Rb-Sr isotope systematics in the magmatic rocks of the Oslo Rift

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

Fifty-one different units of Oslo Rift magmatic rocks have been investigated by the Rb-Sr isotope method. Isochron ages obtained for all but three of the units vary between 295 Ma and 240 Ma. The ages from the southern (Vestfold) segment of the rift are generally older (294 ± 6 Ma to 266 ± 5 Ma) than those from the northern (Akershus) segment (291 ± 8 Ma to 241 ± 3 Ma), suggesting a northward migration of the magmatic activity with time. A similar migration within each of these two segments of the rift is also suggested by the data. Rhomb-porphyry eruptions seem to have started almost simultaneously in the southern and central parts of the rift at around 295-290 Ma. Lava eruption ended earlier (280 Ma) in the southern than in the central area (276 Ma). Caldera formation represents a distinct magmatic stage in the Vestfold segment (269-266 Ma). In the Akershus segment caldera formation seems to have taken place episodically over a longer period of time. Magmatic stages that are distinct in both segments, like the emplacement of multiple larvikite plutons, occurred at a later time in the Akershus (273-266 Ma), than in the Vestfold segment (281-276 Ma). $^{87}Sr/^{86}Sr$ initial ratios obtained for rhomb-porphyry lavas, larvikites and related rocks, $\varepsilon_{Sr}(t)$: -5.6 to -3.5, are compatible with a moderately LIL-depleted mantle source with a Rb/Sr ratio of about .04. Crustal contamination in magma chambers and/or during ascent to the surface is also demonstrated for these rocks.

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Introduction

The Oslo Region, located in the southwestern part of the Fennoscandian Shield, and made classic through the papers of Professor W.C. Brøgger (1851-1940), has continuously evoked interest among geologists mainly because of its extensive magmatic province of mildly alkaline rocks. The magmatic rocks cover 75-80% of the area, the rest being made up of Precambrian basement and Palaeozoic sediments (Ramberg 1976). The magmatic province is structurally associated with the Oslo Graben, a structure some 200 km long and 40 km wide, extending NNE-SSW from the coast of Skagerrak to the lake Mjøsa in SE Norway. The graben and its associated igneous rocks are genetically connected to a rift zone (Oslo Rift), which probably extends from the southern part of Skagerrak (Ramberg & Smithson 1975) to the Särna area of western central Sweden (Bylund & Patchett 1977), some 500 km distant. (For comprehensive definitions of the terms Oslo Region, Oslo Graben, and Oslo Rift, see: Dons, 1978).

Being a currently inactive geological structure eroded down to at least 2-3 km below its original surface, the Oslo Rift represents an unique opportunity to study a dissected continental rift associated with extensive magmatism, and which has completed its evolutionary cycle. In addition, the Oslo Rift has not been noticeably affected by later geological processes other than weathering and erosion. Because of the dissected state of the rift, the Oslo igneous province is characterised by large areas of plutonic rocks. Extrusive rocks have only been preserved in restricted domains.

Geophysical evidence (gravity, magnetic and seismic) from the Oslo Graben (Ramberg 1976, Åm & Oftedahl 1977, Wessel & Huseby 1985) has contributed significantly to the discussion of the petrogenesis of the magmatic rocks and the evolutionary history of the rift (Ramberg & Larsen 1978, Neumann et al. 1986). Geochemical investigation of the magmatic rocks, especially by use of mineral, trace-element and

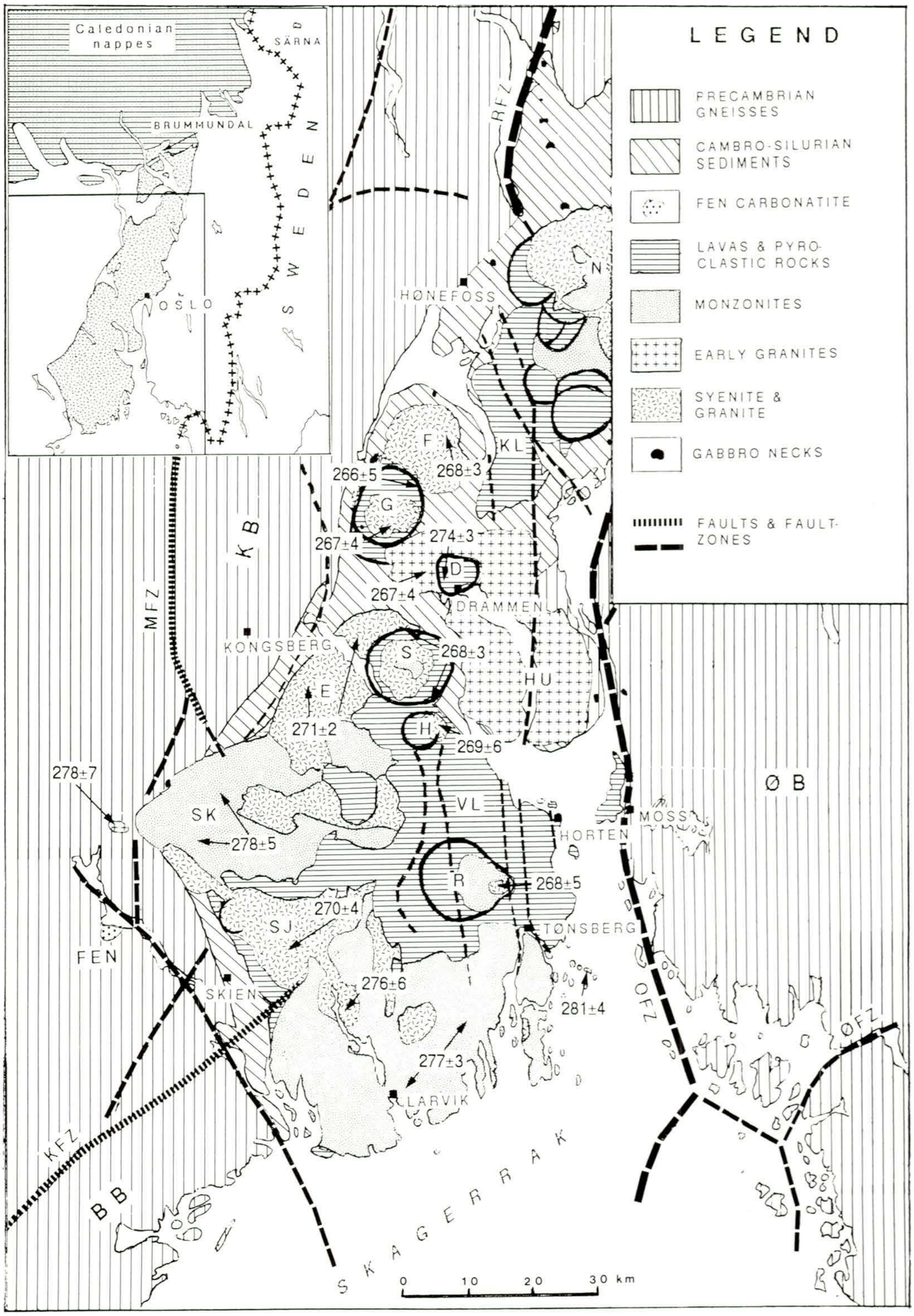

Fig. 1. Geological map showing age determinations from the Vestfold GS. Ages (in Ma) from Table 2 and Rasmussen et al. (1988); geological data from Larsen (1975). BB: Bamble block, D: Drammen, E: Eikeren, F: Finnemarka, G: Glitrevann, H: Hillestad caldera, KB: Kongsberg block, KFZ: Kristiansand-Porsgrunn Fault Zone, KL: Krokskogen lava plateau, MFZ: Meheia-Ådal Fault Zone, N: Nordmarka, OFZ: Oslofjord Fault Zone, R: Ramnes, RFZ: Randsfjord Fault Zone, S: Sande, SJ: Siljan, SK: Skrim, VL: Vestfold lava plateau, ØFZ: Øyemark Fault Zone, ØB: Østfold Block. Inset map showing Oslo Graben and Särna complex.

isotope analysis, has also made notable progress (Neumann 1980, Rasmussen et al. 1988, Neumann et al. 1988). The purpose of this paper is to present the results of a major isotopic investigation of the Oslo magmatic rocks, both from the geochronological point of view and from initial ^{87}Sr/Sr^{86} isotope systematics. Preliminary results from this investigation were presented by Sundvoll (1978b). Some of the data have been published elsewhere (Neumann et al. 1985, Rasmussen et al. 1988). A full discussion of the geochronological aspects in relation to rift evolution is presented in a separate paper (Sundvoll et al. 1990).

Geological and petrological relations

The Oslo Rift is recognised as one of several rifts in an extensive area of NW Europe subjected to rifting during and after the Hercynian orogeny (Dixon et al. 1981, Ziegler 1982). The Oslo Rift is, however, remarkable in being the only rift exposed on land (Oslo Graben) and for its prominent magmatic activity. The Oslo Graben (Fig. 1, inset) can be subdivided into two graben segments (GS) termed the Vestfold GS and the Akershus GS (Ramberg & Larsen 1978).

Within the graben two groups of sedimentary rocks are present: a pre rift Lower Palaeozoic sequence (Henningsmoen 1978), and a proto- to early-rift Upper Palaeozoic sequence (Olaussen 1981). In addition, remnants of synrift sediments are preserved between and above the lavas (Rosendahl 1929, Størmer 1935).

The extrusive rocks are of three principal types: basaltic lavas (B), intermediate rhombporphyry lavas (RP), and trachytes/rhyolites (T/R). (For details of the stratigraphy see Ramberg & Larsen (1978)). The extrusives are preserved in two major areas, the central Vestfold area and the Krokskogen area, which are considered remnants of extensive lava plateaus (Fig. 1). Other minor occurrences of lavas are encountered inside the calderas, and in two small, separate blocks: the Skien area in the extreme southwest, and in the Brummundal area in the extreme northeast, respectively (Fig. 1). (The term caldera is used in this paper for all structures interpreted as collapsed central volcanoes, i.e. including caldera remnant or cauldron.)

Except in the northernmost part of the Oslo Graben (Hurdal-Brummundal), the oldest part of the preserved lava sequence consists of basaltic lavas (B_1-basalts). In the Skien area the lavas are strongly to mildly silica-undersaturated (nephelinites, basanites and ankaramites) (Segalstad 1979, Anthony et al. 1989). In the central Oslofjord area (Moss-Horten) the B_1-basalts are of mildly silica-undersaturated to mildly oversaturated types (ankaramite, alkali-olivine basalt, trachybasalt) (Øverli 1985, Tollefsrud 1987, Schou-Jensen & Neumann 1988). In the area north of Oslo (Nordmarka) the B_1-sequence consists of one lava-flow of tholeiitic composition (Weigand 1975).

The B_1-flows were followed by a thick sequence of rhomb-porphyry (RP-) lavas. This sequence seems to have been present throughout the Oslo Graben (Oftedahl 1952). Due to the lateral extent, chemical composition and timing of eruptions, the RP-lavas have been considered a counterpart to the plateau phonolite lavas of the Kenya Rift (Oftedahl 1967). The total thickness of the preserved RP lava sequence varies from 3000 m in the Vestfold area to about 400 m in the Brummundal area. Scattered basaltic and basanitic flows are encountered within the RP sequence. In the Vestfold area flows of trachytic composition are also found.

