Geochronology of basal gneisses and mangerite syenites of Stadlandet, west Norway

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Grey gneisses from four localities yield Rb-Sr isotopic data points approaching a regression line corresponding to an age of 1760 ± 70 m.y. and an initial $^{87}Sr/^{86}Sr$ ratio of 0.702 ± 0.001. Similar ages have been obtained from U-Pb zircon 'upper' concordia intersections. The grey gneiss precursors were of granodioritic composition and apparently did not have a long previous crustal history. Quartzites and garnet-mica schists give Rb-Sr whole rock ages of *c.* 1500, 1100, and 400 m.y. but are interpreted as Svecofennian sediments affected by open chemical systems during Sveconorwegian and/or Caledonian events. Microcline-rich gneisses yield Rb-Sr isotope ratios which plot below the grey gneiss isochron, while zircon U-Pb systems from one gneiss have been almost completely reset at 400 m.y. These gneisses are considered to be K-metasomatised grey gneisses tentatively associated with Caledonian processes.

U-Pb zircon systems for a mangerite syenite are slightly discordant at 1520 ± 10 m.y. This age is attributed to magmatic crystallisation.

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The basal gneisses of western Norway are a complex series of gneisses, migmatites and unfossiliferous metasediments which lie within the NNE trending, Norwegian Caledonide belt (Fig. 1). Many earlier workers regarded these as essentially Eocambrian to Cambro-Silurian rocks metamorphosed wholly in the Caledonian orogeny (Kolderup 1960, Hernes 1967). Others (e.g. Strand 1960, 1972) recognised a more complex history in which highly metamorphosed Precambrian basement rocks, and rocks of the Caledonian depositional cycle, were together affected by Caledonian metamorphic processes. This more complex picture is supported by recent isotopic age determinations (e.g. Brueckner et al. 1968, Brueckner 1972, Bryhni et al. 1971, Pidgeon & Råheim 1972, Sturt et al. 1975, Råheim 1977) where a combination of U-Pb zircon, K-Ar, and Rb-Sr mineral and whole-rock studies have confirmed the essential polymetamorphic character of the Basal Gneiss giving ages which can generally be referred to the Svecofennian (2.100–1.500 m.y.), Sveconorwegian (1,200–850 m.y.) and Caledonian (550–350 m.y.) events.

Svecofennian and Sveconorwegian metamorphic rocks contain a complex range of often metamorphosed igneous rocks described by Goldschmidt (1916) as the anorthosite kindred. Geological and isotopic studies on such rocks (e.g. Heier & Compston 1969, Griffin et al. 1974, Pasteels & Michot 1975, Versteeve 1975) demonstrate a complex inter-relationship between plutonism and metamorphism. Anorthosite kindred rocks form both large thrust masses within the Norwegian Caledonides (Battey & MacRitchie 1973, Sturt et al. 1975) and smaller masses having a complex involvement with folding and metamorphism and ranging from anorthosites to mangerites and mangerite syenites (Lappin 1966, Brynhni 1966, Brueckner 1977).

Though Svecofennian ages are ubiquitous, the most northerly definite Sveconorwegian age in the basal gneisses comes from the 1009 ± 35 m.y. Hestbrepiggan granite (Priem et al. 1973) in the eastern part of the gneiss outcrop, near Tafjord (Fig. 1). Directly west of this locality, along the coast, is the area of the present study, Stadlandet. Field and structural relationships in this district have been described by Lappin

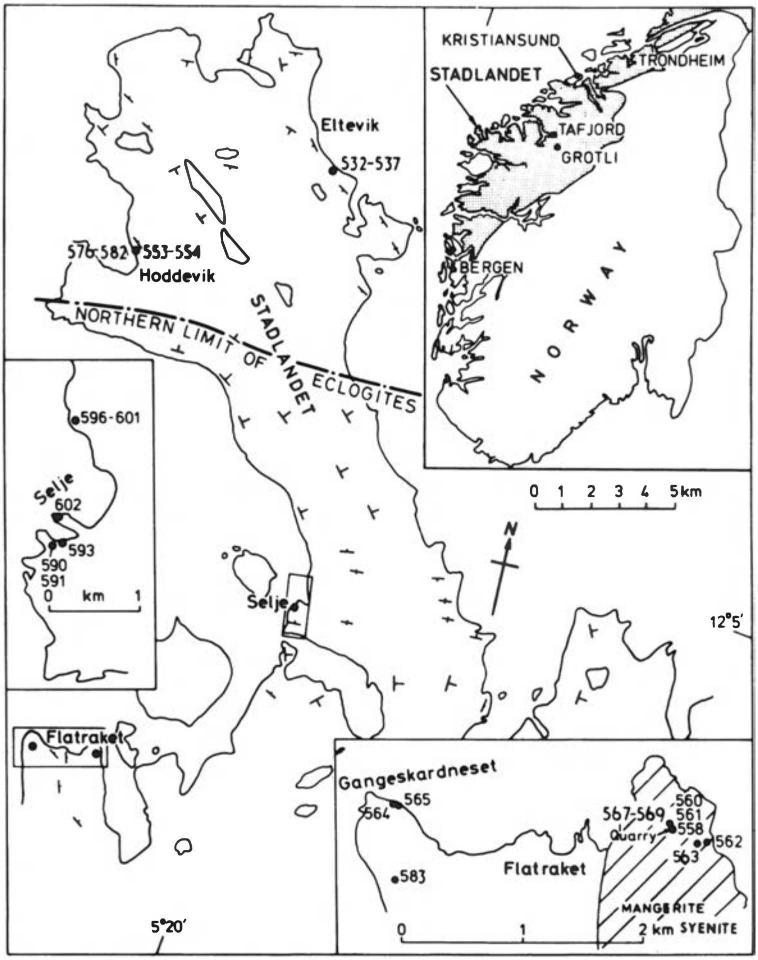

Fig. 1. Map of Stadlandet and neighbouring districts showing sample localities. The inset map of southern Norway shows the distribution of the basal gneisses.

(1966) and, in the adjacent regions of outer Nordfjord, by Bryhni (1966). Extensive studies (O'Hara & Mercy 1963, Brueckner 1969, Lappin 1973, 1974, Brueckner 1974) have been made here on ultramafic rocks and associated eclogites and upon country-rock eclogites (McDougall & Green 1964, Lappin 1960, 1966, Bryhni et al. 1969, Bryhni et al. 1971, Krogh 1977, Brueckner 1977a, Lappin & Smith 1978). These rock types occur only in the southern part of the area studied.

