Planet. Sci. Lett. 74,* 371-386.

Huseby, S. 1971: Studies on the IgneousRock Complex of the Oslo Region. XXII. Permian igneous dikes in the southern part of the Bærum cauldron. *kr. Norske Vitensk.-Akad. i Oslo, I. Mat.-Naturv. Kl. Ny Serie, No. 39,* 1-16.

Ihlen, P.M., Ineson, P.R., Mitchell, J.G. & Vokes, F.M. 1984: K-Ar dating of dolerite dykes in the Kongsberg-Fiskum district, and their relationship with the silver and base metal veins. *Nor. Geol. Tidsskr. 64,* 87-96.

Isachsen, F. 1942: Permiske gangspalter i grunnfjellet vest for Randsfjorden og deres betydning for utformningen av relieffet. (In Norwegian, English summary). *Svensk geografisk Årbok 1942,* 24-38.

Jacobsen, S.B. & Wasserburg, G.J. 1984: Sm-Nd isotopic evolution of Chondrites. *Earth Planet. Sci. Lett. 50,* 139-155.

Klingspor, I. 1976: Radiometric age-determination of basalts, dolerites and related syenites in Skåne, southern Sweden. *Geol. Fören. Stoch. Förh. 98,* 195-216.

Kresten, P., Samuelsson, L. & Rex, D.C. 1982: Ultramafic dykes on the northern Skagerrak coast of Sweden. *Geol. Fören. Stockh. Förh. 103,* 285-289.

Lesher, C.E. 1990: Decoupling of chemical and isotopic exhange during magma mixing. *Nature 344,* 235-237.

Lidmar-Bergström, K. 1973: Tectonic analysis of south-western Sweden by means of ERTS images. *Sver. Geogr. Årsbok 49,* 125-133.

Ljungner, E. 1927: Spaltentektonik und Morphologie derschwedischen Skagerrak-Küste. *Bull. Geol. Inst. Uppsala 21,* 478 pp.

Mearns, E.W. 1986: Sm-Nd ages from Norwegian garnet peridotite. *Lithos 19,* 269-278.

Mulder, F.G. 1971: Palaeomagnetic research in some parts of central and southern Sweden. *Sver. geol. unders. Ser.C, Nr. 653, Årbok 64, Nr. 10,* 56 pp.

Naterstad, J. 1978: Nittedal cauldron (Alnsjø area). *In* Dons, J.A.& Larsen, B.T. (eds.) The Oslo Paleorift. A Review and Guide to Excursions. *Nor. geol. unders. Bull. 337, 99-103.*

Neumann, H. 1960: Apparent ages of Norwegian minerals and rocks. *Nor. Geol. Tidsskr. 40,* 173-191.

Neumann, E.-R., Larsen, B.T. & Sundvoll, B. 1985: Compositional variations among gabbroic intrusions in the Oslo Rift. *Lithos 18*, 35-59.

Neumann, E.-R., Tilton, G.E. & Tuen, E. 1988: Sr, Nd and Pbsotope geochemistry of the Oslo Rift igneous province, southeast Norway. *Geochim. Cosmochim. Acta 52,* 1997-2007.

Neumann, E.-R., Sundvoll, B. & Øverli, P.E. 1990: A mildly depleted upper mantle beneath souteast Norway: evidence from basalts in the Permo-Carboniferous Oslo Rift. *Tectonophysics 178,* 89-107.

Neumann, E.-R., Olsen, K.H., Baldridge, W.S. & Sundvoll, B.1992: The Oslo Rift: A review. *Tectonophysics 208*, 1-18.

Oftedahl, C. 1953: Studies on the igneous rock complex of the Oslo Region. XIII. The cauldrons. *Skr. Norske Vidensk.-Akad. i Oslo, I. Mat.-naturv. Kl. 1953, No. 3,* 108 pp.

Oftedahl, C. 1957: Studies on the igneous rock complex of the Oslo Region. XV. Origin of composite dikes. *Skr. Norske Vidensk.-Akad. i Oslo. I. Mat.-naturv. Kl. 1957, No. 2,* 17 pp.

Patchett, P.J., Breemen, O. van & Martin, R.F. 1979: Sr isotopes and structural sate state of feldspars as indicators of post-magmatic hydrothermal activity in continental dolerites. *Contrib. Mineral. Petrol. 69,* 65-73.

Priem, H.N.A., Mulder, F.G., Boelrijk, N.A.I.M., Hebeda, E.H., Verschure, R.H. & Verdurmen, E.A. 1968: Geochronological and paleomagnetic reconnaissance survey in parts of central and southern Sweden. *Phys. Earth Planet. Interiors 1,* 373-380.

Ramberg, I.B. & Larsen, B.T. 1978: Tectonomagmatic Evolution. *In* Dons, J.A. & Larsen, B.T. (eds.) The Oslo paleorift. A Review and Guide to Excursions. *Nor. geol. unders. 337,* 55-73.

Ro, H.E., Larsson, F.R., Kinck, J.J. & Husebye, E.S. 1990a: The Oslo Rift-its evolution on the basis of geological and geophysical observations. *Tectonophysics 178,* 11-28.