The petrology and geochemistry of the RP lavas have been investigated by Oftedahl (1978b) and Andresen (1985). The RP lavas are mildly silica-undersaturated, saturated and oversaturated types with relatively high concentrations of REE and Th. Oftedahl (1978b) has shown that the lavas in Vestfold generally become more evolved and silica-rich from the bottom to the top of the lava pile. From the data presented by Brøgger (1933) it appears that the same is also valid for the Krokskogen area.

The calderas of the Oslo Rift have been interpreted as collapsed, bimodal, (basalt-trachy-rhyolite), central volcanoes (Oftedahl 1953, Ramberg & Larsen 1978). The basalts are mainly of the alkali-olivine type (Weigand 1975, Ramberg & Larsen 1978). The trachy-rhyolitic members are commonly K-alkaline and in many cases ignimbritic (Sørensen 1975, Oftedahl 1978a). Oftedahl (1978b) claimed that little or no basic lava is associated with most of the calderas, and that they represent the roofs of felsic magma-chambers that collapsed by withdrawal of support below. However, basaltic extrusions of very local extent are spatially associated with a number of calderas (Glitrevann, Drammen, Bærum, Heggeli, Øyangen, Nittedal: Figs. 1 and 3), and in our view support the original model.

The most important rocks in the Oslo Graben, both in volume and areal extent, are the intrusives. Apart from the separate complex of sills and dykes which intrude the pre-rift Lower Palaeozoic sediments (Brøgger 1894, Sæther 1947), the intrusions form four major composite plutons (CP): The Tønsberg-Larvik CP, the Skrim-Eikeren CP, the Hurum-Finnemarka CP, and the Nordmarka-Hurdal CP. In the Tønsberg-Larvik and Skrim-Eikeren areas, monzonitic rocks (larvikites) dominate, and in the Nordmarka-Hurdal area syenites are the most voluminous. In the Hurum-Finnemarka CP granitic rocks are most important. The Tønsberg-Larvik, Skrim-Eikeren and Hurum-Finnemarka complexes are situated within the Vestfold GS, the Nordmarka-Hurdal CP in the Akershus GS. Two small granitic outliers are located west of Skrim (Jacobsen & Raade 1975), and east of Nittedal, (Neff & Khalil 1978).

The overall field relations are relatively well known, although much of the most recent field data is still not published. The Skrim-Eikeren CP has been described by Segalstad (1975) and the Tønsberg-Larvik CP by Petersen (1978a, 1978b). Both found that the earliest intrusions are larvikites. Petersen (1978a, 1978b) also showed that the larvikite intrusions in the Larvik-Tønsberg area, including the nepheline-bearing Hedrum complex north of Larvik, are composed of overlapping semicircular intrusions. The centres of the intrusions were offset successively from east to west. The chemistry of the larvikites in this area has been discussed by Neumann (1980), who found the two earliest intrusions to be mildly silica-oversaturated, whereas the succeeding intrusions became silica-saturated and undersaturated. The younger Hedrum complex is strongly silica-undersaturated (Petersen 1978a).

In the Hurum-Finnemarka area the intrusions are mainly granites (Ihlen et al. 1982), although some intermediate rocks occur in the northern part of the area (Czamanske 1965).

The Nordmarka-Hurdal area has been studied by Sæther (1962), Nystuen (1975b) and Schønwandt & Petersen (1983). They all agree that the earliest intrusions are monzonites which predate syenitic intrusions. The monzonites in the Hurdal area are strongly metamorphosed by later intrusions (Tuen 1985). The monzonites are cut by granites, syenites and associated granites. The granitic intrusions in the Oslo Graben can be divided into two groups (Gaut 1981). One group (BG I of Gaut) intruded early in the CP-forming stage, simultaneously with, or shortly after, the emplacement of the monzonites. These granites have affinities with normal subsolvus granites and show no transition into, or relation to, other rock groups. The granites of group two (BG II of Gaut), are mainly alkaline and hypersolvus and clearly show transition into alkalisyenite.

Some of the syenites have affinities with the monzonites (i.e. the Øyangen syenite; Larsen 1979), others seem to form separate geochemical trends and are possibly of hybrid origin (Andersen 1984, Rasmussen et al. 1988). Sæther (1962) and Nystuen (1975b) also found that in the Nordmarka-Hurdal area the earlier sequence of monzonitic and granitic intrusions were separated from later syenitic-granitic intrusions by a complex of subvolcanic rocks (breccias, ignimbrites, etc.), related to diatremes and ring structures (Nystuen 1975a).

Rb-Sr isotope analysis

Sampling

Fifty-one units of magmatic rocks have been included in this study. The units were selected to cover most rock types, units, geographic areas, and the longest possible time span of the rift history. However, basaltic rocks are under-represented, and rock types such as rhyolites, ignimbrites, breccias, etc., have been avoided due to xenolith content and other inhomogeneities, as well as to the extent of post-magmatic interactions. More units from the Akershus GS (33) have been considered than from the Vestfold GS (18), due to indications of a more complex magma-tectonic evolution in the Akershus GS (Ramberg & Larsen 1978).

Most of the samples used in this study were collected for the exclusive purpose of age determination (size related to texture, no weathering, no veins, etc.). However, in some cases where suitable material existed in the collections of the Mineralogical-Geological Museum in Oslo, this was utilised. For whole-rock age determinations a minimum of six samples was normally used. To assist the sample selection, thin-sections were prepared and studied under the microscope.

Twenty-seven of the units considered have been analysed using the whole-rock method. The other twenty-four units have either been processed with the pure mineral separation technique or a simplified separation into matrix and phenocrysts. The choice of method was primarily related to the availability of suitable samples and the need for adequate dispersion in Rb/Sr ratios.

Analytical methods

All analytical work was carried out in the geochemical laboratories of the Mineralogical-Geological Museum, University of Oslo, in the period 1975 to 1984. The samples were cleaned and crushed to suitable grain size according to the method applied (whole-rock: ≈300 mesh, mineral separation: ≈100 mesh). The samples for mineral-isochron dating were separated using standard mineral-separation techniques: magnetic separators, heavy liquids and hand-picking. The mineral fractions were crushed to appropriate size (300 mesh). Minerals used were: feldspar, pyroxene, biotite, and apatite. Rb-Sr elemental concentrations and Rb/Sr ratios in whole-rock samples were normally determined by XRF-spectrography, using a modified version of the method described by Norrish & Chappell (1967). In some low Sr-high Rb samples, and in all mineral separates, such data were obtained by isotope-dilution techniques using a combined spike of enriched ^{87}Rb and ^{84}Sr as described by Boelrijk (1968).

^{87}Sr/^{86}Sr isotopic ratios were determined by thermal ionization mass-spectrometry using a Micromass MM30 single-collector instrument. The mass-spectrometry analyses were performed according to the procedure de scribed by Jacobsen & Heier (1978). During the period of analysis the NBS 987 standard yielded an average value of .71026±4 on the instrument used. The precision in the determinations of Rb/Sr by XRF is estimated to 1%, and the precision in the isotope dilution analysis ≤.5%. These values were used in the age calculations. Isochron ages for the various rock units were computed using the method described by York (1969). Due to the relatively fresh condition of most samples, only isochron fits yielding MSWD (Mean of Squared Weighted Deviatives) values ≤2.5 were considered as true isochrons (Brooks et al. 1972). The $\varepsilon_{Sr}(t)$ notation follows the definition of DePaolo & Wasserburg (1978a) using the uniform reservoir (UR) values for Rb-Sr (^{87}Rb/^{86}Sr = 0 .0827, ^{87}Sr/^{86}Sr = .7045), reported by DePaolo & Wasserburg (1978b). All ages are based on the value of 1.42×10^{-11} y^{-1} for the decay of ^{87}Rb, as recommended by Steiger & Jäger (1977). All uncertainties quoted are ±2.σ

Results

The analytical results are listed in Tables 1a and 1b. The results of the isochron calculations are listed in Table 2. The data have been divided into two main groups according to the tectonic environment of the units dated, i.e. the Vestfold GS and the Akershus GS, respectively. Furthermore, the data are broadly grouped according to the tectonomagmatic setting of the units, i.e. plateau-lavas, caldera-related lavas and intrusives, and plutons. Isochron ages with MSWD ≤2.5 were obtained for all units except the Hedrum plagi-foyaite, the Slottet larvikite and the Kampehaug quartz-syenite. The ages are, thus, generally interpreted as true extrusion/intrusion ages. As indicated in Table 2, some units yielded an acceptable isochron only when one or more samples were excluded, even though maximum care had been taken in sample selection. In some cases this was anticipated, as more than one rock type was sampled to test co-magmatic and/or coeval evolution, (e.g. Gjærdingen complex). Sampling in areas where field mapping is inadequate may have been the problem in some of the other cases, (e.g. Skrim larvikite). However, partial resetting of the Sr-isotope ratios during late- or post-magmatic processes may also be of importance. The problem of poor MSWD seems to occur most frequently among acidic rock types (Table 2). These intrusions are positively more affected by interaction with middle- and upper-crustal material (Rasmussen et al. 1988), but can also, in some cases, be shown to have been influenced by hydrothermal events. These problems can only be thoroughly elucidated by the application of mineral studies and other isotope methods e.g. U-Pb chronology and O-isotopes.

Table 1a. Elemental and isotopic data. Vestfold graben segment. Rb-Sr concentrations and Rb/Sr ratios obtained by isotope dilution technique are marked #
wr = whole rock, mx = matrix, phen = phenocryst, fsp = feldspar, *cpx = clinopyroxene, afs = alkalifeldspar, plg = plagioclase,* bio = biotite, ap = apatite