In the Stadlandet area grey gneisses, augen and banded gneisses are interbanded on such a scale that mapping of individual units is impossible. Metasedimentary rocks – quartzites and garnet-mica schists – form only a small proportion of the gneissic outcrop as do metabasic rocks – amphibolites and hornblende gneisses – and eclogites, ultramafic rocks, anorthosites, and mangerite syenites. The gneisses are metamorphosed in the amphibolite facies and show no obvious evidence of re-working in terms of relict textures or assemblages. Lappin (1974) estimated T-P conditions to be 650°C–720°C, 8–10 kilobars; Lappin & Smith (1978) update the estimates of maximum pressure to between 9 and 13 kilobars.

In this study we present further field and petrologic evidence, as well as new U-Pb zircon and Rb-Sr whole rock isotopic data, in order to elucidate the age and origin of the early grey gneiss complex; the microcline-rich augen and banded gneisses, which were formed from the grey gneiss; the less abundant metasedimentary rocks; and the mangerite syenite.

Rock types investigated

The grey gneisses, augen and banded gneisses

The grey gneisses are the predominant rock type. Their essential mineralogy is:

quartz – plagioclase – biotite ± allanite-epidote ± garnet ± hornblende ± microcline ± muscovite.

The average grey gneiss is of granodioritic composition (Table 1), similar chemically to Archaean grey gneisses (Tarney 1976), and remarkably similar to Sederholm's (1925) average composition of the Baltic crust. Monotonous amphibolite facies grey gneisses seem to be a characteristic feature of early crustal evolution in many areas (Moorbath et al. 1975, Tarney 1976).

The grey gneisses are medium-grained, banded rocks where the banding is defined essentially by minor variations in the proportions of minerals, or by the development of thin (approx. 2 mm) quartzo-feldspathic foliae, or by

TABLE 1. Average analyses and C.I.P.W. norms of gneisses and mangerite syenite.

	1	2	3	4(1)	5(1)	6(1)	7
SiO_2	69.2	67.6	67.45	66.64	70.06	66.03	64.80
TiO_2	0.34	0.33	0.41	0.61	0.38	0.71	0.75
Al_2O_3	15.9	15.19	14.63	14.91	14.70	15.38	15.74
Fe_2O_3	3.4	1.75	1.27	1.61	0.77	1.87	1.53
FeO	-	1.28	3.13	3.18	1.57	3.24	2.65
MnO	0.06	0.05	0.04	0.09	0.12	0.08	-
MgO	1.5	1.28	1.69	1.85	1.36	1.70	1.11
CaO	3.2	3.22	3.39	3.28	1.36	3.00	2.26
Na_2O	4.2	4.15	3.55	3.40	3.19	2.80	4.65
K_2O	2.3	2.58	3.06	3.22	5.44	4.21	5.24
P_2O_5	-	0.11	0.14	0.17	0.11	0.15	0.41
H_2O	-	-	-	0.40	0.47	0.90	0.80
Total	100.1	97.54	98.76	99.36	99.04	100.07	99.94
Qu	-	-	-	23.1	28.5	22.9	-
Or	-	-	-	19.5	32.3	25.2	-
Ab	-	-	-	28.8	27.3	23.6	-
An	-	-	-	15.6	4.5	14.3	-
Cor	-	-	-	-	1.3	0.9	-
Hyp	-	-	-	8.2	3.7	7.6	-
Mt	-	-	-	2.3	1.2	2.7	-
Hm	-	-	-	1.2	0.5	1.3	-
Ap	-	-	-	0.3	0.3	0.3	-

1. Average of 268 grey gneisses, Laxford Assemblage (Holland & Lambert, 1973).
2. Average of 22 grey gneisses, Harris and Lewis, Outer Hebrides (Sheraton et al., 1973).
3. Average Baltic crust (Sederholm, 1925).
4. Average of 15 grey gneisses, Selje district (analyst S. M. Lindsay).
5. Average of 9 augen and banded gneisses, Selje district (analyst S. M. Lindsay).
6. Average of 6 mangerite syenites, Flatraket mass (analysts S. M. Lindsay & M. A. Lappin).
7. Mangerite syenite, Altøy, Sunnfjord (Kolderup & Kolderup, 1940).

(1). Analyses made by a combination of colorimetric, gravimetric and atomic absorption techniques.

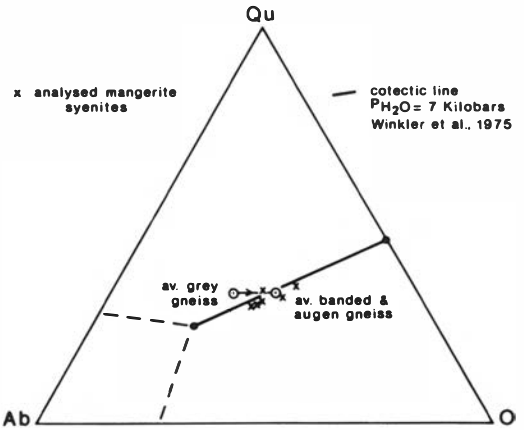

Fig. 2. The system Qz-Ab-Or and the projection of the cotectic line in the system Qz-Ab-Or-An-H_2O at P_{H_2O} = 7 kilobars.

foliae somewhat enriched in minerals such as biotite, epidote, garnet, or ore. In many exposures the grey gneisses grade into banded and augen gneisses. Both rock types have essentially the same mineralogy as the grey gneisses except that K-feldspar rates as an essential mineral with up to 50% modal microcline in contrast to the grey gneisses with <10% modal microcline. Augen and banded gneisses cannot be distinguished chemically and the average K-feldspar-rich gneiss (Table 1) is of granitic composition.

The grey, banded, and augen gneisses share a common foliation (F_1) affected by at least four episodes of folding (Lappin 1966). In the gradation from grey to banded gneiss this foliation becomes accentuated through the development of coarse-grained, quartzo-feldspathic foliae up to 30 mm wide, which on occasions are larger, irregular, and lensoid to vein-like, giving the rocks a complex migmatitic aspect. The augen gneisses consist of a foliated, and sometimes folded, grey gneiss-like matrix which is apparently overgrown by large microcline porphyroblasts which are themselves deformed. Lappin (1966) considered this striking relationship between microcline porphyroblasts and the dominant foliation to indicate relatively late growth of microcline by metasomatic replacement, and found support for this argument in apparent replacement textures involving the development of antiperthitic microcline and myrmekite. He suggested that similar processes operated within the banded gneisses except that the replacement of plagioclase by microcline occurred largely within the coarser, quartzo-feldspathic foliae. A comparison of average grey and average banded and augen gneisses (Table 1, Fig. 2) shows that in normative terms at least (Fig. 2) the process can be considered as a replacement of albite by K-feldspar but involves apparent increases in Si and K with apparent decreases in Fe^{2+}, Fe^{3+}, Mg, Ca, and Na (Table 1). A series of discordant microcline pegmatites was considered to be related to this metasomatic process (Lappin 1966).

