Rb/Sr age determinations on late Proterozoic granitoids from the Evje area, South Norway

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Rb/Sr whole rock age determinations on different orthogneiss units, on one postkinematic granite and on young monzonitic sheets from the Evje area, Central Aust-Agder, have yielded ages ranging from 1350 to 900 m.y. The ages obtained indicate that the penultimate major regional deformation is younger than 1120 ± 31 m.y. and older than 1026 ± 57 m.y., while the last regional deformation is younger than 1026 ± 57 m.y. and probably contemporaneous with the last major period of deformation with accompanying metamorphism dated at about 1000–900 m.y. elsewhere in South Norway. The ages suggest that a major part of the granitic basement rocks in this part of South Norway is younger than 1350 m.y. ($(^{87}Sr/^{86}Sr)_0$ ranges from 0.706 to 0.704 suggesting an origin from Rb poor source regions or from only slightly older crust with normal Rb/Sr ratios.

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Introduction

The Precambrian gneiss region of southern Norway consists of banded gneisses, amphibolites and granitic gneisses with medium- to high-grade mineral assemblages (Barth 1936, Barth & Dons 1960, Barth & Reitan 1963). Recent mapping has revealed that this metamorphic complex can be divided into three major lithological units. These are often conformable and form a sequence of banded gneiss, granitic to granodioritic orthogneisses, and orthogneisses with a marked augen texture and a granodioritic composition (Falkum 1966, 1974). The banded gneiss is probably mostly of magmatic origin with minor layers of paragneiss (Hermans, Tobi, Poorter & Maijer 1975, Petersen 1977). The metamorphic complex was finally intruded by a number of late- to post-kinematic granitic plutons, e.g. the Homme granite (Falkum 1976), the Holum granite (Smithson & Barth 1967) and the Lyngdal granite (Middlemost 1968), and plutons of anorthositic and charnockitic affinities, among which are the Farsund charnockite (Middlemost 1968) and the Rogaland anorthosites (Michot & Michot 1969).

In this paper the results of Rb/Sr age determinations are reported on gneisses and late intrusive rocks which on the basis of field evidence belong to different stages of the evolution of the Precambrian complex in the Evje area, Central Aust-Agder (fig. 1). Major emphasis is placed on relating phases of deformation to the periods of igneous activity in the area.

The data presented were obtained in connection with the Norwegian Geological Survey's systematic mapping for publication on a scale of 1:250000 on the Mandal map sheet (compilation

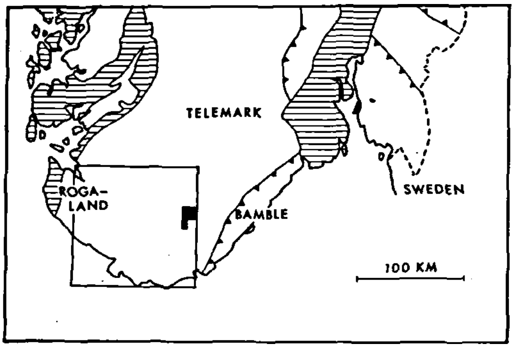

Fig. 1. The location of the area described within the Mandal map sheet. Horizontal ruling indicates rocks within the Caledonian area and the Permian Oslo Palaeorift.

by T. Falkum). In 1973 Rb/Sr age work was started as an integral part of the regional mapping project.

Geology of the Evje area

Intrusive complexes cutting earlier gneisses

Current mapping (Pedersen 1975) has revealed two individual composite plutonic complexes in the Evje area, the Høvringsvatn complex and the Flåt complex (fig. 2). In the Høvringsvatn complex two intrusive episodes can be distinguished, an older characterized by basic, amphibolitic, rocks (metanorites, Barth 1947), and a younger with massive monzonitic and granitic rocks followed by monzonitic conical sheets and radiating dykes (Pedersen 1975). The activity ended with the formation of pegmatites and aplites. The Flåt complex is dominated by a ferrodioritic rock – the Mykleås amphibolite (Barth 1947) – and minor anorthositic rocks. A nickel diorite (Barth 1947, Bjørlykke 1947) is found within the Flåt complex. This diorite may be part of the complex. Mining operations were conducted in the nickel diorite up to 1945. The complex is cut by minor irregular ferrodioritic dykes, by monzonitic sheets and by many pegmatites. Both the members of the Høvringsvatn complex and the Flåt complex are clearly discordant to regional structures although their contacts often tend to become concordant on a local scale. The two complexes together with a third probably independent intrusion farther south at Iveland were collectively described as the Iveland-Evje amphibolite by Barth (1947). The intrusive rocks are considered cosanguineous representing successive intrusive centres.

From the Høvringsvatn complex the granite and the monzonitic conical sheets were selected for Rb/Sr whole rock age determinations. Some mineral analyses from the granite were also carried out. The rocks have been described by Pedersen (1975) and only a short summary will be given.

The monzonitic conical sheets from the Høvringsvatn complex form semicircular outcrops and dip towards a centre just south of Høvringsvatn. Different sheet systems may be present. Widths of the sheets vary from centimetres to a few metres. Rare complex sheets with a width up to around 20 m have been found. The sheets are fine-grained and light grey with a distinct orientation of biotite flakes, amphibole needles and often also sphene, apatite and ore minerals parallel or subparallel to the contact of the dykes. The sheets are rich in sphene (2%) and apatite (1%).

The granite is a medium-grained rock dominated by a red K-feldspar and is low in mafics (<2%). It is very homogeneous over most of the area, but in the west and southwest a more fine-grained variety with cataclastic texture occurs.

Gneiss complex

The rocks of the Høvringsvatn and the Flåt complexes were intruded into a gneissic complex composed of banded grey gneisses and felsic granitic to granodioritic orthogneisses. Three types of orthogneisses have been distinguished: from youngest to oldest the Fennefoss augen gneiss, the Syrtveit granitic gneiss and the Sletthei augen gneiss.

The Fennefoss augen gneiss is a weakly foliated feldspar megacryst granodiorite, the megacrysts (2–3 cm × 1–1.5 cm) being almost euhedral microline or less commonly plagioclase that define a strong lineation plunging to the south. Mantled K-feldspars are occasionally seen. The Fennefoss augen gneiss was previously considered to be a marginal phase of the Flåt complex (Pedersen 1975), but the current mapping has shown it to be older than the Flåt complex, forming an elongated body extending at least 40 km parallel to the regional roughly N–S structural pattern. The Fennefoss augen gneiss shows crosscutting relations towards the other gneisses in the Evje area and contains a great number of xenoliths. Quartz, microline, plagioclase (An_{30}) and antiperthite are the main minerals. The mafics make up only 15% (mainly green biotite and around 1% of amphibole). A high content of accessory sphene (1–3%), apatite (1%) and opaque minerals (2–4%) is observed.