Sample	ppm Rb	ppm Sr	^{87}Rb/^{86}Sr	^{87}Sr/^{86}Sr*
Vestfold rhombporphyry lavas (RP$_{1+2}$)				
ER 1 wr	193.4	1114.1	0.5022#	.70599 ± 8
ER 1 mx	173.2	858.4	0.5835#	.70635 ± 4
ER 1 phen	323.4	2276.5	0.4109#	.70569 ± 9
ER 1 wr	128.3	663.7	0.5591#	.70619 ± 3
VR 1 mx	126.0	462.9	0.7874#	.70724 ± 7
VR 1 phen	75.7	2607.0	0.0840#	.70429 ± 9
Vestfold (Tønsberg) rhombporphyry lavas (RP$_{2\pm3}$)				
SL 1 wr	126.5	810.0	0.4518#	.70577 ± 6
SL 1 mx	128.5	728.0	0.5108#	.70606 ± 6
SL 1 phen	34.7	3429.9	0.0293#	.70402 ± 8
SL 2 wr	123.0	1081.0	0.3290#	.70531 ± 7
SL 2 mx	146.8	496.7	0.8549#	.70751 ± 4
SL 2 phen	86.2	2043.6	0.1220#	.70446 ± 5
Vestfold trachyte lava (T$_1$)				
TR 1 wr	122.3	148.3	2.3884#	.71633 ± 6
TR 1 fsp1	139.8	141.7	2.8564#	.71823 ± 8
TR 1 fsp2	90.9	220.4	1.1938#	.71144 ± 8
TR 1 ap	5.9	689.1	0.0247#	.70660 ± 4
TR 2 wr	134.1	163.8	2.3694#	.71608 ± 7
Vestfold rhombporphyry lava (RP$_{13}$)				
VR 13 wr	143.6	629.8	0.6591#	.70685 ± 5
VR 13 mx	200.9	355.8	1.6336#	.71075 ± 6
VR 13 phen	80.4	1456.8	0.1596#	.70472 ± 4
Vestfold trachyte lava (T$_2$)				
TR 22 wr	103.3	204.8	1.4602#	.71606 ± 4
TR 22 fsp1	51.3	417.1	0.3556#	.71158 ± 3
TR 22 fsp2	97.3	261.9	1.0761#	.71450 ± 7
Vestfold rhombporphyry lava (RP$_{19}$)				
V 21 wr	149.7	588.5	0.7361#	.70711 ± 5
V 21 mx	162.9	288.8	1.6322#	.71082 ± 5
V 21 phen	124.7	1110.2	0.3249#	.70552 ± 5
Vestfold rhombporphyry lava (RP$_{26}$)				
TF 1 wr	142.3	588.7	0.6994#	.70686 ± 6
TF 1 mx	176.7	363.5	1.4062#	.70965 ± 8
TF 1 phen	82.7	971.4	0.2462#	.70499 ± 5
Drammen (Bragernes) rhyolite lava				
DK 1	166.3	32.2	15.0055	.76256 ± 6
DK 2	248.0	35.1	20.6209	.78428 ± 8
DK 3	137.7	39.6	10.0876	.74317 ± 8
DK 4	145.8	41.2	10.2784	.74367 ± 9
DK 5	114.8	77.2	4.3068	.72074 ± 9
Hillestad syeniteporphyry (central intrusion)				
HI 365	286.1	107.7	7.7037	.73340 ± 8
HI 366	110.8	39.2	8.2056	.73721 ± 9
HI 367	107.9	83.1	3.7600	.72011 ± 8
HI 368	151.7	28.4	15.5281	.76540 ± 10
HI 369	204.4	121.6	4.8712	.72399 ± 9
HI 370	238.1	85.8	8.0479	.73598 ± 10
HI 11	235.5	87.1	7.8416	.73555 ± 7
HI 12	88.2	308.4	0.8274	.70748 ± 8
Glitrevann granite (central intrusion)				
GS 732	184.8	20.0	27.04152	.80773 ± 8
GS 760	182.0	9.3	57.7553	.92283 ± 10
GS 761	167.2	29.7	16.39402	.76828 ± 9
GS 773	196.0	19.0	30.2155	.81915 ± 9
GS 774	158.3	65.4	7.0184	.73227 ± 9
GS 775	122.7	68.4	5.2019	.72464 ± 9
Glitrevann syeniteporphyry (ring dyke)				
GS 734	80.9	66.5	3.5251	.71941 ± 7
GS 736	79.1	50.7	4.5173	.72314 ± 7
GS 738	83.9	57.5	4.2331	.72247 ± 9
GS 759	79.1	51.5	4.4564	.72291 ± 10
GS 763	113.3	17.0	19.41702	.77867 ± 10
GS 764	113.3	20.2	16.34822	.76881 ± 7
GS 765	98.4	76.9	3.7074	.71900 ± 8
Larvik-Tønsberg larvikite (Bolærne)				
LV 1 wr	68.4	1226.9	0.1613#	.70468 ± 5
LV 1 cpx	19.7	99.3	0.5730#	.70631 ± 3
LV 1 plg	3.9	1432.4	0.0483#	.70419 ± 5
LV 1 afs	337.5	474.4	2.0592#	.71222 ± 5
LV 1 ap	9.4	352.4	0.0771#	.70428 ± 5
Skrim larvikite				
SL 103	105.8	298.2	1.0271	.70803 ± 10
SL 118	124.0	427.6	0.8390	.70730 ± 8
SL 130	190.8	209.2	2.6403	.71445 ± 5
SL 279	212.6	257.4	2.3911	.71329 ± 8
SL 306	122.5	528.2	0.6711	.70653 ± 7
SL 132	213.3	286.7	2.1535	.71245 ± 9
SL 96	76.3	477.2	0.4628	.70565 ± 9
SL 115	105.9	458.4	0.6683	.70676 ± 10
SL 199	165.6	482.9	0.9925	.70855 ± 6
SL 297	182.0	424.3	1.2413	.70889 ± 10
SL 704	108.2	468.5	0.6683	.70658 ± 5
SL 708	152.1	591.8	0.7435	.70749 ± 7
SL 83	171.2	427.0	1.1603	.70843 ± 10
SL 101	109.1	377.4	0.8361	.70715 ± 7
SL 123	111.5	42.2	7.6724	.73428 ± 10
SL 191	64.5	560.9	0.3327	.70594 ± 10
SL 250	185.3	270.1	1.9855	.71169 ± 10
Hedrum plagifoyaite				
HN 21	111.3	687.1	0.4686	.70569 ± 9
HN 31	156.5	1142.1	0.3963	.70534 ± 7
HN 16	144.8	713.4	0.5872	.70603 ± 7
HN 28	138.6	1237.2	0.3240	.70504 ± 9
HN 436	155.0	760.0	0.5901	.70614 ± 9
HN 45	127.9	779.7	0.4744	.70590 ± 10
HN 8	82.9	341.3	0.7030	.70650 ± 10
Kvelde foyaite				
KN 33	124.8	215.2	1.6786	.71111 ± 9
KN 32	152.6	44.0	10.0753	.74427 ± 9
KN 20	250.5	493.1	1.4702	.71060 ± 10
KN 14	131.8	757.6	0.5034	.70660 ± 10
Siljan nordmarkite (alkalisyenite)				
SY 6	121.3	124.6	2.8200	.71510 ± 10
SY 53	57.0	21.6	7.6544	.73350 ± 10
SY 441	168.2	48.4	10.0969	.74265 ± 9
SY 223	139.3	16.5	24.6838	.80407 ± 8
SY 224	264.1	13.1	59.5316	.93388 ± 10
SY 445	60.5	19.7	8.9059	.73841 ± 3
SY 448	90.7	10.3	25.7754	.80381 ± 10
SY 713	79.8	44.5	5.1900	.72404 ± 7
Drammen granite				
DG 1 wr	228.7	90.4	7.3350#	.73288 ± 7
DG 1 bio	867.6	106.4	23.8078#	.79722 ± 7
DG 1 plg	2.4	33.6	0.2040#	.70618 ± 6
DG 1 afs	640.2	64.2	29.1477#	.81578 ± 5
Finnemarka granite				
FG 1230	184.1	29.4	18.21092	.77373 ± 4
FG 1231	203.7	30.5	19.44302	.77852 ± 4
FG 1229	183.7	26.2	20.41722	.78207 ± 4
FG 749	195.6	57.7	9.8473	.74266 ± 5
FG 752	181.9	69.9	7.5500	.73351 ± 9
FG 756	150.3	85.7	5.0825	.72350 ± 8
FG 742	130.7	435.8	0.8681	.70880 ± 5
FG 741	72.9	482.9	0.4368	.70632 ±
FG 744	85.1	467.6	0.5265	.70669 ± 9
FG 746	188.7	68.4	8.0012	.73556 ± 9

* including standard error

Table 1b. Elemental and isotopic data. Akershus graben segment. Rb-Sr concentrations and Rb/Sr ratios obtained by isotope dilution technique are marked #.
wr = whole rock, mx = matrix, phen = phenocryst, fsp = feldspar, cpx = clinopyroxene, afs = alkali feldspar, plg = plagioclase, bio = biotite, ap = apatite, sø = 'sørkedalite', lv = larvikite