Metasediments

The rare quartzites contain:

quartz – microcline – plagioclase – muscovite – biotite – allanite-epidote – garnet.

They are exposed in large, mullion-like fold cores amongst grey gneisses at Hoddevik (Fig. 1).

The essential mineralogy of the garnet-mica schists is:

quartz – muscovite – biotite – garnet – plagioclase ± kyanite.

They can be distinguished from garnetiferous grey gneisses by abundance of muscovite, a characteristic pleochroism of biotite, and absence of K-feldspar and epidote. Both quartzites and pelites are interlayered with a variety of grey and banded gneisses and, in particular, appear to grade into the former. Sharp boundaries suggestive of supracrustal/infracrustal relationships, or of units juxtaposed by thrusting, were not observed. The metasedimentary types appear to have a similar deformational history to adjacent gneisses.

Microcline augen are locally developed within the quartzites and these may perhaps be attributed to metasomatic processes. In contrast metasomatic effects are not obvious within the garnet-mica schists. Addition of K and other components to rocks of this composition might be expected to result only in larger amounts of muscovite.

The mangerite syenite

The term mangerite syenite is used to describe rocks near Flatraket (Fig. 1) because these rocks resemble mangerite syenites of Kolderup & Kolderup (1940) (cf. Table 1). Bryhni (1966) described the related rocks at Måløy as mangerites. Individual analyses plotted on the Ab-Or-Qu projection (Fig. 2) suggest the possibility of a cotectic-controlled, initial igneous evolution. The mangerite-syenite lies to the E and S of the village of Flatraket (Fig. 1). Similar but larger masses outcrop to the W of Flatraket and on the island of Måløy (Bryhni 1966, fig. 1). An ovoidal facies of the mangerite syenite is the predominant rock type consisting of purple-brown orthoclase set in a matrix consisting of much finer-grained plagioclase, quartz, and various mafic minerals. Garnet tends to form in corona-fashion between mafic phases, such as pyroxene or iron ore, and plagioclase and a typical early mineral assemblage for the freshest mangerite syenite is:

orthoclase – plagioclase – quartz – clinopyroxene – garnet – ore.

Such an assemblage is stable in the granulite facies as in the assemblage:

garnet – clinopyroxene ± plagioclase ± quartz

found in both concordant and cross-cutting dyke-like bodies (the latter cutting single ovoidal orthoclase crystals). Here again the garnet develops in corona fashion.

A varied degree of retrogression is found in the mangerite syenite with the development of wispy biotite, hornblende, saussurite, microcline, and myrmekite. Near the boundaries of the mass, and along zones of internal shearing, the ovoidal mangerite syenite is extensively mylonitised with the development of a finely-laminated, blasto-mylonitic facies. In places there is considerable recrystallisation of the blastomylonites with the development of a mica-rich rock of gneissic appearance containing the following assemblages:

quartz – muscovite – biotite – microcline – kyanite – garnet
quartz – muscovite – biotite – microcline – epidote.

These suggest post-shearing equilibration in the amphibolite facies. Bryhni (1966) records a similar range of assemblages in the mangerites from Måløy.

Detailed mapping shows that conformable basic pods within the mangerite syenite are cut off sharply at the southern contact against basal gneiss. The contacts of the mass are thus tectonic, though this need not necessarily indicate large-scale movement (Bryhni et al. 1970). However, the known thrusting history of other anorthosite kindred rocks within the basal gneisses (Griffin 1971, Furnes et al. 1976), together with tectonic contacts, is taken to indicate that the shearing and amphibolite facies recrystallisation processes are of Caledonian age and are related to the introduction process.

Sampling and analytical procedures

The present sampling was designed to test the age relations and homogeneity of strontium isotopic systems of different rock types within a single locality and for petrographically similar rock types between localities. Four localities near Flatraket and Selje in the south and Eltevik and Hoddevik in the north of the area were chosen (Fig. 1) and details of location and petrography of all the analysed samples are presented in Appendix 1. Appendix 2 provides descriptions of the separated zircons. Sample size (Rb-Sr) varied from 4 to 10 kgs. Rb-Sr and U-Pb isotopic analyses were performed at the Scottish Universities Research and Reactor Centre. Details of the analytical technique are given in Appendix 3. All Rb-Sr ages quoted have been recalculated using λ^{87} Rb $= 1.42 \times 10^{-11}$ y^{-1}.

Isotopic results

Analytical results are presented in Tables 2 and 3 (Rb-Sr) and Table 4 (U-Pb), and plotted in Figs. 3 and 4.

The grey gneisses, augen and banded gneisses

The grey gneisses were sampled at all four localities (Fig. 1, Appendix 1). Rb-Sr whole rock analyses (Table 2 and 3, Fig. 3) show that:

There are systematic age relationships within and between localities;

At each locality the degree of Sr isotopic disturbance in a whole rock sample can be correlated with the amount of K-feldspar. The sample

Table 2. Rb-Sr Whole Rock Analyses

Sample		Rb ppm	Sr ppm	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	Calculated age in m.y.[1]
Flatraket						
RC 558[2]	Mangerite syenite (O)[3]	102.8	304.6	0.979	0.7323	2076
RC 560	" " "	100.2	263.0	1.106	0.7369	2348
RC 561	" " "	107.9	266.7	1.174	0.7376	2395
RC 562	" " "	119.6	317.0	1.094	0.7343	2170
RC 563	" " "	109.7	281.3	1.132	0.7429	2755
		109.6	282.0	1.128	0.7427	2742
RC 567	" " (S)[3]	99.9	275.7	1.051	0.7328	1972
RC 568	" " "	261.0	184.0	4.127	0.7729	1180
RC 569	" " "	252.0	168.0	4.355	0.7727	1120
RC 564	Grey gneiss	108.6	958.0	0.328	0.7092	1318
RC 565	" "	117.3	275.3	1.235	0.7249	1238
		121.1	265.9	1.321	0.7259	1210
		118.2	266.8	1.284	0.7254	1218
RC 583	" "	46.3	798.7	0.168	0.7062	1329
Eltevik						
RC 532	Grey gneiss	95.0	180.9	1.526	0.7409	1728
RC 533	" "	104.3	385.1	0.786	0.7381	
		106.0	199.6	1.542	0.7399	1665
RC 534	" "	102.5	211.6	1.406	0.7378	1722
RC 535	" "	102.3	173.3	1.716	0.7448	1695
RC 536	" "	82.7	257.6	0.932	0.7270	1790
RC 537	" "	100.3	182.2	1.679	0.7429	1654

1. $\lambda^{87}Rb = 1.42 \times 10^{-11} y^{-1}$ $(^{87}Sr/^{86}Sr)$ initial = 0.703
2. Scottish Universities Research and Reactor Centre sample number.
3. O = orbicular S = sheared.

though the pattern of disturbance varies from locality to locality.