The Syrtveit granitic gneiss is a streaky, reddish to greyish medium-grained weakly foliated leucocratic rock of granodioritic to granitic composition. Antiperthite has been observed in a larger number of samples. The mafic minerals make up less than 10% and are dominantly brown biotite and minor hornblende. Accessories

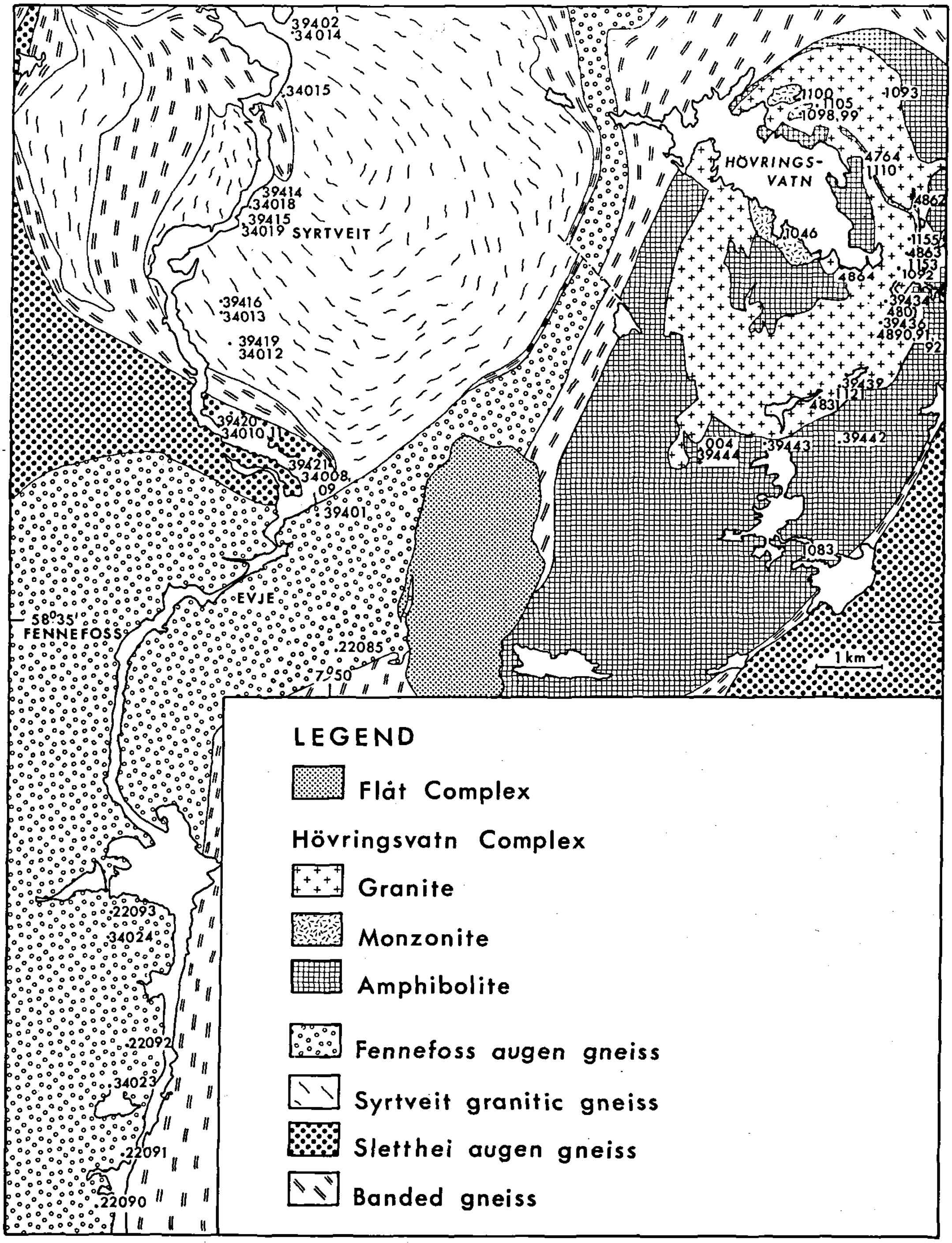

Fig. 2. Geological sketch map of the Evje area with the locations of the studied samples.

are sphene, apatite, zircon, allanite and opaque minerals. Leucocratic veining generally parallel to the foliation but locally discordant to the foliation is seen in places.

The Sletthei augen gneiss is a greyish, well foliated, medium-grained granodioritic rock with a weak to well developed augen texture. The mafic minerals, (a yellow-black biotite, with subordinate amphibole) constitute less than 10%. Accessories are apatite, sphene and opaque minerals. Leucocratic veining similar to that in the Syrtveit granitic gneiss is developed. In zones of strong shearing all traces of augen texture are obliterated and a streaky gneiss is developed. In places the Sletthei augen gneiss contains abundant conformable mafic layers.

The banded gneiss is regarded as the oldest unit in the gneiss complex. These rocks typically consist of alternating mafic and light grey layers but shows a great variation from place to place. Locally there are layers rich in garnet. In the field the mafic parts of the banded gneiss unit can be distinguished from the younger mafic rocks of the Høvringsvatn and the Flåt complex by their totally recrystallized (saccaroidal) texture. In some areas the banded gneiss has been intensively veined by fine-grained granitic rocks.

The gneisses in the Evje area have been deformed during one or more periods of deformation. The Fennefoss augen gneiss is apparently only affected by the youngest of these, which gave rise to the pronounced S-plunging megacryst lineation. In the Syrtveit granitic gneiss older ESE-plunging axes and lineations are dominant. These structures belong to the penultimate phase of deformation. Before the intrusion of the Syrtveit granitic gneiss older fold phases may have affected the banded gneisses.

Major element geochemistry

Chemical analyses of samples from the various rock units used for Rb/Sr age determinations are given in Table 1 and 2. The chemical data is presented graphically in three diagrams: a conventional Harker variation diagram (fig. 3), an Alk–F–M diagram (fig. 4) and a Qz–Ab–Or/An–Ab–Or diagram (fig. 5).

All examined rock types, except the Sletthei augen gneiss from which there are only two analyses, exhibit clear trends in both the Harker variation diagram (fig. 3) and the Alk–F–M diagram (fig. 4) The main differences between rocks from the Høvringsvatn complex and the gneiss complex is a higher FeO_{total}, FeO_{total}/MgO and CaO and a lower K_2O, $Na_2O + K_2O$, Rb and Sr for the gneisses. All rocks have K_2O/Na_2O

TABLE 1. CHEMICAL ANALYSES OF SAMPLES FROM THE HØVRINGSVATN COMPLEX.

	MONZONITES										GRANITE					
	1105	1046	1093	1092	1098	4890	1083	4801	1155	004	4864	39436	39444	4831	39434	39442
SiO_2	54.89	56.81	58.05	58.77	59.23	59.29	59.64	59.81	62.24	66.18	67.40	68.02	69.30	69.66	69.87	70.14
TiO_2	1.34	1.64	1.26	1.04	1.23	1.39	1.50	1.43	1.29	0.90	0.63	0.59	0.41	0.45	0.40	0.37
Al_2O_3	14.46	15.10	14.63	15.21	14.54	14.56	14.78	14.99	14.47	14.95	14.51	13.87	14.23	13.12	14.11	14.28
Fe_2O_3	1.87	2.75	1.80	2.45	2.69	2.76	2.26	2.61	2.58	1.43	1.52	1.53	0.56	1.19	0.94	0.80
FeO	4.49	3.89	3.63	3.78	3.32	3.33	4.10	2.73	2.95	1.79	1.72	1.68	2.01	1.31	1.53	1.45
MnO					0.11									0.05		
MgO	4.38	3.54	3.59	2.81	2.73	2.42	3.05	2.08	2.03	1.18	1.08	1.18	0.64	0.85	0.68	0.55
CaO	4.82	3.84	4.56	3.71	4.65	3.73	3.74	3.08	3.02	2.67	1.70	1.59	1.48	1.55	1.34	1.47
Na_2O	2.48	3.83	3.28	3.79	3.42	3.77	3.10	2.72	3.69	3.95	3.56	3.07	3.09	3.83	3.19	3.33
K_2O	6.72	3.46	5.03	4.84	6.02	5.13	4.20	6.44	4.67	3.83	5.62	5.95	6.06	5.81	5.87	5.43
P_2O_5	0.97	0.90	0.88	0.56	0.94	0.77	0.79	0.70	0.61	0.31	0.21	0.21	0.09	0.17	0.10	0.08
LOI	1.28	2.52	1.32	1.05	0.66	0.83	1.38	0.94	0.61	0.78	0.67	0.99	0.75	1.74	0.79	0.80
SUM	97.69	98.29	98.04	93.02	99.54	97.98	98.54	97.53	98.16	97.98	98.63	98.67	98.61	99.73	98.82	98.70
K_2O/Na_2O	2.71	0.90	1.53	1.28	1.76	1.36	1.35	2.37	1.27	0.97	1.58	1.94	1.96	1.52	1.84	1.63
FeO^x/MgO	1.41	1.80	1.45	2.13	2.11	2.40	2.01	2.44	2.59	2.61	2.86	2.59	3.93	2.81	3.49	3.95
Rb(ppm)	192	114	145	141	151	112	291	280	219	200	123	176	238	181	189	184
Sr(ppm)	1749	912	2231	2089	1673	2167	1387	1320	1599	830	976	785	574	614	498	584