Sample	ppm Rb	ppm Sr	^{87}Rb/^{86}Sr	^{87}Sr/^{86}Sr*
Krokskogen basalt lava (B_1-Kolsås)				
OB 6	54.4	477.1	0.3298	.70655±7
OB 8	13.0	371.8	0.1012	.70572±5
OB 15	149.6	490.4	0.8825	.70902±5
OB 24	53.6	894.0	0.1736	.70596±7
OB 71	170.2	718.2	0.6857	.70805±4
OB 72	75.2	894.9	0.2430	.70631±6
OB 73	241.0	1575.4	0.4426	.70719±10
OB 78	23.5	670.3	0.1012	.70573±6
OB 80	16.3	388.5	0.1215	.70584±6
OB 83	122.7	701.3	0.5063	.70738±6
OB 84	23.2	891.5	0.0752	.70557±10
OB 85	163.4	585.6	0.8073	.70863±9
OB 86	157.7	697.7	0.6539	.70791±8
OB 88	10.2	537.9	0.0550	.70545±8
Krokskogen rhombporphyry lava (RP_1)				
Q 120	114.5	1111.8	0.2979	.70535±8
Q 115	155.7	1226.3	0.3674	.70548±8
Q 810	139.7	950.3	0.4252	.70580±8
Q 917	213.9	967.8	0.6393	.70660±7
Q 936	157.7	1659.9	0.2748	.70503±8
Q 817	159.1	1223.6	0.3760	.70551±5
Q 820	181.4	1251.3	0.4194	.70573±4
Q 943	127.0	492.4	0.7464	.70708±6
Q 817L	99.2	1140.5	0.2516	.70500±8
Q 817M	207.4	1249.5	0.4802	.70597±9
Q 810L	114.7	1219.9	0.2719	.70512±9
Q 810M	239.4	1330.3	0.5207	.70617±6
Krokskogen rhombporphyry lavas (RP_{2A+B})				
RP 114 mx	215.7	834.7	0.7478	.70693±6
RP 114 phen	82.7	2768.0	0.0864	.70423±7
RP 114 wr	148.8	1489.1	0.2890	.70503±8
RP 815	158.5	861.2	0.5323	.70611±8
RP 951	133.7	891.3	0.4339	.70571±5
RP 21K	116.2	589.3	0.5704	.70624±4
RP 941	138.2	231.9	1.7243	.71101±4
Krokskogen rhombporphyry lava (RP_5)				
K 1501	195.2	753.5	0.7495#	.70734±2
K 1502 wr	185.5	813.1	0.6601#	.70693±3
K 1502 phen	43.9	1272.2	0.0997#	.70463±9
K 1502 mx	240.7	524.3	1.3283#	.70965±8
Krokskogen rhombporphyry lava (RP_6)				
K FS 3	156.7	1047.2	0.4328#	.70583±8
KFS 2	157.8	1229.1	0.3715#	.70552±8
KFS 6 wr	147.4	633.3	0.6731#	.07669±7
KFS 6 fsp	168.9	646.6	0.7558#	.70709±5
KFS 6 cpx	17.2	204.6	0.2439#	.70502±6
KFS 6 ap	1.3	776.2	0.0048#	.70403±6
Krokskogen rhombporphyry lava (RP_7)				
KFS 7 wr	225.7	447.3	1.4603#	.70995±6
KFS 7 fsp1	67.1	1194.4	0.1625#	.70483±5
KFS 7 fsp2	232.9	211.0	3.1968#	.71702±6
Krokskogen rhombporphyry lava (RP_{11})				
K 1515 wr	142.7	654.4	0.6308#	.70686±4
K 1515 phen	43.1	1002.6	0.1242#	.70491±7
K 1515 mx	172.5	411.3	1.2133#	.70924±5
K 1509 wr	152.4	670.6	0.6573#	.70698±8
K 1509 phen	177.0	1924.4	0.2660#	.70555±6
K 1509 mx	169.1	336.4	1.4547#	.71025±7
Krokskogen rhombporphyry lava (RP_{12})				
KFS 12 wr	121.6	580.6	0.6059#	.70700±7
KFS 12 cpx	2.7	56.8	0.1358#	.70519±10
KFS 12 fsp1	137.9	822.8	0.4849#	.70655±10
KFS 12 fsp2	137.4	1241.9	0.3200#	.70579±10
KFS 12 fsp3	123.1	775.8	0.4590#	.70643±7
KFS 12 mx	118.5	531.0	0.6458#	.70719±6
KFS 12 ap	2.0	2064.4	0.0025#	.70463±6
Storflåten rhombporphyry lava ($RP_{13}C$)				
Q 72 wr	124.5	753.5	0.4778#	.70639±8
Q 72 mx	153.8	358.4	1.2419#	.70936±6
Q 72 phen	75.1	1321.8	0.1644#	.70509±6
Storflåten rhombporphyry lavas ($RP_{14A+14B}$)				
Q 34 wr	211.5	845.8	0.7234#	.70688±7
Q 34 mx	235.0	484.2	1.4046#	.70965±5
Q 34 phen	64.3	1455.5	0.1278#	.70461±5
Q 128 wr	143.6	855.9	0.4853#	.70599±9
Q 129 mx	155.7	416.9	1.806#	.70840±5
Q 129 phen	96.0	1232.8	0.2252#	.70496±8
Brumunddal rhombporphyry lava (RP_4)				
BRP 1 mx	187.2	207.1	2.6182#	.71705±8
BRP 1 FSp	186.5	476.3	1.1335#	.71118±7
BRP 1 FSp	186.5	476.3	1.335#	.71118±7
BRP 2 mx	188.6	204.8	2.6668#	.71717±7
BRP 2 FSp	212.2	502.8	1.2214#	.71157±10
BRP 3 FSp3	160.3	383.7	1.2093#	.71142±3
BRP 3 wr	130.5	264.5	1.4273#	.71211±7
BRP 3 FSp1	153.8	326.3	1.3731#	.71201±7
BRP 3 FSp2	167.7	441.2	1.1001#	.71094±6
Øyangen basalt lava				
Ø-543 wr	11.8	326.7	0.1047#	.70479±3
Ø-543 plg	21.2	2202.7	0.0278#	.70453±3
Ø-543 afs	138.4	499.9	0.8007#	.70759±3
Kampen syeninite-porphyry				
KS 1 fsp1	168.1	213.1	2.2839#	.71571±8
KS 1 cpx	35.0	37.6	2.6919#	.71715±6
KS 1 fsp2	36.3	264.5	0.3966#	.70826±7
Heggelia syenite-porphyry				
OH 1 wr	206.4	258.2	2.3139#	.71524±5
OH 1 fsp1	205.0	280.6	2.1153#	.71462±8
OH 1 fsp2	190.4	260.6	2.1148#	.71470±5
OH 1 fsp3	189.5	224.4	2.4457#	.71574±7
OH 1 ap	9.7	275.0	0.1021#	.70683±3
Oppkuven syenite-porphyry				
OP 1 cpx 1	7.1	61.1	0.3345#	.70705±7
OP 1 cpx2	12.3	120.8	0.2946#	.70680±8
OP 1 fsp1	60.7	835.4	0.2103#	.70655±7
OP 1 fsp2	290.9	436.0	1.9314#	.71319±7
OP 1 fsp3	58.1	898.6	0.1869#	.70644±9
OP 1 wr	220.5	621.2	1.0270#	.70969±9
OP 1 ap	1.0	2011.1	0.0143#	.70571±5
Øyangen ring-dyke (Stubdal syenite)				
RS 1	120.8	381.1	0.9171	.70705±9
RS 2	108.6	485.0	0.6480	.70643±4
RS 3	141.0	154.8	2.6373	.71397±8
RS 4	119.2	354.8	0.9721	.70769±10
RS 5	199.9	22.5	25.9628	.80323±5
RS 6	114.5	421.1	0.7869	.70695±10
Øyangen central intrusion (Ringkollen syenite)				
RS 7	211.7	21.8	28.4339	.81264±10
RS 8	155.2	95.8	4.6935	.72191±10
RS 9	220.0	18.1	35.5718	.83905±10
Stryken syeniteporphyry				
HS 1	102.3	313.0	0.9461	.70796±7
HS 2	68.6	410.6	0.4831	.70603±8
HS 3	77.0	218.2	1.0213	.70816±9
HS 4	81.8	156.7	1.5106	.71005±10
HS 5	63.5	520.7	0.3529	.70558±7
HS 6	96.9	24.0	11.7391	.74936±10
HS 7	100.6	581.8	0.5004	.70611±6
HS 8	82.2	170.6	1.3948	.70957±10

Table 1b (continued)

Sample	ppm Rb	ppm Sr	^{87}Rb/^{86}Sr	^{87}Sr/^{86}Sr*
Bærum syenite-porphyry (ring-dyke)				
SP 1	97.6	60.9	4.6471	.72184 ± 8
SP 2	134.7	112.6	3.4640	.71880 ± 10
SP 3	163.0	59.7	7.9160	.73419 ± 11
SP 4	201.1	28.7	20.3837	.77693 ± 9
SP 5	236.4	33.7	20.4111	.77606 ± 10
SP 6	98.4	78.4	3.6374	.71769 ± 10
SP 7	141.2	41.0	9.9967	.74105 ± 8
SP 8	168.9	59.8	8.1898	.73558 ± 10
SP 9	248.3	13.9	52.6249	.89553 ± 8
SP 10	269.8	12.7	62.6590	.92576 ± 10
SP 11	171.1	40.8	12.1794	.74836 ± 7
Slottet larvikite				
KL 1	23.5	651.9	0.1041	.70430 ± 10
KL 2	178.4	759.1	0.6798	.70660 ± 10
KL 3	152.0	273.4	1.6091	.71066 ± 9
KL 4	107.0	673.1	0.4600	.70681 ± 7
KL 5	115.4	894.7	0.3731	.70533 ± 9
KL 6	142.1	840.7	0.4889	.70576 ± 8
KL 7	113.4	852.2	0.3847	.70613 ± 10
KL 8	152.9	831.0	0.5323	.70614 ± 10
KL 9	88.0	1275.7	0.1996	.70460 ± 10
KL 10	106.9	848.4	0.3645	.70584 ± 8
Kjeldsås larvikite				
KL 11 sø	67.8	1059.1	0.1851	.70453 ± 7
KL 12 sø	67.6	669.4	0.2921	.70497 ± 7
KL 13 sø	130.6	1061.7	0.3558	.70524 ± 10
KL 14 wr	190.8	1114.2	0.4953#	.70603 ± 6
KL 14 fsp1	310.4	1031.7	0.8705#	.70757 ± 9
KL 14 fsp2	24.8	1039.6	0.0689#	.70430 ± 9
KL 14 cpx	18.9	66.2	0.8277#	.70730 ± 4
KL 14 bio	845.7	29.1	86.8389#	1.03904 ± 8
KL 14 ap	6.1	293.1	0.0603#	.70428 ± 4
Kampehaug quartz-syenite				
KL 15	132.1	455.6	0.8391	.70833 ± 6
KL 16	145.6	444.0	0.9491	.70981 ± 9
KL 17	143.5	421.9	0.9838	.70901 ± 9
Øyangen syenite				
ØS 1	96.5	264.6	1.0445	.70807 ± 9
ØS 2	138.4	167.8	2.3881	.71305 ± 8
ØS 3	108.3	707.7	0.4426	.70561 ± 10
ØS 4	149.2	255.1	1.6930	.71031 ± 9
ØS 5	176.1	30.9	16.6159	.77418 ± 8
ØS 6	96.7	221.9	1.2616	.70874 ± 7
ØS 7	96.3	341.6	0.8158	.70702 ± 10
ØS 8	105.8	604.3	0.5062	.70592 ± 6
Gjærdingen syenite/larvikite				
	SG 1 69.1	401.9	0.4975	.70585 ± 9
SG 2	202.1	10.6	56.5090	.90981 ± 10
SG 3	116.4	210.6	1.6004	.70986 ± 10
SG 4	150.0	223.9	1.9391	.71097 ± 6
SG 5	113.6	178.1	1.8464	.71080 ± 5
SG 6 lv	76.5	1779.4	0.1244	.70414 ± 8
SG 7 lv	129.3	1469.5	0.2545	.70475 ± 9
Grua granite				
GG 1	232.4	137.2	4.9090	.72417 ± 3
GG 2	159.1	26.5	17.5053	.77146 ± 9
GG 3	333.6	26.4	36.9914	.84435 ± 8
GG 4	403.1	90.9	12.8829	.75339 ± 11
GG 5	270.2	98.3	7.9744	.73469 ± 12
GG 6	236.2	7.8	90.6305	1.04317 ± 10

Sample	ppm Rb	ppm Sr	^{87}Rb/^{86}Sr	^{87}Sr/^{86}Sr*
Harestua nordmarkite (alkali-syenite)				
SS 1	78.3	262.8	0.8622	.70762 ± 5
SS 2	93.2	45.9	5.8836	.72586 ± 8
SS 3	99.0	108.0	2.6546	.71363 ± 9
SS 4	136.2	23.5	16.8838	.76527 ± 10
SS 5	136.3	8.4	47.7945	.87603 ± 10
SS 6	256.1	8.0	95.4957	1.04650 ± 3
SS 7	253.1	4.7	164.0007	1.29180 ± 10
Grefsen syenite				
GS 1	121.0	104.0	3.3707	.71686 ± 9
GS 2	152.9	66.2	6.6972	.72904 ± 7
GS 3	126.8	212.0	1.7307	.71081 ± 8
GS 4	146.3	80.2	5.2884	.72384 ± 8
GS 5	120.7	111.3	3.1389	.71625 ± 8
GS 6	224.0	18.9	34.6482	.83014 ± 9
GS 7	106.0	63.4	4.8419	.72321 ± 10
GS 8	106.6	209.8	1.4701	.71010 ± 9
GS 9	95.1	144.7	1.9016	.71176 ± 10
GS 10	102.0	91.6	3.2264	.71845 ± 8
Tryvann alkali-granite				
TG 1	180.7	123.9	4.2235	.72041 ± 7
TG 2	152.1	13.8	32.1916	.81802 ± 10
TG 3	209.2	45.3	13.4067	.75169 ± 10
TG 4	*175.2*	*88.1*	*5.7645*	*.72539 ± 5*
TG 5	198.4	17.8	32.6030	.81667 ± 10
TG 6	120.5	100.2	3.4838	.71737 ± 9
Storøyungen granite				
SG 1	286.7	23.8	35.2894	.83703 ± 8
SG 2	269.3	118.8	6.5702	.72994 ± 8
SG 3	263.5	93.8	8.1548	.73897 ± 10
SG 4	273.6	55.8	14.2511	.75927 ± 9
SG 5	275.4	129.7	6.1579	.72887 ± 8
SG 6	290.5	73.2	11.5345	.74831 ± 8
SG 7	353.1	39.7	25.9903	.80333 ± 6
SG 8	245.9	60.4	11.8344	.75146 ± 8
Hersjø granite				
HG 1	199.6	52.7	10.9954	.74671 ± 10
HG 2	161.9	164.5	2.8493	.71626 ± 6
HG 3	160.3	241.1	1.9251	.71339 ± 10
HG 4	146.1	179.5	2.3567	.71461 ± 10
HG 5	180.1	266.0	1.9597	.71302 ± 9
HG 6	168.7	46.8	10.4593	.74499 ± 6
HG 7	168.0	255.0	1.9077	.71326 ± 10
Røtjern granite				
RG 1	177.1	226.9	2.2617	.71388 ± 5
RG 2	166.9	242.0	1.9974	.71291 ± 5
RG 3	194.0	242.1	2.3202	.71395 ± 6
RG 4	184.8	241.8	2.2219	.71358 ± 6
RG 5	197.4	135.0	4.2650	.72102 ± 7
RG 6	156.2	238.3	1.9057	.71249 ± 3
Fjellsjøkampen syenite				
FS 1	135.7	131.7	2.9823	.71557 ± 6
FS 2	106.0	246.6	1.2443	.70982 ± 9
FS 3	192.0	89.1	6.2498	.72753 ± 10
FS 4	80.7	52.2	4.4790	.72117 ± 7
FS 5	110.3	312.5	1.0214	.70890 ± 7
FS 6	84.9	9.9	25.1317	.79471 ± 10
FS 7	171.0	22.6	22.1055	.78253 ± 10
Brennhaugen per-alkaline-granite (ekerite)				
BE 1	219.2	58.4	10.9063	.74484 ± 10
BE 2	553.0	14.3	116.7523	1.11166 ± 10
BE 3	411.0	27.5	43.7398	.82752 ± 10
BE 4	123.1	97.8	3.6467	.71925 ± 10
BE 5	545.7	26.9	59.5617	.86542 ± 9
BE 6	251.2	15.1	49.0046	.87695 ± 3