Grey gneiss samples with <2 percent of modal K-feldspar include all six samples from Eltevik. These samples, RC 532-537, define a single line on an isochron plot with a calculated age of 1540 ± 130 m.y. and an initial ratio of 0.706 ± 0.003. Two Flatraket samples RC 564 and RC 583 have similar amounts of K-feldspar and, with higher strontium contents and lower Rb/Sr ratios, fall essentially upon the same straight line as the Eltevik grey gneiss points. If, however, they are considered along with RC 565 which has between 5–10 percent K-feldspar then they lie close to a 1200 m.y. reference line (Fig. 3). This pattern is similar to that recorded at Selje (Fig. 1). Two grey gneisses, RC 593 and RC 600, are K-feldspar-poor and lie along the straight line defined by other K-feldspar-poor grey gneisses (Fig. 3). The K-feldspar-rich augen gneisses from this locality RC 590, 591, 592 and the banded gneiss, RC 602, have a range of strontium values (384–418ppm) within the range

Table 2 (cont.)

Sample		Rb ppm	Sr ppm	$\frac{^{87}Rb}{^{86}Sr}$	$\frac{^{87}Sr}{^{86}Sr}$	Calculated age in m.y.[1]
Hoddevik						
RC 553	Quartzite	93.1	52.9	5.128	0.7842	1106
RC 579	"	97.8	62.1	4.598	0.7841	1231
RC 582	"	129.5	68.9	5.489	0.7951	1172
RC 554	Grey gneiss	182.3	134.6	3.955	0.8043	1780
	" "	182.3	134.6	3.957	0.8040	1775
	" "	182.8	136.0	3.926	0.8038	1785
RC 578	" "	85.1	369.7	0.667	0.7165	1411
RC 580	" "	101.1	336.0	0.873	0.7240	1674
RC 581	" "	99.8	237.0	1.222	0.7333	1725
RC 576	Schist	105.4	131.9	2.324	0.7527	1490
RC 577	"	116.8	119.4	2.846	0.7630	1469
Selje						
RC 590	Augen gneiss	207.6	383.8	1.569	0.7280	1113
RC 591	" "	209.4	418.0	1.452	0.7222	925
RC 596	Schist	143.0	81.4	5.106	0.7519	671
RC 597	"	137.6	118.2	2.377	0.7391	1061
RC 598	"	108.0	94.9	3.305	0.7427	840
RC 599	"	75.8	78.0	2.819	0.7288	642
RC 601	"	75.0	98.1	2.215	0.7260	727
RC 593	Grey gneiss	85.2	455.2	0.543	0.7175	1855
RC 600	" "	90.1	232.3	1.125	0.7305	1700
		90.4	227.6	1.152	0.7302	1643
RC 602	Banded gneiss	184.0	394.3	1.352	0.7224	1003

1. $\lambda^{87}Rb = 1.42 \times 10^{-11} y^{-1}$ $(^{87}Sr/^{86}Sr)$ initial = 0.703

2. Scottish Universities Reaearch and Reactor Centre sample number.

for the two grey gneisses (228–455ppm) but have high rubidium values (184–209ppm compared with 85–90ppm). The data points for these three samples fall to the right of the grey gneiss isochron and cluster, along with data point for RC 565, the anomalous sample from Flatraket (Fig. 3). The pattern for Hoddevik (Fig. 1) is somewhat different. Three samples RC 578, 580, and 581 have similar rubidium and strontium values and Rb/Sr ratios to other grey gneisses. All the Hoddevik grey gneisses have somewhat larger amounts of modal K-feldspar than grey gneisses from other localities and lie on, or close to, the grey gneiss line (Fig. 3). The fourth grey gneiss RC 554 has a notably higher Rb/Sr ratio than other grey gneisses, though a similar modal K-feldspar content, and lies on the extension of the grey gneiss line (Fig. 3). This specimen was collected from a gradational zone between quartzite and grey gneiss and the former has still higher Rb/Sr ratios (Table 2). The four Hoddevik samples have a calculated age of 1850 ± 135 m.y. and an initial ratio of 0.700 ± 0.003.

For the Flatraket and Selje localities increas-

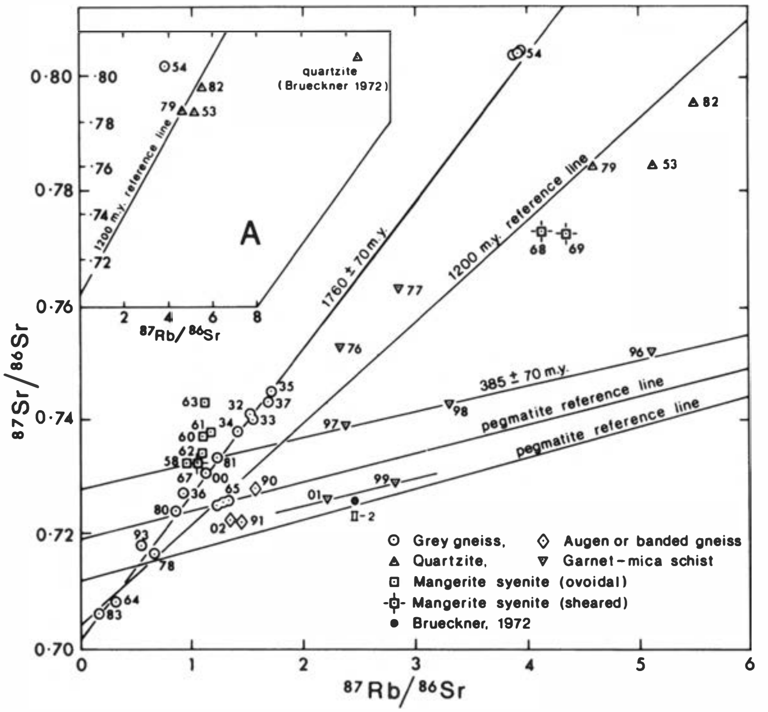

Fig. 3. Rb-Sr isochron plot for basal gneisses, metasediments and mangerite syenites.

ing K-feldspar content apparently correlates with data points lying to the right of the grey gneiss isochron. This is not so for the Hoddevik samples, suggesting that there are two generations of K-feldspar – an early K-feldspar present in the Hoddevik samples and a later K-feldspar responsible for subsequent isotopic disturbance at Flatraket and Selje.