ANALYST (MAJOR ELEMENTS): IB SØRENSEN, GREENLAND GEOLOGICAL SURVEY

TABLE 2. CHEMICAL ANALYSES OF SAMPLES FROM THE GNEISS COMPLEX.

	FENNEFOSS AUGEN GNEISS							SYRTVEIT GRANITIC GNEISS						SLETTHEI AUGEN GNEISS	
	22085	22093	34024	22090	34023	22092	22091	34019	34014	34018	34015	34012	39416	34008	34011
SiO_2	59.74	60.72	61.98	62.60	64.46	64.56	65.90	70.71	71.22	71.63	72.03	73.31	73.34	71.32	71.43
TiO_2	1.42	1.31	1.24	1.08	1.04	0.99	0.95	0.52	0.48	0.43	0.40	0.31	0.33	0.35	0.44
Al_2O_3	14.88	14.78	14.61	13.92	14.15	14.39	13.98	12.90	12.81	12.70	12.75	12.39	12.44	13.99	13.37
Fe_2O_3	3.17	2.77	2.83	2.30	1.96	2.19	2.30	0.72	1.02	0.50	0.51	0.52	1.02	0.39	1.12
FeO	4.05	3.95	3.35	3.04	3.35	2.99	2.60	3.31	2.89	2.97	2.70	2.16	1.81	2.11	2.47
MgO	1.95	1.80	1.71	1.35	1.34	1.28	1.30	0.57	0.58	0.48	0.37	0.30	0.34	0.67	0.69
CaO	4.84	4.22	3.92	3.21	3.30	3.16	3.08	1.88	1.75	1.65	1.53	1.16	1.24	2.21	2.11
Na_2O	3.65	3.92	3.77	3.38	3.51	3.56	3.45	4.12	3.93	4.00	4.14	3.92	3.84	3.65	3.54
K_2O	3.26	3.64	3.87	4.07	4.20	4.36	4.43	3.81	3.95	4.05	3.95	4.41	4.34	3.65	3.55
P_2O_5	0.72	0.56	0.49	0.45	0.44	0.38	0.40	0.12	0.11	0.10	0.08	0.06	0.07	0.07	0.10
LOI	0.81	0.92	0.87	0.80	0.87	0.73	0.59	0.49	0.56	0.63	0.54	0.50	0.46	0.50	0.51
SUM	98.49	98.59	98.65	96.20	98.61	98.60	98.99	99.14	99.31	99.16	99.00	99.04	99.22	98.91	99.32
K_2O/Na_2O	0.89	0.93	1.03	1.20	1.20	1.22	1.28	0.92	1.01	1.01	0.95	1.13	1.13	1.00	1.00
FeO^x/MgO	3.54	3.58	3.45	3.79	3.82	3.88	3.59	6.94	6.57	7.12	8.54	8.76	8.02	3.67	5.04
Rb(ppm)	76	89	98	147	122	118	149	109	143	127	149	140		138	98
Sr(ppm)	861	720	715	515	525	523	513	123	109	103	98	69		154	116

ANALYST (MAJOR ELEMENTS): IB SØRENSEN, GREENLAND GEOLOGICAL SURVEY.

ratios equal to or higher than one. Both complexes show typical calc-alkaline trends in the Alk–F–M diagram (fig. 4). The scatter observed for the monzonites may be due to the representation of more than one dyke system within the samples.

The composition of the analysed rock types in terms of normative Qz–Ab–Or/An–Ab–Or relations are given in fig. 5. In the figure comparison is made with the cotectic lines at $P_{H_2O} = 5$ Kb (Winkler et al. 1975) which is close to the indicated minimum pressure at 4.5 Kb reached during the peak metamorphic conditions in the nearby Flottorp area (Konnerup-Madsen 1979). None of the rock types appear to represent minimum melt compositions at the chosen pressure (fig. 5). Early crystallization of plagioclase may be involved in the evolution of both the monzonitic sheets and the Fennefoss augen gneiss. The Høvringsvatn granite and the Syrtveit granitic gneiss are however situated close to the qz + plag + 1 + v and the alk + qz + 1 + v cotectic surfaces respectively. Small changes in total pressure and/or water pressure would however shift these compositions towards a possible eutectic composition.

Sampling and analytical technique

Most of the samples from the Syrtveit granitic gneiss, the Sletthei augen gneiss and the Høvringsvatn granite weighed between 10 and 20 kg. Samples from the Fennefoss augen gneiss weighed between 20 and 25 kg. The samples of the monzonitic conical sheets were usually around 1 kg. All samples were free of any mobilizate. Sample localities are given in fig. 2.

The analytical work was carried out at the isotope laboratory of the University of Copenhagen. The Rb/Sr analyses of whole rock samples and some mineral samples were carried out on XRF (Philips pw 1410) using GSP–1 and G–2 as standards (Rb/Sr ratios: 1.093 and 0.355 respectively). Two pellets of each sample were analysed twice. Counting time was 400 sec. total for each element. The $^{87}Sr/^{86}Sr$ ratios were determined on unspiked samples on a Varian MAT TH–5 mass spectrometer. All values refer to an Eimer & Amend value for the $^{87}Sr/^{86}Sr$ ratio of 0.7080. Biotite samples from the Høvringsvatn granite were analysed by conventional isotope dilution technique using ^{84}Sr and ^{87}Rb enriched spikes. The ages were calculated with the aid of