Ro, H.E., Stuevold, L.M., Faleide, J.I. & Myhre, A.M. 1990b: Skagerrak Graben - the offshore continuation of the Oslo Graben. *Tectonophysics 178,* 1-10.

Rock, N.M.S. 1977: The nature and origin of lamprophyres: some definitions, distinctions, and derivations. *Earth Sci. Rev. 13,* 123-169.

Samuelsson, L. 1967: Multiple intrusion in some rhomb porphyry dikes of the Swedish Skagerrak-Coast. *Teknik och Natur 1967,* 369-383.

Samuelsson, L. 1971: The relationship between Permian dikes of dolerite and rhombporphyry along the Swedish Skagerrak coast. *Sver. geol. unders. Ser. C. No. 663, Årsbok 65, No. 9,* 49 pp.

Scott, R.W. & Middleton, R. 1983: Camptonite and Maenaite sills near Gran, Hadeland, Oslo Region. *Nor. geol. unders. 389,* 1-26.

Selmer-Olsen, R. 1950: Om forkastningslinjer og oppbrytningssoner i Bambleformasjonen. (In Norwegian). *Nor. Geol. Tidskr. 28,* 171-191.

Smithson, S. B. 1963: Granite studies: II. The Precambrian Flå granite. *Nor. geol. unders. 219,* 212 pp.

Steiger, K.H. & Jäger, E. 1977: Subcommission on geochronology: convention on use of decay constants in geo- and cosmochronology. *Earth Planet. Sci. Lett. 36,* 359-362.

Størmer, L. 1935: Contribution to the geology of the southern part of the Oslofjord. *Nor. Geol. Tidsskr. 15, 43-114.*

Strand, T. 1938: Nordre Etnedal. Beskrivelse til det geologiske gradteigskart. (In Norwegian, English summary). *Nor. geol. unders. 152,* 71 pp.

Strand, T. 1954: Aurdal. Beskrivelse til det geologiske gradteigskart. (In Norwegian, English summary). *Nor. geol. unders. 185,* 71 pp.

Suleng, H. 1919: Spaltedannelser og yngre eruptiver i Arendal-Grimstadtraktene. (In Norwegian). *Naturen 43,* 288-291.

Sundvoll, B. & Larsen, B.T. 1990: Rb-Sr systematics in the Oslo rift magmatic rocks. *Nor. geol. unders. Bull. 418,27-46*

Sundvoll, B., Neumann, E.-R., Larsen, B.T. & Tuen, E. 1990: Age relations among Oslo Rift magmatic rocks: implications for tectonic and magmatic modelling. *Tectonophysics 178,* 67-87.

Sundvoll, B., Larsen, B.T. & Wandaas, B. 1992: Early magmatic phase in the Oslo Rift and its related stress regime. *Tectonophysics, 208,* 37-54.

Sundvoll, B. & Larsen, B.T. 1993: Architecture and early development of the Oslo Rift. *Tectonophysics (in press).*

Swensson, E. 1990: Cataclastic rocks along the NesoddenFault, Oslo Region, Norway: a reactivated Precambrian shear zone. *Tectonophysics, 178,* 51-65.

Sæther, E. 1945: Studies on the igneous rock complex of the Oslo Region. III. The south-eastern part of the Bærum-Sørkedal cauldron. *Skr. Norske Vidensk.-Akad. i Oslo. I. Mat.-naturv. Kl. 1945, No. 6,* 60 pp.

Sæther, E. 1946: Studies on the igneous rock complex of the Oslo Region. VII. The area of lavas and sediments in Nittedal. Skr. *Norske Vidensk.-Akad. i Oslo. I. Mat. naturv. Kl. 1946. No. 6,* 34 pp.

Sæther, E. 1947: Studies on the igneous complex of the Oslo Region. VIII. The dykes in the Cambro-Silurian lowland of Bærum. *Skr. Norske videsk.-Akad. i Oslo, Mat.-naturv. Kl. 1947, No. 3,* 60 pp.

Sæther, E. 1962: Studies on the igneous rock complex of the Oslo Region. XVIII. General investigation of the igneous rocks in the area north of Oslo. *Skr. Norske Vidensk.-Akad. i Oslo. I. Mat.-naturv. Kl. Ny serie, No. 1,* 150 pp.

Walder, I.F. 1985: *En petrologisk og geokjemisk undersøkelse* *av to rombeporfyrganger, en sentralt i og en øst for Oslograben.* (In Norwegian). Thesis in geology, University of Oslo. 112 pp.

Werenskiold, W. 1911: Fornebolandet og Snarøen i østre Bærum. (In Norwegian, English summary). *Nor. geol. unders. 58,* 36 pp.

York, D. 1969: Least squares fitting of a straight line with correlated errors. *Earth Planet. Sci. Lett. 5,* 320-324.

Zeck, H.P., Andriessen, P.A.M., Hansen, K., Jensen, P.K. & Rasmussen, B.L. 1988: Paleozoic paleo-cover of the southern part of the Fennoscandian Shield - fission track constraints. *Tectonophysics* 149, 61-66.

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