Our best estimate of the age of the grey gneisses, based upon 13 apparently undisturbed data points from all four localities, is 1760 ± 70 m.y. with an initial ratio of 0.7018 ± 0.0010. This age is in reasonable agreement with the age of 1672 ± 60 m.y. reported by Pidgeon & Råheim (1972) for the Kristiansund gneisses.

Zircon fractions (Table 3) were separated from two grey gneisses – RC 537 from Eltevik and RC 583 from Flatraket. Both fractions have a limited range in discordance (Fig. 4) which considerably limits the precise estimate of the age of zircon formation or resetting.

The 'best-fit' chord through the four fractions from RC 537 has a very uncertain upper intersection with the concordia of *c.* 1650 m.y. – apparently lower than the Rb-Sr whole-rock age. The points from RC 537 fall essentially on the zircon chord from the Kristiansund Group (Fig. 4) (Pidgeon & Råheim 1972) which supports a major isotopic event at this time. The data points for RC 583 do not lie upon this chord, but are strongly discordant, and cannot be used by themselves to define a meaningful upper intersection. A chord drawn through both sets of grey gneiss data points yields an upper intersection on the concordia at *c.* 1700 m.y.

The lower intersections of grey gneiss discordia and concordia are again uncertain, being the result of long extrapolations. In general, intersections range from about 400-600 m.y., suggesting that some isotopic disturbance may be correlated with 'Caledonian' events.

A remarkable contrast is seen in the three size fractions from the zircon population of the banded gneiss from Selje (RC 602) which are almost completely discordant at *c.*400 m.y. (Fig. 4) with a possible upper intersection at *c.*1100 m.y. This strongly suggests new zircon growth, or a major reconstitution of older zircon, during the Caledonian. An examination of grain mounts gives no indication of a major growth of new zircon (Appendix 2).

Metasediments

Quartzites and garnet-mica schists were analysed from Hoddevik and garnet-mica schists at Selje. As a group, Rb/Sr points from the metasediments show a scatter to the right of the grey gneiss isochron (Fig. 3). Three quartzite points from Hoddevik (RC 553, 579, 582) with model ages of 1106 to 1231 m.y. (Table 2) do not define an isochron (Fig. 3). These analyses can be considered with results from the grey gneiss, RC 554, which is gradational into quartzite and also those from a quartzite (Fig. 3A) from Lote, Nordfjord some 45 km ESE of Selje (Brueckner 1972). These quartzites all contain feldspar and muscovite and have high Rb/Sr ratios. Brueckner considers the Lote quartzite to be a Caledonian geosynclinal sediment with a calculated age of 548 m.y. assuming an initial ratio of 0.705. RC 554, in contrast to the quartzites, lies on the grey gneiss isochron (Fig. 3), though having a high Rb/Sr ratio, and thus suggests that the quartzite and grey gneiss were contemporaneous.

The garnet-mica schists fall into two local groups. The Hoddevik samples, RC 576 and 577, lie to the right of the grey gneiss isochron (Fig. 3) and have calculated ages of 1469 and 1490 m.y. (Table 2). Petrographically these schists can be distinguished from those at Selje only by the apparent absence of kyanite. The Selje schists were collected over a limited distance across strike. Four samples from a 10 metre wide zone, RC 596, 597, 598, 600 (the latter collected as a garnet-mica schist though identified in thin section as a grey gneiss), indicate an approximate regression line of 385 ± 70 m.y. Two additional samples RC 599 and RC 601 collected some 12 and 7 metres to the south and north of the other specimens plot below this line (Fig. 3). The muscovite-epidote schist from Sandvik, Stadlandet (Brueckner 1972) lies near these points (Fig. 3) and, with a mineral/whole rock age of 383 ± 12 m.y., is considered by Brueckner to be a Caledonian geosynclinal sediment.

Table 3. Zircon U-Pb isotopic analyses

ZIRCON SAMPLE (size in microns)	Pb (rad.) µg/gm	U µg/gm	$^{206}Pb/^{204}Pb$	Atom percent radiogenic lead			Atomic Ratios		
				206	207	208	$^{207}Pb/^{206}Pb$	$^{207}Pb/^{235}Pb$	$^{206}Pb/^{238}Pb$
RC 537 Grey Gneiss - Eltevik									
1. + 106µ NM	137.5	583.4	1614	86.44	8.484	5.079	.09816	3.206	.2369
2. -106 + 84µ NM	137.6	580.6	2062	86.44	8.509	5.051	.09844	3.233	.2382
3. - 61 + 45µ NM	129.6	547.5	2382	86.03	8.435	5.538	.09805	3.200	.2367
4. -45µ NM	140.4	608.5	2019	85.55	8.377	6.068	.09791	3.098	.2294
RC 558 Mangerite syenite - Flatraket									
5. + 165µ NM	72.4	285.9	4260	82.21	7.688	10.100	.09352	3.113	.2414
6. -165 + 142µ NM	81.3	321.2	14150	82.59	7.761	9.651	.09398	3.150	.2430
7. -142 + 106µ NM	89.8	352.2	19975	82.80	7.809	9.289	.09432	3.190	.2453
8. -106 + 84µ NM	87.5	365.7	7340	83.00	7.807	9.195	.09406	2.991	.2306
9. -45µ NM	113.7	468.3	6495	83.34	7.846	8.817	.09415	3.052	.2351
10. -165µ M1°	87.7	333.5	13925	82.34	7.704	9.952	.09356	3.248	.2518
11. - 61 + 45µ M3°	108.0	454.8	2800	82.76	7.720	9.516	.09328	2.936	.2283
RC 583 Grey Gneiss - Flatraket									
12. + 142µ NM	53.4	303.6	3444	82.35	7.206	10.440	.08750	2.032	.1684
13. -106 + 84µ NM	45.1	234.1	10280	81.50	7.254	11.249	.08901	2.237	.1823
14. - 84 + 61µ NM	43.6	224.9	8135	80.91	7.159	11.931	.08848	2.226	.1825
15. -45µ NM	40.2	207.1	12580	79.55	7.059	13.385	.08872	2.198	.1797
RC 602 Banded Gneiss - Selje									
16. -165 + 142 NM	65.2	862.5	3062	89.77	5.374	4.853	.05987	.6514	.07891
17. -106 + 84 NM	38.4	477.4	1138	87.39	5.324	7.281	.06092	.6874	.08184
18. -45 NM	35.1	492.4	5270	88.94	5.228	5.828	.05877	.5965	.07361

NM - Zircons with no magnetic susceptibility. M - Zircons with slight magnetic susceptibility.