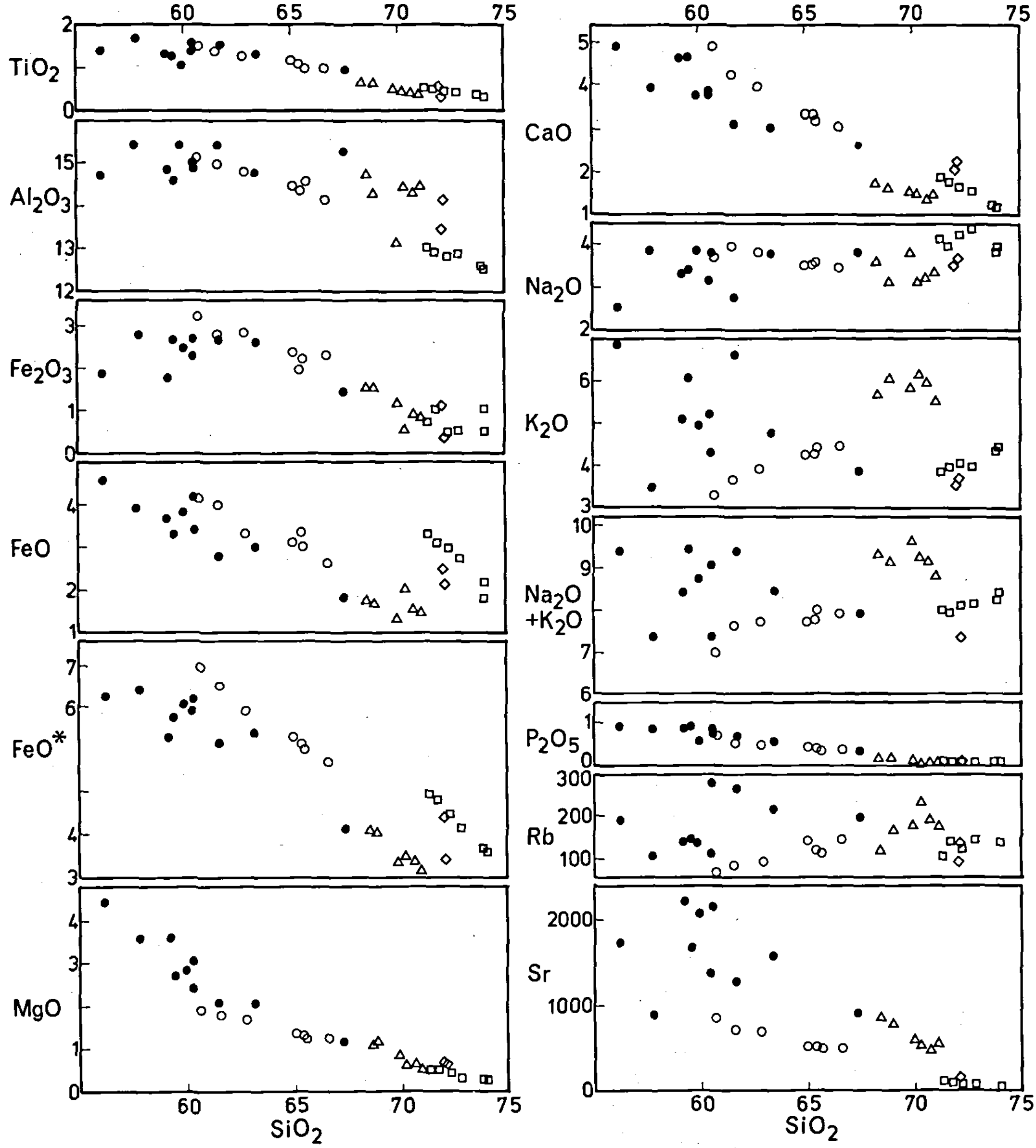

Fig. 3. Chemical analyses of examined rock types plotted on Harker variation diagrams. Dots: Høvringsvatn monzonite, triangles: Høvringsvatn granite, circles: Fennefoss augen gneiss, squares: Syrtveit granitic gneiss, diamonds: Sletthei augen gneiss.

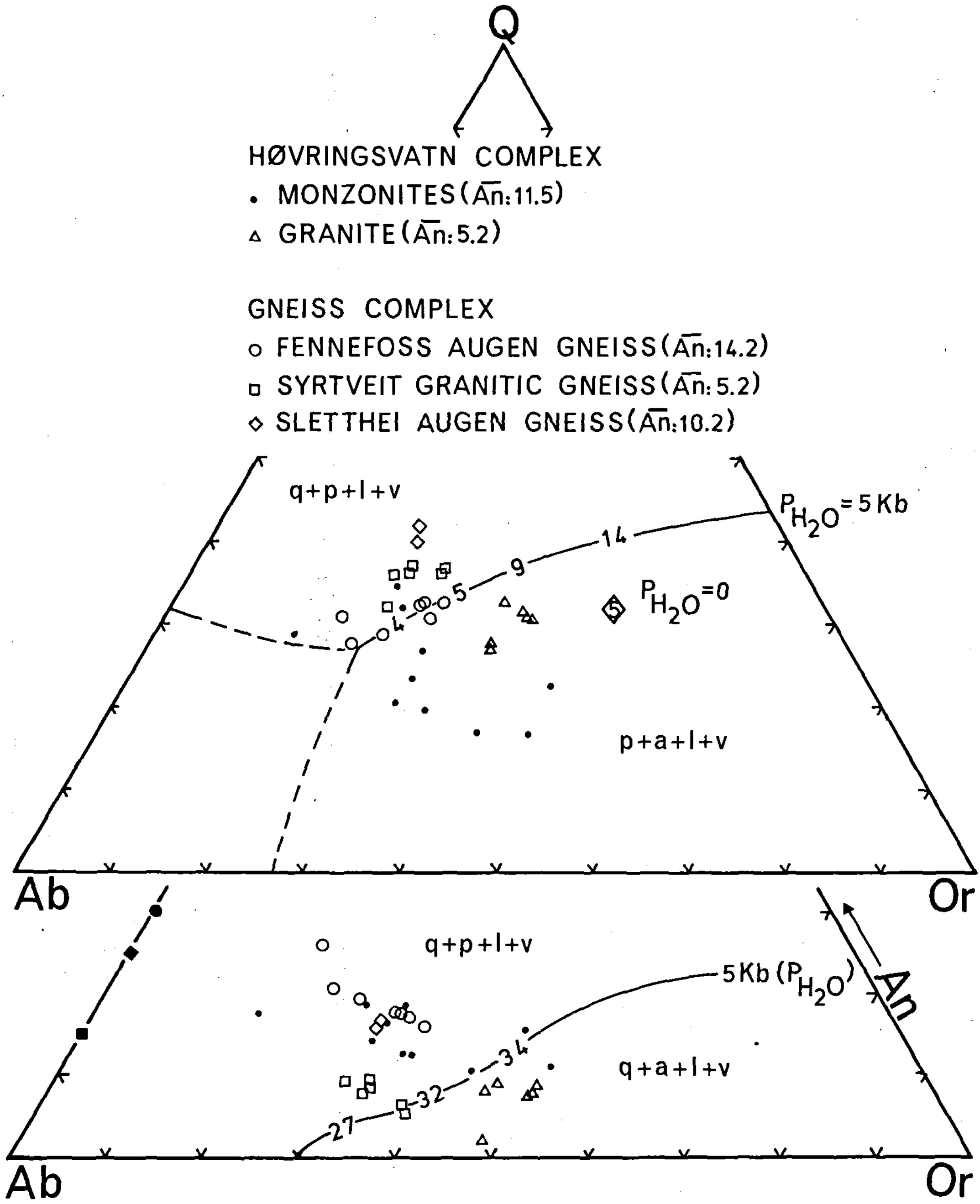

Fig. 5. Q–Ab–Or–An normative compositions (calculated from a modified mesonorm programme (Parslow 1969)) of examined rock types plotted on Q–Ab–Or and An–Ab–Or diagrams (Winkler et al. 1975). Filled symbols indicate mean compositions of plagioclase from the corresponding open-symbol rock types.