* including standard error

Table 2. Rb-Sr age determinations and ^{87}Sr/^{86}Sr initial ratios.
MSWb = $\sqrt[2]{X^2/N-2}$ where X = (^{87}Sr/^{86}Sr)$_{\text{measured}}$ - (^{87}Sr/^{86}Sr)$_{\text{isochron}}$, N = number of samples, B = basalt, RP = rhombporphyry, T = trachyte, R = rhyolite, larv. = larvikite, sy. = syenite, foy. = foyaite, nord. = nordmarkite, gr. = granite, porph. = porphyry, qz. = quartz, alk. = alkaline, w.r. = whole rock, min. = minerals; * : *5/6 means 5 of 6 analysed samples are used to define the* isochron. Error quoted at 2 level.

Rock unit	Age (Ma)	(^{87}Sr/^{86}Sr)$_I$	MSDW	Met.	N
VESTFOLD GRABEN SEGMENT					
Plateau lavas:					
RP$_{1+2}$ Vestfold	291 ± 18	0.70392 ± 14	0.69	min.	6
RP$_{2+3}$ Vestfold	294 ± 6	0.70392 ± 4	0.20	min.	6
T$_1$ Vestfold	288 ± 4	0.70650 ± 8	0.99	min.	5
RP$_{13}$ Vestfold	288 ± 7	0.70409 ± 8	2.07	min.	3
T$_2$ Vestfold	285 ± 7	0.71010 ± 10	0.01	min.	3
RP$_{19}$ Vestfold	284 ± 10	0.70418 ± 12	1.07	min.	3
RP$_{26}$ Vestfold	283 ± 8	0.70401 ± 8	0.36	min.	3
Caldera lavas and intrusions:					
R-lava Drammen	274 ± 3	0.70390 ± 40	0.76	w.r.	5
Hillestad sy. porph.	269 ± 6	0.70555 ± 52	1.10	w.r.	6/8*
Glitrevann gr.	267 ± 4	0.70519 ± 52	1.78	w.r.	6
Glitrevann sy. porph.	266 ± 5	0.70614 ± 36	1.72	w.r.	6/7*
Plutonic intrusions:					
Bolærne larv.	281 ± 4	0.70401 ± 5	0.38	min.	5
Skrim larv.	278 ± 5	0.70392 ± 8	0.77	w.r.	14/17
Hedrum plagifoy.		no isochron		w.r.	7
Kvelde foy.	276 ± 6	0.70464 ± 18	1.90	w.r.	4
Siljan nord.	270 ± 4	0.70420 ± 30	0.35	w.r.	7/8*
Drammen gr.	267 ± 4	0.70539 ± 90	2.09	min.	4
Finnemarka alk. gr.	268 ± 3	0.70466 ± 12	1.46	w.r.	9/10*
AKERSHUS GRABEN SEGMENT					
Plateau lavas:					
B$_1$ Krokskogen	291 ± 8	0.70528 ± 6	0.91	w.r.	14
RP$_1$ Krokskogen	292 ± 20	0.70398 ± 14	0.54	w.r.	12
RP$_{2A+B}$ Krokskogen	290 ± 4	0.70388 ± 4	0.26	w.r.	7
RP$_5$ Krokskogen	288 ± 9	0.70424 ± 10	0.44	min.	4
RP$_6$ Krokskogen	284 ± 7	0.70402 ± 6	0.32	min.	6
RP$_7$ Krokskogen	281 ± 6	0.70417 ± 10	0.76	min.	3
RP$_{11}$ Krokskogen	276 ± 6	0.70446 ± 8	0.99	min.	6
RP$_{12}$ Krokskogen	278 ± 8	0.70462 ± 4	0.22	min.	7
RP$_{13C}$ Storflåten	278 ± 12	0.70446 ± 12	0.37	min.	3
RP$_{14A+B}$ Storflåten	278 ± 5	0.70408 ± 6	0.36	min.	6
RP$_4$ Brummundal	279 ± 9	0.70660 ± 20	0.96	min.	8
Table 2 (continued)					
Caldera lavas and intrusions:					
B-lava Øyangen	280 ± 7	0.70440 ± 5	1.20	min.	3
Kampen sy. porph.	274 ± 6	0.70672 ± 16	1.61	min.	3
Heggelia sy. porph.	270 ± 4	0.70644 ± 6	1.24	min.	5
Oppkuven sy. porph.	272 ± 6	0.70571 ± 6	0.19	min.	7
Stubdal sy.	268 ± 5	0.70395 ± 9	0.08	w.r.	5/6*
Ringkollen sy.	268 ± 5	0.70404 ± 56	0.20	w.r.	3
Stryken sy. porph.	271 ± 3	0.70421 ± 6	0.38	w.r.	8
Bærum sy. porph.	243 ± 3	0.70681 ± 36	1.25	w.r.	7/11*
Plutonic intrusions:					
Slottet larv.		no isochron		w.r.	10
Kjeldsås larv.	273 ± 4	0.70400 ± 10	0.87	min.	6
Kampehaug qz.-sy.		no isochron		w.r.	3
Øyangen sy.	266 ± 8	0.70399 ± 14	0.61	w.r.	7/8*
Gjærdingen sy./larv.	256 ± 5	0.70402 ± 14	0.64	w.r.	5/7*
Grua gr.	262 ± 3	0.70570 ± 50	1.85	w.r.	6
Harestua nord.	252 ± 3	0.70448 ± 12	2.07	w.r.	7
Grefsen sy.	255 ± 4	0.70472 ± 18	1.09	w.r.	8/10*
Tryvann alk. gr.	241 ± 3	0.70570 ± 30	1.44	w.r.	6
Storøyungen gr.	263 ± 4	0.70560 ± 60	0.92	w.r.	6/8*
Hersjø gr.	263 ± 5	0.70570 ± 30	0.47	w.r.	5/7*
Røtjern gr.	253 ± 10	0.70565 ± 35	0.57	w.r.	6
Fjellsjøkampen sy.	248 ± 4	0.70535 ± 14	0.76	w.r.	6/7*
Brennhaugen alk. gr.	245 ± 4	0.70660 ± 40	0.35	w.r.	4/6*

The average time resolution (mean of errors on the isochron ages, Table 2), on all units is ≈6 million years. Excluding the two very imprecise ages on the lowermost RP lavas at Vestfold and Krokskogen, we obtain a time resolution of about 5 million years, which is used in this paper as the average minimum time resolution measurable with this technique. The data will be discussed below in the same sequence as they appear in Table 2.

Discussion

I) Vestfold GS

a) Plateau-lavas

In the Vestfold lava area some forty to fifty different lava flows have been recognised, most of which are of the RP type (Oftedahl 1978). Six of the dated units are from the main lava plateau, and one is from the Tønsberg area (Fig. 1). The oldest unit considered (RP_{1-2}) comprises two samples from RP_1- and RP_2- lavas in the Horten area. In the second unit (RP_{2-3}), samples from RP_2- and RP_3- lavas from the Tønsberg (Slottsfjellet) area are considered. There is no conclusive field evidence to show that the stratigrapy in these two areas is identical; in fact, there are several indications that the stratigraphy of the Tønsberg area is different from that of the Horten area. Thus, the separate treatment of the samples from the two areas is appropriate, although the initial $^{87}Sr/^{86}Sr$ ratios are indistinguishable and the two isochrons overlap.

Five additional lava units were sampled along an E-W traverse across the Vestfold plateau west of Horten. The T units are thick, trachytic flows (Oftedahl 1978b). The high initial Sr isotopic ratios of the T units (Table 2) are discussed below. The RP_{26} unit is the uppermost identified lava in the Vestfold plateau (Oftedahl 1978b), and its age of 283±8 Ma may be considered the upper time limit of the plateau volcanism in this area. However, some caution should be observed as the lava area south of the Skrim pluton has not yet been completely mapped. The total time span of the plateau volcanic activity in the Vestfold area would be about 10 million years, from ≈295 Ma to ≈285 Ma (Table 2).

b) Caldera lavas and intrusions

The calderas of the Vestfold GS have been studied by Sørensen (1975), Segalstad (1975) and Oftedahl (1978a). The proposed caldera at Skrehelle has not been investigated by us. The other calderas (Ramnes, Hillestad, Sande, Drammen and Glitrevann, Fig. 1) form a conspicuous N-S row approximately along the central axis of the GS. Only one extrusive unit, a rhyolitic ignimbrite from the Drammen caldera, has been dated. This flow is situated between the RP_{11} and RP_{12} flows in this area (Halsen 1981). A similar unit is also present in the southwestern part of the adjacent Glitrevann caldera, where we find an analogous, thick, rhyolitic ignimbrite at the corresponding stratigraphic level (Oftedahl 1978b, Gaut 1981). There is compelling field evidence that this huge ignimbrite had its origin in the Glitrevann caldera (thickness variation, size and distribution of clasts & xenoliths, etc). The whole-rock isochron age implies that the central volcano was initiated no later than 274±3 Ma (Table 2). The occurrence of local basaltic lavas below this rhyolite suggests an even earlier date for the initiation of the central volcano in this area.

Detailed studies of the lavas associated with the Ramnes caldera (Sørensen 1975, Oftedahl 1978b) have suggested that the central volcano here probably was initiated at the time when the youngest RP lavas of the Vestfold plateau were extruded. Based on the data on RP_{19-26} lavas above, this would mean an age of around 280-285 Ma.