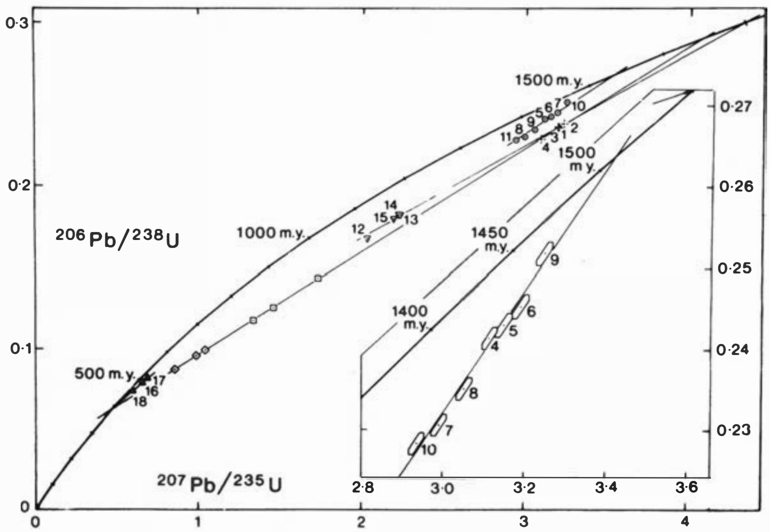

Fig. 4. Concordia plot showing U-Pb analyses of zircons from grey gneisses RC 537 (1–4, crosses) and RC 583 (12–15, inverted trangles); for the banded gneiss RC 602 (16–18, triangles); and for the mangerite syenite RC 558 (5–11, diamonds). The error boxes in the inset diagram of the mangerite syenite concordia were calculated using the overall uncertainties in isotopic ratio determination given in Appendix 3.

The mangerite syenite

Five whole-rock samples of orbicular mangerite syenite were uniform in Rb (100–120ppm) and Sr (263–317ppm) contents (Table 2) and consequently have a restricted spread in Rb/Sr. Data points on an isochron plot (Fig. 3) fall on a poorly-defined line to the left of the grey gneiss isochron. The slope of the Rb-Sr line suggests that the orbicular mangerite syenite is older than the grey gneiss. RC 563 is somewhat distinctive petrographically (Appendix 1) and gives the oldest apparent age (Table 2). Two samples of sheared mangerite syenite, RC 568 and 569, have higher Rb values (252–261ppm) and lower Sr (168–184 ppm) than orbicular mangerite syenites, whilst RC 567 with 100ppm Rb and 276ppm Sr is similar to the orbicular mangerite syenites. Other sheared mangerite syenites show a variable enrichment in Rb (Table 4).

Seven size and magnetic fractions of zircon from a single block of mangerite syenite (RC 556) define a discordia (Fig. 4) with an upper concordia intersection of 1520 ± 10 m.y. and a lower intersection of *c.* 400 m.y.

Discussion

The fundamental grey gneiss-forming event

We have demonstrated that data points of Rb-Sr whole rock samples of the grey gneisses approximately fall on the same line on an isochron plot although from widely separated localities. A regression (York 1969) through 13 data points gives an age of 1760 ± 70 m.y. with an initial ratio of 0.7018 ± 0.0010 (M.S.W.D. 9.2). Isochrons calculated for individual localities range from 1540 ± 130 m.y. to 1850 ± 135 m.y. with initial ratios ranging up to 0.7063. These could reflect real age and initial ratio differences between localities or later isotopic disturbance. Nevertheless, the correlation of the grey gneiss points is striking and we interpret this to indicate a common Svecofennian history for this rock type. Although approximately linearly correlated, the small spread in discordance of the zircon fractions in the grey gneisses leads to a large uncertainty in the point of intersection of

Table 4. Rb-Sr analyses of mangerite syenites

		ovoidal mangerite syenite (1)	sheared & gneissic mangerite syenite (2)
Rb	average	103	163
	range	84 - 120	72 - 334
Sr	average	268	231
	range	228 - 305	152 - 304
Rb/Sr	average	0.38	0.71

1. 8 samples of ovoidal mangerite syenite including those in Table 2.
2. 12 samples of sheared and gneissic mangerite syenite including those in Table 2.

Samples other than those in Table 2 analysed by X-ray fluorescence. University of Aberdeen.

zircon chords and concordia: estimates range from *c.*1650–1700 m.y.

The geological significance of the Svecofennian ages is debatable. They could record either the age of formation of the pre-metamorphic parent rocks, or the age of amphibolite facies metamorphism, or the culmination of both processes.

The average grey gneiss composition listed in Table 1 is similar to Archaean grey gneisses, and suitable parent rocks for the abundant Archaean and for these grey gneisses are granodiorites/tonalites or greywackes (Tarney 1976). This author argues that the Archaean grey gneisses are of igneous parentage largely upon the basis of discrimination between sedimentary and igneous rocks based upon TiO_2–SiO_2 abundance levels. The grey gneisses analysed so far span the fields of both igneous and sedimentary rocks. Grey gneisses are the dominant gneiss type of the North Atlantic Archaean but are not restricted to Archaean rocks (Wynne-Edwards & Hasan 1972). There is thus no evidence that these grey gneisses represent reworked Archaean rocks; indeed, the low initial ratio 0.7018 $\pm$ 0.0010 argues against any extended earlier crustal history and, following the arguments developed by Moorbath et al. (1975) for Hebridean grey gneisses, favours an essentially igneous volcanic parentage formed at a time not much before their whole-rock ages. Råheim (1977) also considers that the basal gneisses (of the Surnadal syncline) are volcanic in origin.