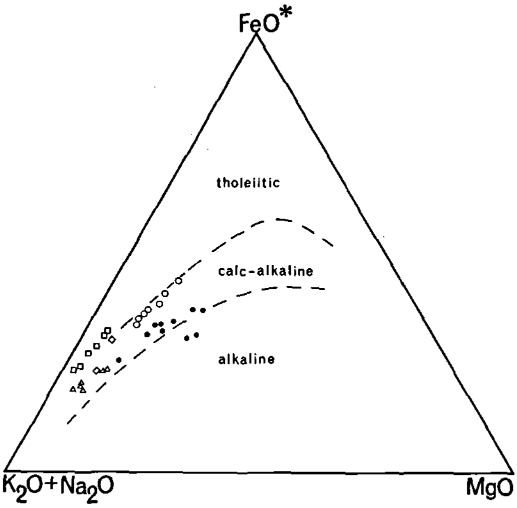

Fig. 4. Chemical analyses of examined rock types plotted on a $(Na_2O + K_2O) - (FeO + 0.9\ Fe_2O_3) - MgO$ triangular diagram (weight %). Symbols as in fig. 3.

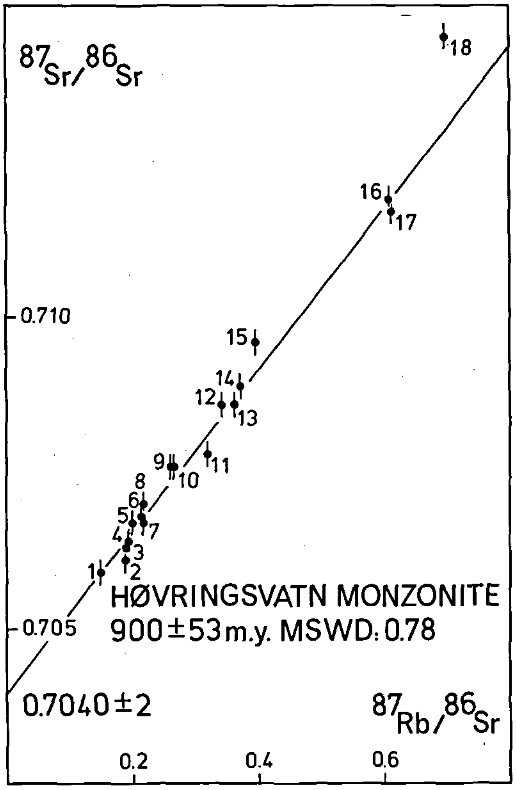

Fig. 6. Rb/Sr evolution diagram for the monzonitic conical sheets from the Høvringsvatn complex. Errors in $^{87}Sr/^{86}Sr$ are shown by vertical bars.

the programme by McIntyre et al. (1966) using a decay constant of $1.42 \cdot 10^{-11} \cdot y^{-1}$ (Steiger & Jäger 1977). Errors in ages and initial Sr isotope ratios are given at the 2σ-level. Errors in the $^{87}Sr/^{86}Sr$ ratios were calculated from suites of 20 double determinations (including the chemistry) carried out at the different times during the investigation. Errors in the $^{87}Rb/^{86}Sr$ ratios were calculated from the counting statistics and from differences between the standards used. Experimental details are given in Table 3, 4, 5, 6, 7 and 8.

Results

The Høvringsvatn complex

The majority of samples from the monzonitic conical sheets define an isochron with an age of 900 ± 53 m.y. and an initial Sr isotope ratio of 0.7040 ± 0.0002 (Table 3 and fig. 6). From the character of the sheets in the field they were divided into several types. Nearly all the samples investigated come from a light-grey fine-grained type with approximately equal amounts of biotite and amphibole (around 10% of each mineral). Exceptions are samples 1083 and 004. The sheet represented by 1083 is dominated by large grains of biotite and contains abundant felsic veins. The Rb/Sr results fall inside the pattern defined by the light grey sheets. Sample 004 is of a more homogeneous rock type, with a chemistry different from the grey sheets (for example much higher in SiO_2). It falls well outside the isotopic pattern defined by the other monzonitic sheets.

The whole rock samples from the Høvringsvatn granite define an isochron nearly identical to that defined by the monzonitic conical sheets (Table 4 and fig. 7). It yields an age of 945 ± 53 m.y. with an initial Sr isotope ratio of 0.7041 ± 0.0007. Some scatter of points about the isochron is observed. As most of the granite samples were collected in a zone with an intense development of monzonitic rocks, this scatter may be caused by the later intrusion of the monzonitic conical sheets or a younger disturbance which is reflected in a granite mineral age from this zone (see below). Samples 4864 and 39442 were collected outside this zone, but both occur near monzonitic

TABLE 3. ANALYTICAL DETAILS OF SAMPLES FROM THE HØVRINGSVATN COMPLEX: MONZONITIC CONICAL SHEETS.

NO. ON DIAGRAM	SAMPLE NO.	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
1	4890	0.1499 ± 14	0.7059 ± 2
2	1093	0.1878 ± 17	0.7061 ± 2
3	4891	0.1898 ± 18	0.7063 ± 2
4	1092	0.1953 ± 17	0.7064 ± 2
5	1100	0.201 ± 2	0.7067 ± 2
6	4892	0.215 ± 2	0.7068 ± 2
7	1121	0.217 ± 2	0.7067 ± 2
8	1099	0.218 ± 2	0.7070 ± 2
9	1098	0.261 ± 2	0.7076 ± 2
10	1153	0.266 ± 2	0.7076 ± 2
11	1105	0.320 ± 3	0.7078 ± 2
12	4764	0.342 ± 3	0.7086 ± 2
13	1046	0.362 ± 4	0.7086 ± 2
14	1110	0.373 ± 3	0.7089 ± 2
15	1155	0.397 ± 3	0.7091 ± 2
16	1083	0.608 ± 4	0.7119 ± 2
17	4801	0.614 ± 5	0.7117 ± 2
18	004^{x}	0.698 ± 5	0.7145 ± 2

Age: 900 ± 53 m.y. $(^{87}Sr/^{86}Sr)_o$: 0.7040 ± 2.
MSWD: 0.78

^{x}: not used in the regression analysis

rocks. Sample 4864 was collected near the massive, central part of the monzonitic intrusion (Pedersen 1975), while 39442 is situated some 200 metres from the nearest known outcrop of monzonitic rocks.

The minerals plagioclase, K-feldspar, biotite and in one case sphene from the granite were investigated and yield somewhat younger ages (Table 5 and fig. 8.). A complete homogenisation between the different mineral phases has not occurred or has been disturbed due to later events. The Rb/Sr biotite – whole rock age of 874 ± 28 m.y. obtained in sample 4831 is close to that obtained by K/Ar on biotite from the same sample (856 ± 62 m.y. (Pedersen 1973), recalculated after Steiger & Jäger (1977)), while the biotite – whole rock age of 929 ± 20 m.y. on sample 4864 is higher. A mineral-isochron age calculation for this sample yielded 921 ± 34 m.y. (pl, kf, biot, wr, but minus sphene) with a MSWD of 0.94,

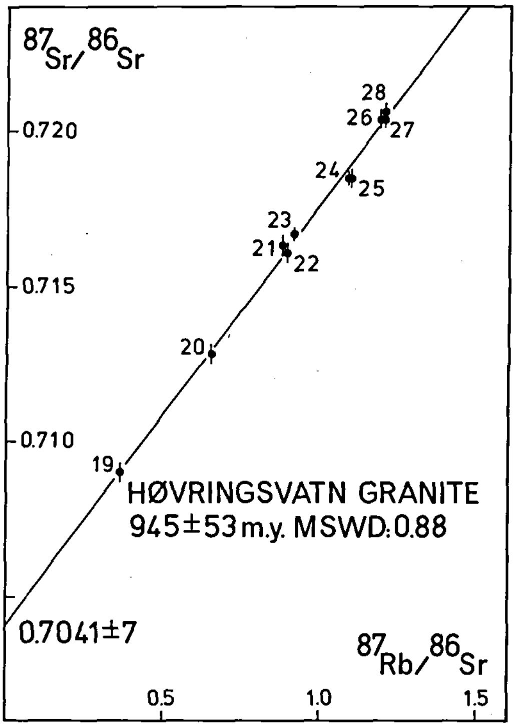

Fig. 7. Rb/Sr evolution diagram for whole rock samples from the Høvringsvatn granite. Vertical bars indicate errors in $^{87}Sr/^{86}Sr$.