Age determinations on intrusions from the Ramnes caldera (central intrusion: 268±5 Ma) and the Sande caldera (ring-dyke intrusion: 268±3 Ma) have already been presented by Rasmussen et al. (1988). Whole-rock isochron ages on intrusions from the Hillestad caldera (central intrusion: 269±6 Ma), and the Glitrevann caldera (ring-dyke intrusion: 266±5 Ma, central intrusion: 267±4 Ma) are presented in Table 2. The data imply that the calderas along the N-S axis of the Vestfold GS were contemporaneous, and that the associated magmatic activity terminated at 270 to 265 Ma. The activity apparently ended a little later (≥5 million years) in the north (Glitrevann) than in the south (Ramnes). Magmatism associated with the calderas probably started during the last part of the plateau lava stage (280-285 Ma), implying that the average life time of these magma systems was about 10 million years. This value is similar to values obtained on central volcano/caldera associations from other areas.

c) Plutonic intrusions

Whole-rock data on the larvikites from the Tønsberg-Larvik CP (Fig. 1), have been presented by Rasmussen et al. (1988). The samples utilised in that paper were taken from four, central, SiO_2-saturated intrusions labelled III-VI by Petersen (1978a). The age and Sr initial ratio obtained, 277±3 Ma and .70391±5 (MSWD = 1.31), indicate that these intrusions are comagmatic and emplaced within a space of time shorter than the error limits. The oldest (Bolærne) intrusion, labelled I by Petersen (1978a), was analysed by the mineral method and gave an age of 281±4 Ma (Table 2). The youngest units indicated by field relations of this multiple intrusion, the Hedrum plagi-foyaite (Petersen 1978a, labelled IX and X), however, did not yield any isochron at all (Fig. 2). The Kvelde foyaite, cutting the sequence of larvikites and plagi-foyaites, gives an isochron age of 276±6 Ma with errors overlapping the age of the intrusions III-VI (Table 2). The obtained ages are not significantly different. However, they suggest a gradual younging from east to west, and thus support the multiple intrusion model of Petersen (1978a, 1978b). The total time span of this intrusion phase must be ≤5 million years (281-276 Ma), i.e. less than the resolution of the method applied.

The Tønsberg-Larvik multiple larvikite intrusion and the Kvelde foyaite is cut in the northwest by the Siljan composite syenite pluton which consists of alkali-syenites (nordmarkites) and peralkaline granites (ekerites) (Fig. 1). The syenites yielded an isochron age of 270±4 Ma (Table 2). This is in accordance with the field evidence. The total time span for the intrusions in the southern part of the Vestfold GS is thus about 10 million years (281-270 Ma).

In the central Skrim-Eikeren area, the field relations are somewhat different to those in the Larvik area (Fig. 1). The successive intrusions seem not to be nested in any regular way, the older larvikite complex being invaded by later intrusions of syenites and alkali-granites in a complex pattern (H. Sørensen, pers. comm. 1989). Some of the syenites resemble hybrid rock types like those described by Andersen (1984) from the central area of the Sande caldera. The larvikite itself is most certainly a multiple intrusion, as is the large peralkaline-granitic body to the northeast called the Eikern ekerite (T. Hansteen, pers. comm. 1989). A whole-rock age of 271±2 Ma (MSWD=2.25) from this last intrusion has been reported by Rasmussen et al. (1988). To the west of the Skrim pluton, and separated from the main CP by Precambrian basement rocks, there is a small intrusion of biotite granite, the Nordagutu granite, which has been dated by Jacobsen & Raade (1975). Their age, recalculated to the new ^{87}Rb decay-constant, is 278±7 Ma. The larvikite at Skrim yielded a similar whole-rock isochron age of 278±5 Ma (Table 2). These results taken together, suggest that the entire intrusion phase in the Skrim-Eikeren area was slightly shorter (≈7 million years), and a little younger (278-271 Ma), than in the Tønsberg-Larvik area.

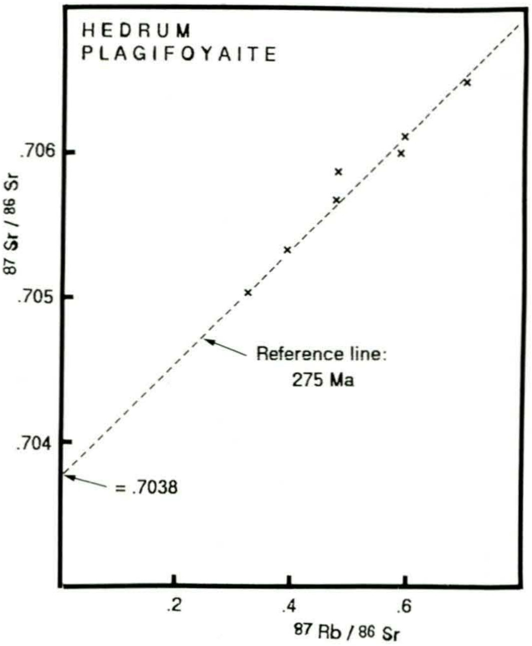

Fig. 2. Isochron plot of Hedrum plagi-foyaite ('lardalite') samples, Vestfold, (intrusion IX of Petersen, 1978b). Data from Table 1a.

In the northeast part of the Vestfold GS, the Hurum-Finnemarka area, granitic intrusions dominate (Fig. 1). The southern part of this complex is occupied by the Drammen composite granite pluton (Ihlen et al. 1982). This granite has not been satisfactorily dated, but the data of Heier & Compston (1969), recalculated by Sundvoll (1978a), suggest an age of ≈278 Ma for the southern part of this intrusion. A Rb-Sr mineral isochron from the northwestern part of the Drammen granite, however, indicates an age of 267±4 Ma (Table 2). It is to be noted that the sample used for this mineral date was collected very close to (‹300 m) the western edge of the Drammen caldera, which cuts (i.e. is younger than) the Drammen granite (Gaut 1981). We believe that this age reflects resetting during caldera-formation, and that the evidence for an intrusion age ›270 Ma is still valid. However, more work has to be done to settle this.

The Finnemarka granite, which is more alkaline than the Drammen granite and probably belongs to group BGII of Gaut (1981), yielded a whole-rock isochron age of 267±3 Ma. This age indicates that the intrusion is among the youngest in the Vestfold GS. It cuts a complex of older and more basic rocks which are also cut by the ring-dyke intrusion of the Glitrevann caldera (Schønwandt & Petersen 1983), dated to 266±5 Ma (Table 2). Using the dates and the age-estimates above, we may assume a time span for the emplacement of the Hurum-Finnemarka CP of ≤10 million years, which is similar to the other two composite plutons of the Vestfold GS. However, we infer that the intrusions generally are younger in the northern (278-267 Ma) than in the southern (281-276 Ma) part of the Vestfold GS, the difference being about 5 million years.

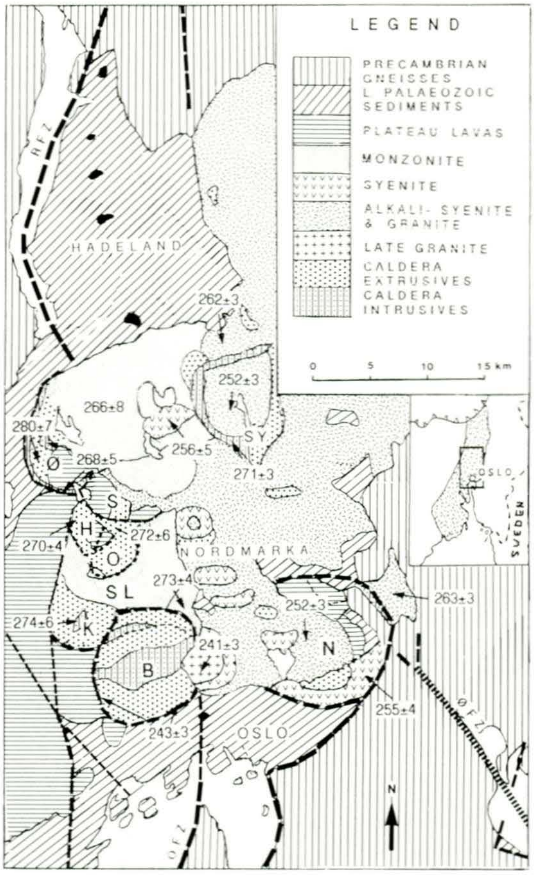

Fig. 3. Geological map showing age determinations from the southwestern part of the Akershus GS. Ages (in Ma) from Table 2; geological data from Sæther (1962) and Larsen (1978). Gabbroic intrusions are shown in black. B: Bærum caldera, H: Heggelia caldera, K: Kampen caldera, N : Nittedal caldera, O: Oppkuven caldera, S: Svarten caldera, SL: Slottet larvikite, SY: Stryken ring complex, Ø: Øyangen caldera. Other abbreviations as in Fig. 1.

II) Akershus GS

a) Plateau-lavas

The lavas of the Krokskogen area have been studied by Oftedahl (1952) and Larsen (1978). The stratigraphy of the main plateau lava field is fairly well known (Ramberg & Larsen 1978). Patches of RP-lavas are also preserved within the calderas to the east and north of the plateau, but these are not easily correlated with those of the main plateau (Fig. 3). Larsen (1978) has proposed a correlation scheme that depends on the widespread distribution of RP-lavas in the upper part of the lava sequence (i.e. RP$_{11}$ and RP$_{12}$), an assumption that is questionable. Another complication in the understanding of the stratigraphic correlation in this area has been the RP$_{13}$ unit termed 'rectangular porphyry' (Oftedahl 1952). It has been realised from new mapping in the Bærum caldera that most of the lavas assigned to the RP$_{13}$ unit actually are plagioclase-phyric basalts belonging to the central volcano sequence (Naterstad, pers. comm. 1988). Similar reevaluation of RP$_{13}$ units elsewhere in the Krokskogen area may improve correlations.

The data obtained on seven different RP-lava units and one basalt from the Krokskogen area, do show a progressive younging from the bottom to the top, as expected (Table 2). The isochron ages of the lowermost lavas B$_1$, RP$_1$, and RP$_{2A\&B}$ (291±8 Ma, 292±20 Ma, and 290±4 Ma) are similar to the oldest RP-lavas from the Vestfold area, and suggest an almost synchronous initiation of the RP volcanism in the two areas. The ages of the uppermost lavas RP_{11} and RP_{12} (276±6 Ma and 278±8 Ma) imply that the minimum total time span of the plateau volcanic stage at Krokskogen was about 15 millon years (292 to 277), or at least 1.5 times that obtained in the Vestfold area.

The two RP-lava units from the Storflåten area (RP_{13} and RP_{14A+B}) within the Øyangen caldera (Fig. 3) are similar in age (278±12 Ma and 278±5 Ma) to the uppermost lavas from the plateau region, and much of the basalts occurring below these units (Øyangen and Langlia basalts, Larsen 1978) must be older than the uppermost lavas of the plateau. This seems to be confirmed by the age obtained on a basaltic lava from the Øyangen caldera, dated to 280±7 Ma, suggesting that the estimated time span of the plateau volcanism at Krokskogen is valid.