An alternative explanation is that the 1760 m.y. age records the process of amphibolite facies metamorphism and gneiss formation. Pidgeon & Råheim (1972) advocate this as an explanation of the 1670 m.y. age (initial ratio 0.7038) they record at Kristiansund, largely on the basis that such a metamorphism is likely to cause at least partial disturbance of Rb-Sr whole rocks systems and may well reconstitute zircon U-Pb systems. Råheim (1977) explains the 1671 ± 63 m.y. age (initial ratio 0.7026) at Surnadal in a similar fashion, but also states that unpublished isotopic studies of palaeosomes and neosomes support such a hypothesis. Mysen & Heier (1972) apparently assume that the age of 1650 m.y. for the Hareidland gneiss is likewise an age of metamorphism. The 1710 m.y. age recorded by Sturt et al. (1975) for augen gneisses at Sotra, Bergen district is considered, because of the low initial ratio (0.7015 ± 0.002), possibly to indicate an original age. These rocks contain granulite facies relicts and could thus have been re-worked. These ages, however, spread over some 350 kilometres of the west Norwegian seaboard, testify to the importance of the Svecofennian event within the basal gneiss. The well-defined, and low, initial ratios for the grey gneisses described here, for the augen gneisses of Sotra, and the Kristiansund and Surnadal gneisses, together with the less-well defined, but apparently low, initial ratios of gneisses from Hareidland (Mysen & Heier 1972) and Dovrefjell (Brueckner 1972), together with the limited evidence of earlier reworking, suggest that the *c.* 1700 m.y. events are the combination and culmination of initial igneous and later metamorphic events during Proterozoic, granodioritic, crust-forming processes similar to those inferred for the Archaean by various authors (Tarney 1976, Moorbath 1976).

The formation of the microcline-rich gneisses

The granitic migmatitic and augen gneisses are regarded as the metasomatised grey gneisses (Lappin 1966) and, in the simplest terms, we assume this metasomatism involves addition of K (Table 1, Fig. 2) and geochemically associated elements, particularly Rb. A suite of associated, discordant, microcline pegmatites indicates that the metasomatic medium may be pegmatitic in character. If the metasomatic process is modelled upon an isochron plot then the position of whole-rock data points for metasomatised rocks will depend on the degree of homogenisation of $^{87}Sr/^{86}Sr$ between the rock and the pegmatitic fluid and upon the amount of Rb added. For a suite of rocks subject to a variable degree of homogenisation and addition a scatter would result though a special case, when rock and pegmatitic fluid have similar initial ratios, can be envisaged. In this case the metasomatic process would be seen on the isochron plot as ^{87}Rb addition, though subjected to post-metasomatic radiogenic decay processes. It is possible to model such processes in Fig. 3. Pidgeon & Råheim (1972) show that thin, cross-cutting, microcline pegmatites in the Kristiansund area have varied initial ratios (0.712–0.718) and Caledonian Rb/Sr whole rock and whole rock-mineral ages (364 and 372 ± 7 m.y. respectively). The pegmatite reference lines of Fig. 3 are for the Kristiansund pegmatites. The K-feldspar-rich grey gneisses RC 564 and 590, the augen gneiss RC 591, and the banded gneiss RC 602 cluster within, or close to, the pegmatite reference lines. These rocks can be modelled in terms of Rb addition at the time of pegmatite formation. The amount of Rb addition (calculated relative to the grey gneiss isochron) for RC 590, 591, samples with a slightly modified grey gneiss fabric, averages some 60%. Perhaps coincidentally the implied addition of K_2O in transforming average grey gneiss to average K-feldspar-rich gneiss (Table 1) is 59%. This modelling process cannot conclusively show that the metasomatic process is of Caledonian age. However, the strongest evidence for a fundamental Caledonian event is provided by the strong disturbance of the migmatitic banded gneiss (RC 602) zircons at *c.* 400 m.y. Lower concordia intersections of the grey gneiss zircons, though subject to long extrapolation, likewise suggest a Caledonian influence.

There are parallels in the varied degrees of disturbance of the zircon U-Pb systems between this migmatitic gneiss and associated grey gneisses (Fig. 4) and the granitised gneisses from the Strona-Ceneri zone of the South Alps (Koppel & Grunenfelder 1971). In the latter rocks zircons are almost concordant, the degree of disturbance increasing with K-feldspar content, whilst associated paragneisses have extremely discordant zircons of varied apparent age. Koppel & Grunenfelder attribute this difference to new zircon growth during anatectic granitisation and associated metasomatism. Likewise Pidgeon & Johnson (1974) relate zircon stability to alkalinity in magmatic rocks.

It seems reasonable to suggest that U-Pb systems may be almost totally reset during alkali metasomatism, and thus the 400 m.y. zircon age provides the best estimate of this metasomatic event within the basal gneisses.

The metasediments

The metasediments have a range of apparent ages (Tables 2, 3) but only one sample from Hoddevik (RC 554), and samples from Selje can be related directly to the Svecofennian and Caledonian processes described in preceding sections. RC 554 lies along the extension of the grey gneiss isochron (Fig. 3). Compositionally it is intermediate between grey gneiss and quartzite and, if the former are of volcanic origin, must be volcano-clastic in origin and formed contemporaneously with the grey gneiss precursors. The high Rb and Sr values for this sample link it to the other Hoddevik quartzites with younger apparent ages (Table 2) and to a quartzite of supposedly Caledonian age (Brueckner 1972). The varied apparent ages of these quartzites and related rocks suggests either quartzite deposition and metamorphism at various times or, as is considered more likely, a varying degree of metasomatic addition and homogenisation as is inferred for the grey and microcline-rich gneisses. Microcline augen developed in the border facies of some of the quartzites may be evidence for a Caledonian metasomatic event.

The Selje garnet-mica schists yield an Rb/Sr whole-rock age of 385 ± 70 m.y. The Hoddevik garnet-mica schists have older apparent ages (Table 2). These metasediments can again be interpreted as two groups of rocks belonging to the Caledonian and Sveconorwegian depositional and metamorphic cycles or as Svecofennian or Sveconorwegian cycle rocks variably affected by, and locally equilibrated during, a Caledonian metamorphic/metasomatic process. Since both the quartzites and the garnet-mica schists grade into grey gneisses and share a common deformational history they are tentatively regarded as Svecofennian cycle rocks variably affected by Caledonian processes.

The mangerite syenite

The mangerite syenite and associated basic rocks have a complex evolution ranging from initial magmatic crystallisation through the development of granulite facies mineralogy to the minor retrogression associated with the development of wispy biotite and amphibole and also mylonitisation and amphibolite facies recrystallisation associated with shear zones.