TABLE 4. ANALYTICAL DETAILS OF SAMPLES FROM THE HØVRINGSVATN GRANITE.

NO. ON DIAGRAM	SAMPLE NO.	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
19	4864	0.365 ± 4	0.7090 ± 3
20	39436	0.652 ± 7	0.7128 ± 3
21	4831	0.878 ± 9	0.7163 ± 3
22	39443	0.892 ± 7	0.7161 ± 3
23	39442	0.913 ± 7	0.7167 ± 2
24	39439	1.087 ± 8	0.7185 ± 2
25	39434	1.098 ± 8	0.7185 ± 3
26	4862	1.194 ± 8	0.7204 ± 3
27	4863	1.203 ± 8	0.7204 ± 3
28	39444	1.203 ± 8	0.7206 ± 3

Age: 945 ± 53 m.y. $(^{87}Sr/^{86}Sr)_o$: 0.7041 ± 7.
MSWD: 0.88

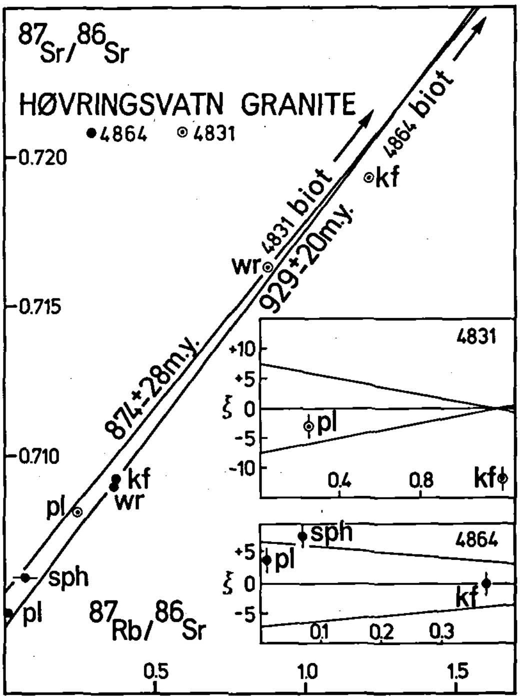

Fig. 8. Rb/Sr evolution diagram for minerals from samples 4831 and 4864 from the Høvringsvatn granite. The indicated lines gives the ages of the biotite-wr pairs. Error in $^{87}Rb/^{86}Sr$ for the sphene sample (4864) is shown by the horisontal bar. The insert shows the deviation ξ (in 10^{-4}) of the measured $^{87}Sr/^{86}Sr$ ratios of the plagioclase, K-feldspar and sphene from the biotite-wr reference line. The thin lines indicate 2σ errors.

TABLE 5. ANALYTICAL DETAILS OF SAMPLES FROM THE HØVRINGSVATN GRANITE: MINERAL SAMPLES.

SAMPLE NO./ MINERAL	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
4864/plag	0.011 ± 2	0.7047 ± 2
/sph[x)]	0.068 ± 35	0.7059 ± 2
/wr	0.365 ± 4	0.7090 ± 3
/kf	0.373 ± 3	0.7092 ± 2
/biot	100.6 ± 2.0	2.0402 ± 15

Age: 921 ± 34 m.y. $(^{87}Sr/^{86}Sr)_0$: 0.7044 ± 0.0003
MSWD: 0.94

x): not used in the regression analysis

Age (biot-wr): 929 ± 20 m.y.

SAMPLE NO./ MINERAL	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
4831/plag	0.243 ± 5	0.7081 ± 2
/wr	0.878 ± 9	0.7163 ± 3
/kf	1.211 ± 7	0.7193 ± 2
/biot	20.1 ± 4	0.9564 ± 22

Age: 853 ± 28 m.y. $(^{87}Sr/^{86}Sr)_0$: 0.7051 ± 0.0004
MSWD: 6.41
Age (biot-wr): 874 ± 28 m.y.

whereas a similar calculation for sample 4831 yielded 853 ± 28 m.y. (pl. kf, biot, wr) but with a MSWD of 6.41. This value does not qualify the regression line of sample 4831 as an isochron. The much better fit of the minerals of sample 4864 to a mineral isochron may be due to the position of the sample outside the zone with the younger development of the monzonitic conical sheets. The mineral ages of sample 4864 are best interpreted as reflecting the cooling of the granite or an influence of the monzonitic activity (the ages are unfortunately not significantly different from those of the granite and the monzonitic sheets), while the lower biotite-wr age of sample 4831 reflects a younger disturbance of the isotope system probably connected to the zone of intense monzonitic sheet formation.

In an earlier study of the Høvringsvatn granite and some of the monzonitic sheets (Pedersen 1973) a common age of 1016 ± 84 m.y. was obtained (recalculated after Steiger & Jäger 1977). The present study gives a slight although not significant indication of two different isotopic patterns with lower ages and initial Sr isotope ratios than earlier obtained.

The gneiss complex

The Fennefoss augen gneiss: Fig. 9 gives the Rb/Sr evolution diagram for the Fennefoss augen gneiss (analytical data in Table 6). The isochron age obtained is 1026 ± 57 m.y. with an initial Sr isotope ratio of 0.7044 ± 0.0005. One sample of a banded gneiss xenolith from the northern part of the unit falls outside the isotopic pattern defined by the augen gneiss, indicating that homogenisation between intrusion and xenolith did not occur either at intrusion or later (the sample is not shown in fig. 9 due to technical drafting reasons).

The good fit of the isochron and the low initial

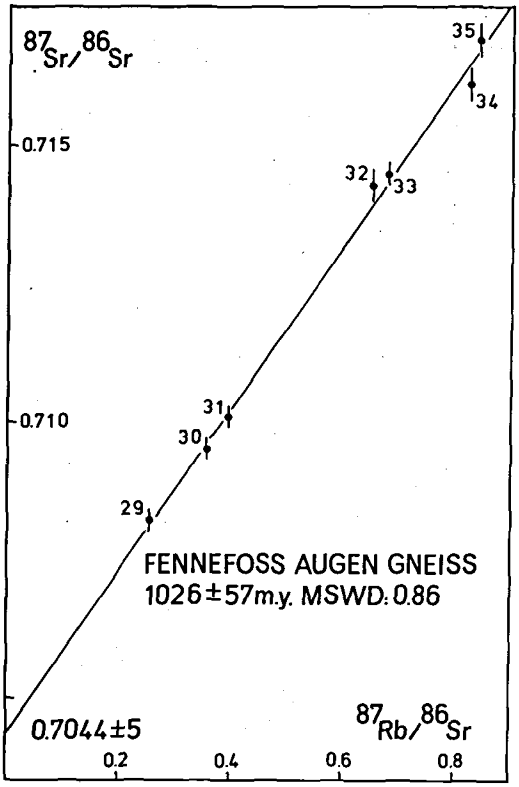

Fig. 9. Rb/Sr evolution diagram for the Fennefoss augen gneiss. Vertical bars indicate errors in $^{87}Sr/^{86}Sr$.

TABLE 6. ANALYTICAL DETAILS OF SAMPLES FROM THE FENNOFOSS AUGEN GNEISS.