The Brummundal area (Fig. 1, inset) has been investigated by Rosendahl (1929) who established that the RP lava sequence in this area is restricted to four flows ($RP_{x,y,z}$ and RP_u of Rosendahl, corresponding to $RP_{1\text{-}4}$ of Ramberg & Larsen, 1978). Only the uppermost flow RP_4 has been sampled for this work, and the isochron age obtained was 279±9 Ma (Table 2). This result shows that the RP volcanism in the Brummundal area is younger than that of Krokskogen and Vestfold, but not as young as has been suggested from paleomagnetic work (Storetvedt et al. 1978), or lithological considerations of the associated sandstone sediments (Spjeldnæs 1972). The occurrence of a relatively thick sandstone between RP_2 and RP_3 in this area suggests that the volcanism started somewhat earlier than indicated by the age determination on RP_4, and thus may have lasted a few million years.

b) Caldera lavas and intrusions

The calderas of the Akershus GS do not form as simple a pattern as in the Vestfold GS (Larsen 1978, Oftedahl 1978b). All the identified calderas are situated in the Nordmarka area (Fig. 3), and are considered in this paper. In the western part of the Nordmarka area, adjacent to the Krokskogen lava plateau, there exists a chain of nested calderas with an approximately SSW-NNE axis of evolutionary trend: the Kampen, Oppkuven, Heggelia, Svarten and Øyangen calderas (Larsen 1978). At the southern end of this chain a later caldera, the Bærum caldera, is superimposed on this earlier group. Only one extrusive unit has been investigated, a basalt lava from the Øyangen caldera. This basalt yielded a mineral isochron age of 280±7 Ma. The result shows that the central volcano precursors in this caldera chain were initiated before the end of the RP plateau-lava stage (discussed above). The results of dating of ring-dykes and central intrusions associated with these calderas (Kampen syenite phorphyry, Oppkuven syenite porphyry, Heggelia syenite porphyry, the Stubdal syenite, and the Ringkollen syenite), reported in Table 2, show that the caldera chain was terminated around 270 Ma. This also fits with the age of the Øyangen syenite (266±8 Ma), which has invaded and partly destroyed the Øyangen and Svarten calderas. Due to the limitations in the age-resolution of the method, no details can be ascertained about the relationship between the caldera intrusions and the intervening Slottet larvikite pluton (discussion below), but the data do not contradict field observations. The total life span for the caldera chain including the central volcano stage, may, from the data in Table 2 be estimated to about 10 million years (approximately from 280 Ma to 270 Ma), and the time span for the collapse stage to <5 million years.

In the northeastern part of the Nordmarka area (Fig. 3), a ring-complex, centred on the lake Harestua, (and partly obscured by the later Harestua nordmarkite intrusion), exhibits rocks and magmatic features commonly related to calderas in the Oslo Graben (P. Scott, pers. comm. 1980). The structure, however, seems to demonstrate a deeper level of dissection than most of the established calderas. Similar observations have also been made in the Hurdal area (Nystuen 1975a). Data on the sub-volcanic, ring-shaped body (Stryken syenite-porphyry) gave a whole-rock isochron age of 271±3 Ma. This possible caldera may then be of a similar or slightly later age than those in the western part of the Nordmarka area.

In the southeastern part of the Nordmarka area (Fig. 3) we find the Nittedal caldera (Naterstad 1978). The ring-dyke of this caldera (or possibly a replacing intrusion), the Grefsen syenite, yielded an isochron age of 255±4 Ma. To the east, this caldera cuts the Holterkollen granite, which is dated to 263±3 Ma (Rasmussen et al. 1988). Thus, the Nittedal caldera must be younger than those in the western part of the Nordmarka area. The caldera is intruded by the Nittedal nordmarkite with an age of 252±3 Ma (Rasmussen et al. 1988).

From the Bærum caldera in the southwestern part of the area (Fig. 3), a whole-rock isochron age of 243±3 Ma has been obtained on the syenite ring-dyke. The age demonstrates that the latest caldera collapse here must have taken place much later than for those discussed in the first part of this section, as individual life-times of central-volcanoes/calderas seem to be no more than 10-15 million years. This result is also supported by the observation of Sæther (1962) that the caldera must be younger than the group (c) plutonic intrusions in the Nordmarka area (discussed below).

c) Plutonic intrusions

The Nordmarka-Hurdal CP, (Figs. 3 and 5), has been studied by Sæther (1962), Nystuen (1975b), Gaut (1981), and Schønwandt & Petersen (1983). The best known are the Nordmarka (Fig. 3) and the central Hurdal areas (Fig. 5).

From field evidence the Nordmarka intrusions can be divided into five successive groups (a-e): (a) An early group of monzonites (larvikites) associated with some syenites confined to the western part of the area. (b) An early group of subvolcanic, fine-grained rocks termed felsite and syenite porphyries. The rocks of this group occur mainly inside calderas in the western part of the area, but also scattered over most of the eastern area. (c) An intermediate group, mainly of syenites (Grefsen type of Oftedahl, 1948), occurring in the central and southeastern part. Some of the syenites termed transitional by Sæther (1962), almost certainly belong to this group and possibly also some biotite granites. (d) A group of alkali-syenites (nordmarkites) and peralkaline granites (ekerites) predominant in the eastern part. (e) A group of late alkali-granites occur in the southern and southeastern areas (Sæther 1962).

Group (a) is represented in this work by the Slottet larvikite, Kampehaug quartz-syenite (actually a border-zone of the Slottet intrusion), the Kjeldsås larvikite and the Øyangen syenite (pulaskite of Sæther 1962). Samples from the Slottet intrusion did not yield any isochron (Fig. 4), but mineral separates from one sample (KL-14) from the Kjeldsås larvikite gave an isochron age of 273±4 Ma (Table 2). Three samples from the associated body of larvikite cumulate termed 'sørkedalite' (Bose 1969) do not fit on this isochron (Fig. 4). The samples from the other unit belonging to this group, the Øyangen syenite, yielded an isochron age of 266±8 Ma. Thus, a NNE migration of the successive larvikite intrusions is confirmed, as suggested from the field observations (Sæther 1962). The time occupied by the emplacement of these intrusions would be ≤7 million years.

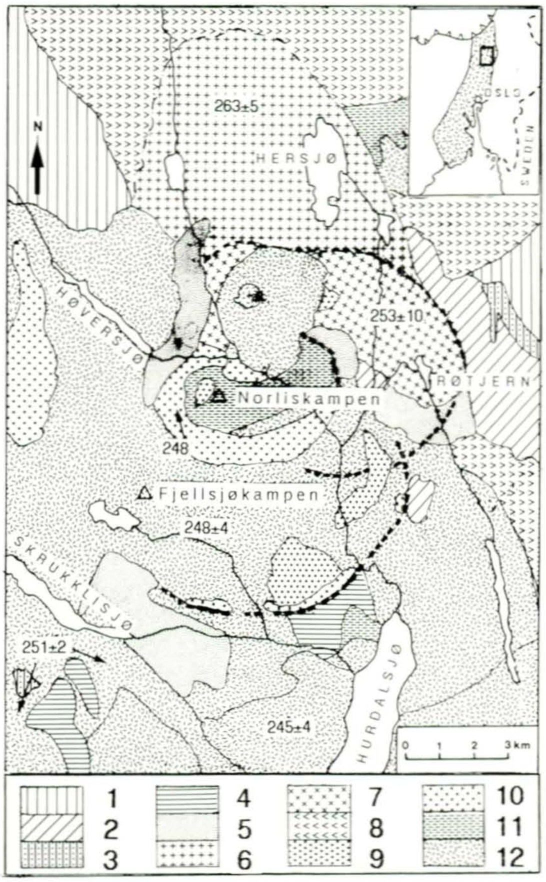

Fig. 4. Geological map showing age determinations in the Hurdal area in the central part of the Akershus GS. Ages (in Ma) from Table 2 and Rasmussen et al. (1988); geological data from Nystuen (1975b), Schønwandt and Petersen (1983). Legend: 1: Precambrian gneisses, 2: Cambro-Silurian sediments, 3: gabbros and mafic sills, 4: lavas, 5: monzonites, 6: early biotite granites, 7: granite, 8: early syenite & alk. granite, 9 : pyroclastic rocks, 10: alkali granites, 11: alkali granite porphyries, 12: late composite alkali syenite-granite complexes.

The intrusions of group (b) are represented by the Stryken syenite porphyry, which yielded an isochron age of 271±3 Ma. If this unit is

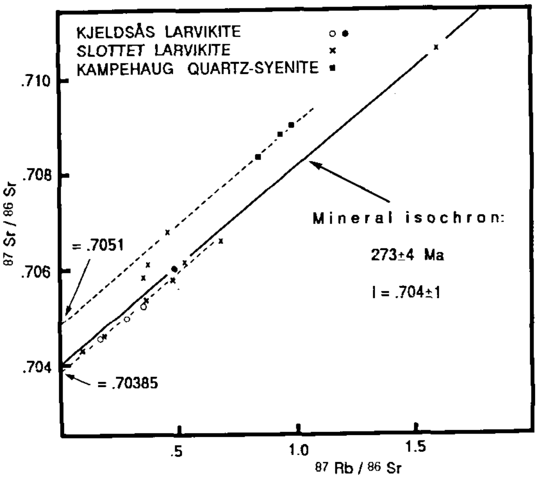

Fig. 5. Isochron plot of samples from the Kjeldsås, Slottet and Kampehaug intrusions, Nordmarka area. Kjeldsås intrusion: larvikite- (o), 'sørkedalite'- (o). Slottet intrusion: larvikite (x). Kampehaug intrusion: quartz-syenite (11). Data from Table 1b.

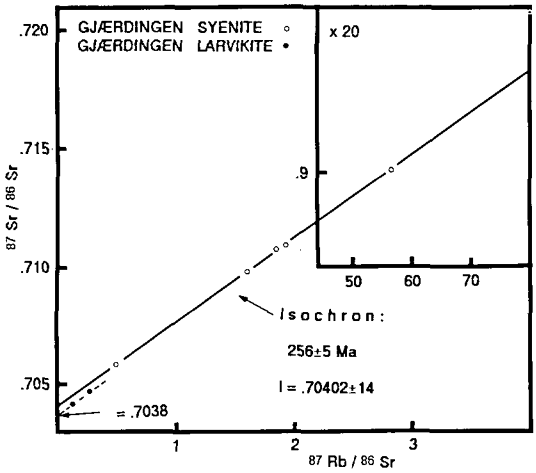

Fig. 6. Isochron plot of syenite (x) and larvikite (o) samples from the Gjerdingen intrusion, Nordmarka area. Data from Table 1b.

representative of group (b), it is more or less contemporaneous with group a. Group (c) is represented by the Grua granite and the Grefsen syenite, yielding whole-rock isochrons of 262±3 Ma and 255±4 Ma, respectively. These data suggest a time interval of about 8 million years for this phase. However, the position of the granite in this scheme is not quite clear. The Gjærdingen syenite, which Sæther (1962) termed transitional between syenite, nordmarkite and monzonite, also fits into this group, yielding an isohron age of 256±5 Ma. Two samples of the larvikite body west of Gjærdingen included in this unit, however, plotted below the isochron (Fig. 6). This larvikite intrusion is clearly older than both the Gjærdingen syenite and the Øyangen syenite (Sæther 1962).

Group (d) is represented by the Harestua nordmarkite, which gave a wholerock isochron age of 252±3 Ma. Data on another intrusion belonging to this group, the Nittedal nordmarkite, has been presented in Rasmussen et al. (1988), and yielded a similar age to that of the Harestua intrusion. The data do not suggest any time interval for the emplacement of this group of intrusions, but they are all older than the group (e) (Sæther 1962), which will imply a time interval between 3 and 10 million years.

Group (e) is represented by the Tryvann alkali-granite, which gave a whole-rock isochron age of 241±3 Ma. This date is so far the youngest Rb-Sr age encountered among the magmatic rocks of the Oslo Rift. Incidentally, the Tryvann granite is cut by diabase dykes, which must be even younger.

In the Hurdal area (Fig. 5), a similar division of the intrusions may be discerned, the main difference being that the biotite granites belong to group b and the subvolcanic intrusions to group c, according to Nystuen (1975a). Later investigations by Schønwandt & Petersen (1983), however, indicate a more complex intrusion record with possibly two periods of explosive volcanism. Only five units have been considered in our study, representing group (b), (d) and (e) intrusions. The Storøyungen and the Hersjø biotite granite of group (b) gave ages of 263±4 Ma and 263±5 Ma, respectively.