NO. ON DIAGRAM	SAMPLE NO.	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
29	22085	0.255 ± 4	0.7082 ± 2
30	22093	0.357 ± 4	0.7095 ± 2
31	34024	0.396 ± 4	0.7101 ± 2
32	22092	0.651 ± 6	0.7143 ± 3
33	34023	0.680 ± 7	0.7145 ± 2
34	22090	0.825 ± 7	0.7162 ± 2
35	22091	0.842 ± 7	0.7169 ± 3
xenolith of banded gneiss	39401^{x}	1.45 ± 2	0.7382 ± 3

Age: 1026 ± 57 m.y. $(^{87}Sr/^{86}Sr)_o$: 0.7044 ± 5.
MSWD: 0.86

^{x}: not used in the regression analysis

Sr isotope ratio suggest that the age obtained on the Fennefoss augen gneiss reflects the time of its intrusion. The small scatter observed for some points in fig. 9 might conceivably be due to the later metamorphic and deformational episode, which has been dated to 1000–990 m.y. in the Flekkefjord area (Falkum & Pedersen 1979). The interpretation of the age as an intrusive age narrows down the interval between the intrusion of this youngest orthogneiss and the late-kinematic granites, e.g. the Homme granite with an age of 997 ± 14 m.y. (Pedersen et al. 1978, Falkum & Pedersen 1979), and the oldest post-kinematic granite, the Holum granite, which has been dated to 980 ± 33 m.y. (Wilson et al. 1977). The Fennefoss augen gneiss seems to be contemporaneous with an augen gneiss in the Mandal region, which gives a Rb/Sr reference age of 980 m.y. with an age of intrusion probably not much higher (Wilson et al. 1977). Moreover, augen gneisses farther to the west in the Rogaland area give U/Pb zircon ages in the same range (Michot & Pasteels 1972).

The Syrtveit granitic gneiss: The samples from the Syrtveit granitic gneiss yield an isochron age of 1120 ± 31 m.y. with an initial Sr isotope ratio of 0.7062 ± 0.0016 (fig. 10 and Table 7). The age recorded for the Syrtveit granitic gneiss is considered to reflect the time of intrusion of the unit since the isotopic pattern of the Syrtveit granitic gneiss is completely different from that in the apparently older Sletthei augen gneiss (see fig. 10). The two units are separated by a thin zone of banded gneiss, but a sharp isotopic border would nevertheless be difficult to imagine if metamorphic processes were responsible for the observed isotopic distribution. A similar difference in isotopic patterns is observed between the Syrtveit granitic gneiss and the banded gneiss located in a fold closure in the northern part of the Syrtveit granitic gneiss. Preliminary Rb/Sr results indicate that the samples of the banded gneiss fall outside the isotopic pattern defined by the Syrtveit granitic gneiss regardless of their composition. The low initial Sr isotope ratio of the Syrtveit gneiss supports this interpretation.

The scatter of data points in the Rb/Sr evolution diagram indicates some secondary disturbing on the isotope system. This could be due to the regional metamorphism.

The Syrtveit granitic gneiss was apparently af-

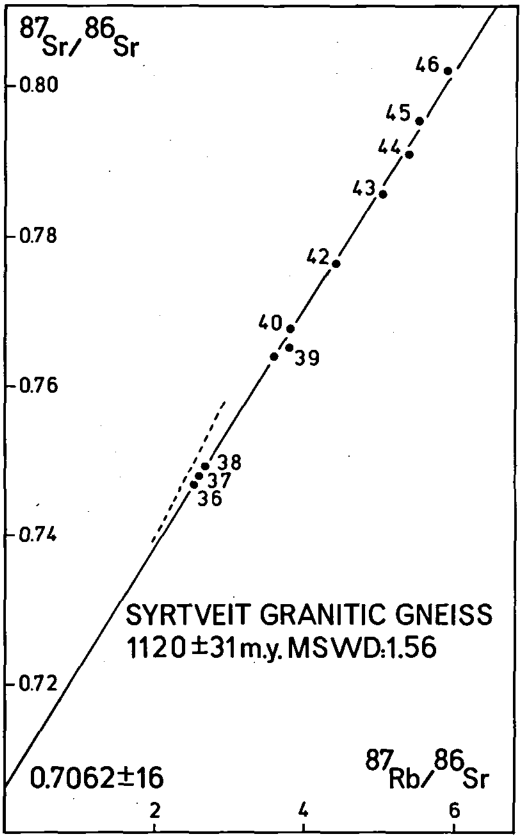

Fig. 10. Rb/Sr evolution diagram for the Syrtveit granitic gneiss. Stippled line indicates the position of the Sletthei augen gneiss samples.

TABLE 7. ANALYTICAL DETAILS OF SAMPLES FROM THE SYRTVEIT GRANITIC GNEISS.

NO. ON DIAGRAM	SAMPLE NO.	^{87}Rb/^{86}Sr	^{87}Sr/^{86}Sr
36	39415	2.52 ± 4	0.7469 ± 2
37	34019	2.58 ± 3	0.7480 ± 2
38	39414	2.66 ± 3	0.7493 ± 3
39	34018	3.59 ± 4	0.7634 ± 2
40	39402	3.80 ± 6	0.7677 ± 3
41	34014	3.80 ± 4	0.7652 ± 2
42	34015	4.40 ± 4	0.7764 ± 2
43	39416	5.02 ± 8	0.7857 ± 2
44	39419	5.38 ± 8	0.7931 ± 2
45	34013	5.50 ± 7	0.7955 ± 2
46	34012	5.89 ± 7	0.8021 ± 2

Age: 1120 ± 31 m.y. $(^{87}\mathrm{Sr}/^{86}\mathrm{Sr})_o$: 0.7062 ± 16.
MSWD: 1.56

fected by the last two main deformations, so the age obtained places some constraints on the timing of the penultimate deformation in the Evje area.

The Sletthei augen gneiss: The investigated samples from the Sletthei augen gneiss were collected from only two localities (three samples from each) both of which have suffered strong deformation. The Rb/Sr evolution diagram is given in fig. 11 and the analytical data in Table 8. The data points lie close to a reference isochron of 1350 m.y. with an initial Sr isotope ratio of 0.701. The actual age calculated is 1348 ± 80 m.y. with a MSWD of 3.58. From the age calculation statistics this MSWD value does not allow the age to qualify as an isochron age. The low initial Sr isotope ratio suggests the age should be regarded as a maximum age of the rock.

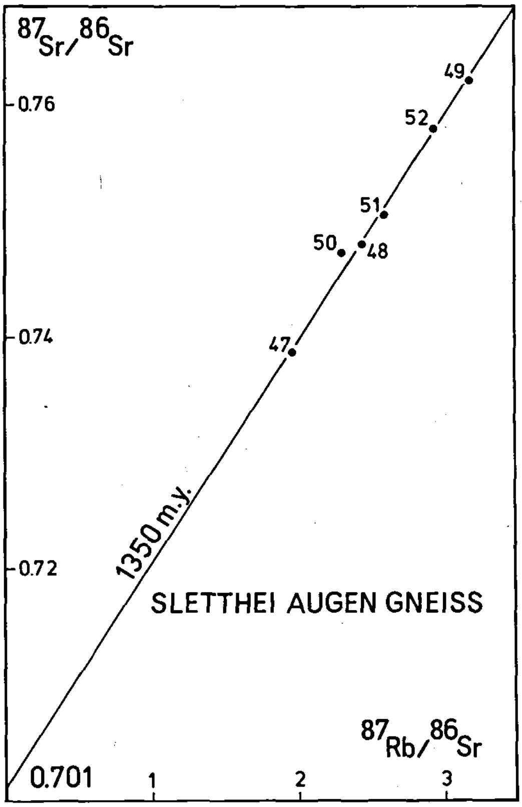

Fig. 11. Rb/Sr evolution diagram for the Sletthei augen gneiss. The filled-out circles represent samples from the northern locality and the dot in open circle symbols samples from the southern locality.

TABLE 8. ANALYTICAL DETAILS OF SAMPLES FROM THE SLETTHEI AUGEN GNEISS.

NO. ON DIAGRAM	SAMPLE NO.	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
Northern locality			
47	34010	1.97 ± 2	0.7387 ± 2
48	34011	2.44 ± 3	0.7479 ± 2
49	39420	3.17 ± 3	0.7620 ± 3
Southern locality			
50	39421	2.30 ± 2	0.7472 ± 3
51	34008	2.59 ± 3	0.7505 ± 2
52	34009	2.93 ± 3	0.7579 ± 2

Age: 1348 ± 80 m.y. $(^{87}Sr/^{86}Sr)_0$: 0.701 ± 0.003.
MSWD: 3.58

Geochronological summary

The results from the Evje area compare well with ages obtained elsewhere in southern Norway. In the Rogaland area higher ages of 1400–1500 m.y. are found, but according to Versteeve (1975) the Sveconorwegian orogenic period started around 1200 m.y. ago with folding and metamorphism and ended around 950 m.y. ago. Similarily Pasteels & Michot (1975) concluded that most activities in the Rogaland area occurred after 1200 m.y. In the Telemark area similar ages as in the Rogaland area are found (Priem et al. 1973). An age of 1105 ± 24 m.y. obtained on the Kviteseidvatn gneisses (Priem et al. 1973) is of particular interest as it was concluded that this age defined the time of anatectic melting, gneissification and strontium isotope migration. More recent age determinations from the Telemark area (Kleppe & Råheim 1979) also yielded ages on granitic gneisses of around 1100 m.y. In the Bamble area it was concluded from K/Ar data

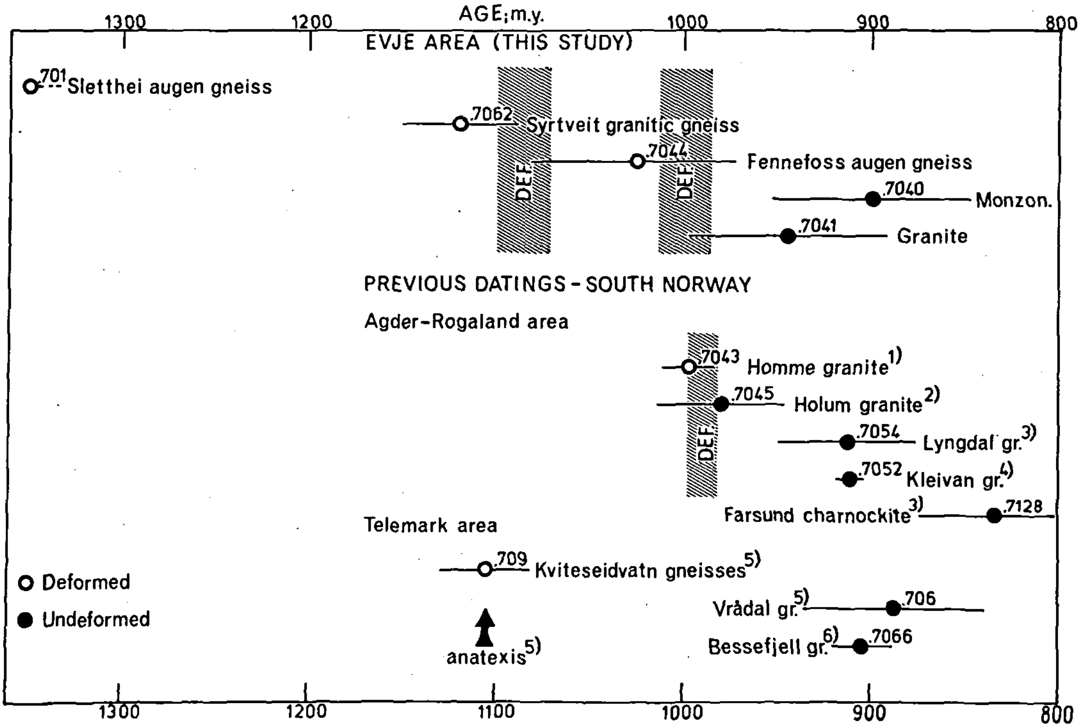

Fig. 12. Chronological scheme of granitoids from the Evje area and of similar rocks from adjacent areas. References: 1) Falkum & Pedersen (1979), 2) Wilson et al. (1977), 3) Pedersen & Falkum (1975), 4) Petersen & Pedersen (1978), 5) Priem et al. (1973), 6) Killeen & Heier (1975a).

(O'Nions et al. 1969) that the thermal maximum of a regional event was reached at 1100 m.y. This conclusion was supported by Rb/Sr and U/Pb work on gneisses from the Levang gneiss dome (O'Nions & Baadsgaard 1971).

Ages on postorogenic rocks younger than 1000 m.y. are similarily recorded from many places in South Norway (Brueckner 1972, Priem et al 1973, Killeen & Heier 1975a, b, Priem et al. 1976).

The results obtained on the various rock types from the Evje area during this study are summarized in fig. 12, together with a comparison with some previous age determinations on similar rock types from elsewhere in southern Norway. The results permit some constraints to be placed on the evolution of the Precambrian of the Evje area.

1. Ages on the post-kinematic intrusives and the youngest orthogneiss (the Fennefoss augen gneiss) date the last deformational episode to around 1000 m.y. A similar age for this deformation has been obtained for other parts of the Precambrian in southern Norway (fig. 12).

2. The low initial Sr isotope ratios obtained on both the rocks from the Høvringsvatn complex and the Fennefoss augen gneiss are consistent with an origin from Rb poor source regions or from only slightly older crust with normal Rb/Sr ratios. Addition of material to the crust in the Evje area in the period from around 1025 to 900 m.y. is suggested from the data.

3. The age of the Fennefoss augen gneiss, only affected by the last deformational episode, and of the more deformed Syrtveit granitic gneiss limit the age of the main early deformation to between 1025 and 1120 m.y.

4. The oldest orthogneiss in the Evje area (the Sletthei augen gneiss) yielded an errorchron age of about 1350 m.y. Its low initial Sr isotope ratio may indicate that the age of 1350 m.y. should be considered a maximum age for the rock unit.

A further conclusion is that the deformational and metamorphic events in southern Norway between 1100 and 1000 m.y. affected the Sr isotope systems of the rocks in the Evje area only very slightly.

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Dansk sammendrag

Rb/Sr aldersbestemmelser på orthognejser og sene udeformerede proterozoiske intrusiver fra Evjeområdet, Aust-Agder, giver isokronaldre fra 1120 til 900 mill. år. En stærkt deformeret øjegnejs giver en referencealder på 1350 mill. år, der er tolket som bjergartens maksimale alder. Aldrene viser, at hovedparten af de granitiske basementbjergarter i området er yngre end 1120 mill. år (evt. 1350 mill. år), og at hoveddeformationerne har fundet sted i intervallet 1120–ca. 1000 mill. år. De oprindelige Sr-isotopforhold peger på en oprindelse fra et Rb-fattigt udgangsmateriale eller fra en lidt ældre skorpe med »normale« Rb/Sr forhold.

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