The Storøyungen granite (north of the Nittedal caldera) may represent a small exposure of a larger granite body now hidden below Quaternary sediments in the western part of the Romerike area. Geophysical evidence for the existence of such a body has been presented by Ramberg (1976). The patches of similar granites cropping out at the southwestern end of the Hurdal lake and at Holterkollen in Nittedal (Fig. 2, east of Nittedal caldera), are most certainly additional exposures of the same intrusion. This premise is supported by the data on the Holterkollen granite presented by Rasmussen et al. (1988), which indicate the same age (263±3 Ma) and same $^{87}Sr/^{86}Sr$ initial ratio (.7056±1) as the Storøyungen granite (.7056±6). Thus, similarly large, early, granitic intrusions also exist in this GS as has been demonstrated for the Vestfold GS.

The Røtjern granite, which is a younger intrusion than (or alternatively a remobilised part of) the Hersjø granite (Schønwandt & Petersen 1983), gave an isochron age of 253±10 Ma. The group (d) Fjellsjøkampen syenite yielded a whole-rock isochron age of 248±4 Ma. This age agrees fairly well with the ages obtained on other group (d) intrusions in the Nordmarka area. The Brennhaugen ekerite (peralkaline-granite, west of the Hurdal lake, Fig. 4) of group (e) intrusions gave a whole-rock isochron age of 245±4 Ma.

The central Hurdal area has also been investigated by whole-rock Rb-Sr methods by Tuen (1985). That study included units from group (a) monzonites. However, no isochron age was obtained, probably due to partial resetting by the effects of later intrusions. Tuen (1985) also dated units from the Nordliskampen ring-complex (Schønwandt & Petersen 1983), belonging to group (c) or (d) intrusions, and reported two ages at about 248 Ma. Rasmussen et al. (1988) also reported an age of 251±2 Ma on a complex of alkali-syenites and granites from the Øyangen area, in the southwestern part of Hurdal. The ages of the intrusions from the Hurdal area generally match the development models of Nystuen (1975b) and Schønwandt & Petersen (1983). However, more work has to be done to obtain as detailed a picture as in the Nordmarka area.

III) Sr isotopic variation

The lowest $^{87}SR/^{86}Sr$ initial ratios reported in this work (Table 2), are .70388 -.70391 (early RP-lavas, larvikites and plagi-foyaites), corresponding to $\varepsilon_{Sr}(t)$ of -5.6 to -3.5. Sr-isotopic data on basaltic lavas have yielded values as low as -10 to -14 (Jacobsen 1984, Neumann et al. 1988, Anthony et al. 1989). Such values are compatible with a mantle source with a Rb/Sr ratio of about .04, which is lower than the CHUR source (.084), but higher than a MORB source (.027). Thus, a moderately LIL-depleted source of some kind may have been involved in the genesis of the Oslo magmas. Nd and Pb isotopic studies of the Oslo igneous rocks have been reported by Jacobsen (1978), Neumann et al. (1988), Anthony et al. (1989) and Neumann et al. (1990), and for further discussion of the origin of the Oslo magmas we refer the reader to those papers. Discussion of the initial Sr isotope relations in the syenitic and granitic rocks has been presented by Rasmussen et. al. (1988).

Initial $^{87}Sr/^{86}Sr$ isotopic variations within the intermediate rocks show some interesting features. In the Larvik larvikite massif a definite trend of $^{87}Sr/^{86}Sr$ initial ratio versus silica content is observed. The oldest (and outermost) intrusions (Bolærne and Tønsberg, Petersen 1978a) have both higher SiO_2 concentrations (Neumann 1978) and higher $\varepsilon_{Sr}(t)$ than the younger intrusions: -2.2 for the Bolærne (and Tønsberg), and approx. - 3.6 for the others. The lowest values of about -5.6, (derived from the best-fit line drawn in Fig. 2, ≈275 Ma.), are recorded on the plagi-foyaites in the inner Hedrum complex. These phenomena may be explained by the stoping mechanism of the larvikite emplacement: Because of the huge volumes of larvikite magmas produced, they were presumably not much affected by interaction with wall-rock. The first intrusions, however, have been emplaced into Precambrian (and possibly Lower Palaeozoic sediments) and assimilated some of the wall- and roof-rocks during their ascent to their final position. The later intrusions, on the other hand, intruded mainly into the preceding larvikites and have therefore been affected to a lesser degree.

Similar relationships are also observed among the larvikite intrusions in the Nordmarka area. The (early) Kjeldsås larvikite has an $\varepsilon_{Sr}(t)$ of -2.2, and the (later) Gjærdingen larvikite an $\varepsilon_{Sr}(t)$ of -5.6, (Fig. 6). That the earlier larvikites have assimilated crustal material is also obvious from the contact relationship of the Slottet larvikite (Sæther 1962). The pluton is capped on one side by a transition zone of quartzsyenitic composition, the Kampehaug quartz-syenite, which has an $\varepsilon_{Sr}(t)$ of 13.5 (Fig. 4).

In the RP-lavas, however, we find the opposite trend to that observed among the larvikite plutons. The first RP-flows in both lava plateaus (RP_1, RP_2 and RP_3) have $\varepsilon_{Sr}(t)$ between -2.5 and -4.0, whereas all later RP- and T-lavas investigated have higher $\varepsilon_{Sr}(t)$ values. It has been noted by Oftedahl (1967) that the lavas in both the Vestfold and the Krokskogen

Table 3. ε_{Sr} (t) and SiO_2 values for RP- and T- lavas from Vestfold and Krokskogen lava areas.

Lava unit	$Å_{Sr}(t)^1$	$SiO_2(\%)^2$
RP_{1+2} Vestfold	-3.4	53.7
RP_{2+3} Vestfold	-3.3	58.8
T_1 Vestfold	33.2	64.3
RP_{13} Vestfold	-1.0	55.3
T_2 Vestfold	84.3	67.4
RP_{19} *Vestfold*	.2	59.5
RP_{26} Vestfold	-2.5	—
RP_1 Krokskogen	-2.5	54.3
RP_{2+3} Krokskogen	-4.0	54.9
RP_5 Krokskogen	1.1	56.4
RP_6 Krokskogen	-2.1	55.4
RP_7 Krokskogen	0.0	59.2
RP_{11} Krokskogen	4.0	57.7
RP_{12} Krokskogen	6.4	56.3

1) Data calculated from table 2.

2) Mean values calculated from Andresen (1985), Brøgger (1933), and Oftedahl (1967).

areas generally tend to become more SiO_2-rich upward in the stratigraphy. Oftedahl (1967) explained this with progressive differentiation in the magma-chambers forming the RP- and T- lavas. As the $\varepsilon_{Sr}(t)$ also increases with SiO_2 (Tables 2 & 3 and Fig. 7), an additional mechanism may be envisaged: a time-related increase in crustal contamination of the magma-chambers from which the RP and T magmas were derived. Thus, fractional cystallisation is at least accompanied by interaction with wallrock in magma-chambers and/or conduits.

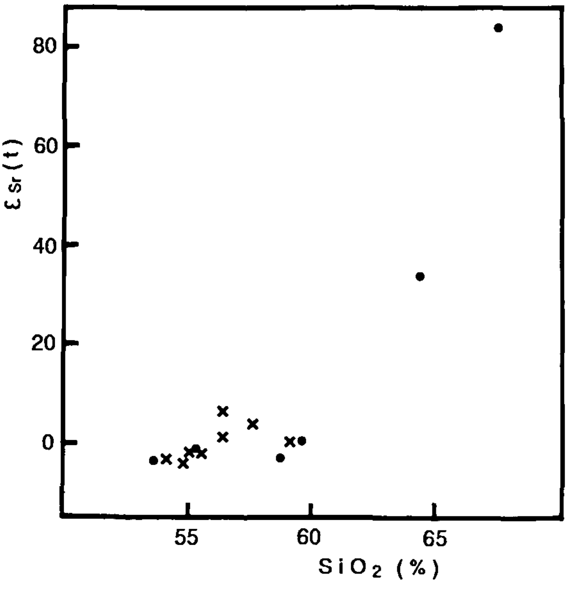

Fig. 7. ε_{Sr} (t) versus SiO_2 for RP- and T- lavas from Vestfold (o) and Krokskogen (x) lava areas. Data from Table 3.

Sr-isotope investigation of late intrusions of syenites and granites in the Hurdal area suggests a similar decrease in $\varepsilon_{Sr}(t)$ with age as that among the larvikites, and has also been explained as a consequence of the overhead stoping intrusion mechanism (Tuen 1985).

Conclusions

The following conclusions can be reached from this investigation of the 51 units of magmatic rocks from the Oslo Rift:

(1) The magmatism associated with the rifting lasted at least 55 million years, from 295 Ma to 240 Ma. The magmatic rocks from the southern (Vestfold) GS are generally older (295-266 Ma) than those from the northern (Akershus) GS (290-240 Ma). This suggests a northward migration of the rift magmatism with time.

(2) The data also suggest a similar migration from south to north within both of the GS, but are not conclusive due to the age resolution of the method (5 million years).

(3) The eruption of RP-lavas seems to have started almost simultaneously in the southern (Vestfold) and central (Krokskogen) areas (≈295-290 Ma), and probably a little later in the northernmost (Brummundal) area (≳279±9 Ma). However, eruption terminated earlier in the Vestfold area (280 Ma) than in the Krokskogen area (276 Ma).

(4) Caldera formation represents a distinct phase in the Vestfold GS (269-266 Ma), whereas in the Akershus GS such tectonomagmatic events took place repeatedly between 274 Ma and 243 Ma.

(5) Magmatic phases that are distinct in both GS, such as the emplacement of the multiple larvikite plutons, occurred later in the Akershus GS, (273-266 Ma), than in the Vestfold GS (281-276 Ma). In both GS the emplacement of biotite granites accompanied or followed closely the emplacement of the multiple larvikite plutons (ages about 278-270 in the Vestfold GS, and about 263 Ma in the Akershus GS).

(6) The emplacement of intrusions in the Akershus GS was more complicated and prolonged (≈35 million years) than in the Vestfold GS, (≈25 million years).

(7) The RP-lavas, the larvikites and related rocks have $^{87}Sr/^{86}Sr$ initial ratios of about .70388 - .70391, ($\varepsilon_{Sr}(t)$ = -5.5 to -3.5). Together with published data on basaltic rocks, these values

are compatible with a moderately LIL-depleted mantle source with Rb/Sr = .04.

(8) Detailed studies of the RP-lavas from the Vestfold and Krokskogen areas, and from two of the multiple larvikite plutons, are consistent with models invoking some crustal contamination of the magmas in crustal chambers and/or during ascent.

Acknowledgements

We thank K.S. Heier for inspiring this study, I.B. Ramberg for enduring and stimulating discussions on the Oslo Rift and T. Enger and B. Nilssen for their steady and patient help with the analytical work. We also thank E.-R. Neumann and two anonymous reviewers for constructive criticism that improved this paper considerably. The work was made possible through grants from the Norwegian Research Council for Science and Humanities (NAVF).

Norwegian ILP Contribution No. 115.

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Manuscript received Desember 1989; revised typescript April 1990; accepted May 1990.