The limited discordance of zircons from the mangerite syenite and the experience of zircon U-Pb studies in similar Adirondack rocks (Silver 1969) suggests that the zircon U-Pb 'upper-intersection' age of 1520 ± 10 m.y. is most likely to represent a magmatic crystallisation age. In contrast to the Adirondacks (cf. Silver 1969, Barton & Doig 1977) where Rb-Sr whole rock isochrons give ages compatible with zircon U-Pb ages, the geochemical behaviour of Rb and Sr within the Flatraket mangerite syenite is complex. The ovoidal mangerite syenite whole-rock data suggest an age older than 2000 m.y. (Table 2, Fig. 3). Such an apparently old age can be produced either by the loss of Rb or a gain in ^{87}Sr. A process which may have resulted in the former is the granulite facies metamorphism. However, a loss of alkalis from the ovoidal mangerite syenite is not supported by its cotectic composition (Fig. 2). We therefore favour a hypothesis of radiogenic Sr addition or exchange during later processes of K-metasomatism and/or shearing. Such a process might also explain why the sheared mangerite syenites, whilst enriched in Rb (Table 4), do not yield Caledonian ages (Fig. 3). It should be noted, however, that the only other radiometric evidence for a Caledonian event in the mangerite syenite is the *c.* 400 m.y. "lower intersection" zircon U-Pb age and a 488 ± 2 m.y. K-Ar biotite age from Måløy (Bryhni et al. 1971).

The Flatraket mangerite syenite has a different age from mangerites and associated rocks from both north and southwest Norway. In the former area Rb-Sr whole-rock ages of 1737 ± 20 m.y. and 1664 ± 20 m.y. are recorded for metamorphosed and non-metamorphic mangerites respectively (Heier & Compston 1969, Griffin et al. 1974). In southwest Norway Versteeve (1975) found Rb-Sr ages ranging from 1180 ± 70 m.y. for a synmetamorphic syenite to 842 ± 30 m.y. for a late plutonic monzonite. These mangerites are therefore temporally associated with the Svecofennian and Sveconorwegian orogenies. Unmetamorphosed syenites (and related rocks) of intermediate age do occur in the Svecofennian foreland to the east (Padget 1973, Welin & Lundquist 1975).

The Sveconorwegian event in Stadlandet

We find limited positive evidence for Sveconorwegian events within the gneisses and metasediments of Stadlandet. The apparent ages of the quartzites are *c.* 1100–1200 m.y. (Table 2) though a similar quartzite has a calculated age of 548 m.y. (Brueckner 1972). The upper concordia intersection for the migmatitic gneiss (RC 602) gives a *c.* 1100 m.y. age but involves considerable extrapolation.

McDougall & Green (1964) quote K-Ar age for hornblendes from eclogites in the range 980–1170 m.y. and these data, treated by the K-Ar isochron method (Krogh 1977), give *c.* 940 m.y. There are two difficulties in accepting these data as an unequivocal record of a Sveconorwegian event. Firstly, the K-Ar technique has yet to be adequately tested in these eclogites, especially since associated pyroxenes may contain excess argon (McDougall & Green 1964). Secondly, although some workers (Bryhni et al. 1971, Krogh 1977) argue that the eclogites are in-situ, others (Lappin 1966, Lappin & Smith 1978) believe that these rocks are tectonic introductions and may thus have a different history.

Sveconorwegian ages are certainly found in eastern outcrops of the Basal Gneiss (Fjordane Complex) (Brueckner et al. 1968, Brueckner 1972) some 100 km E of the area under consideration. Sturt et al. (1975) record Svecofennian and Sveconorwegian events within the Bergen Arc system. The only record from the western Basal Gneiss outcrops comes from Almklovdalen some 10 km east southeast of Selje (Fig. 1) (Brueckner 1972) where an apparent 1175 m.y. isochron, defined by samples of a wide petrographic range and considerable scatter (M.S.W.D. 26), is recorded. Lappin (1966) considers that the Almklovdalen gneisses are similar in both paragenesis and fabric to the gneisses described here. Indeed, Brueckner's data can be interpreted in a fashion similar to the grey gneisses and microcline-rich gneisses of Fig. 3. Thus samples which seem to be petrographically similar to grey gneisses lie close to the 'Svecofennian' grey gneiss isochron of Fig. 3 whilst granitic gneisses and a pegmatite lie below this line.

It is possible, however, that both the Sveconorwegian and Caledonian metamorphic events were of similar grade (amphibolite facies) to the Svecofennian. In such a situation Rb and Sr migration during the Sveconorwegian and/or Caledonian may have been largely limited to diffusion between adjacent minerals while the catalytic/transport effect of Caledonian fluids (perhaps following preferred pathways) may be necessary to disturb effectively the whole rock systems. Taylor (1975) suggests a rather similar explanation for the survival of an older age pattern in the Vikan gneisses affected by 2300 m.y. and 1875 m.y. granulite facies events.

Conclusions

The fundamental grey gneiss complex was formed around 1750 m.y. ago. It is believed that granodioritic magmatic activity gave rise to the grey gneiss precursors. Low $^{87}Sr/^{86}Sr$ initial ratios, however, preclude a long previous crustal history.

Gradational contacts between the grey gneisses and metasediments suggest that these are coeval, event though Rb-Sr whole rock isotopic systems in the latter have been disturbed during subsequent events.

The mangerite syenite crystallised 1520 ± 10 m.y. ago. We cannot at this stage date either the age of the granulite facies metamorphism or the tectonic emplacement of the mangerite syenite.

Little evidence has been found for a significant Sveconorwegian event; neither can such an event be ruled out.

The transformation of grey gneisses to augen and banded gneisses has been attributed to K-metasomatism tentatively linked with the Caledonian orogeny.

Appendix 1. Description and location of samples

Flatraket

Two groups of specimens were collected in the vicinity of Flatraket (Fig. 1 and 1:50,000 map Måløy Blad 1118 1). The first set (RC 558, 560, 561; RC 567–569) ovoidal and sheared mangerite syenites, were collected from a quarry 500 m south of the point of Naneset to the northeast of Flatraket, just west of the quarry on the roadside (RC 560), and then RC 562 and RC 563 100 m and 250 m to the south-southeast on the road towards Seljeneset. The second set (RC 564, 565, 583), grey gneisses, come from the point Gangeskardneset 20 m and 50 m west of a prominent amphibole eclogite (Eskola 1921, Lappin 1966). RC 583 was collected near the western entrance of the road tunnel at Gangeskard.

RC 558 Mangerite syenite

In hand specimen this is a coarse-grained quartz syenite with characteristic large ovoids of purple-brown K-feldspar up to 10 cms diameter. In section the large feldspars – both K-feldspar (approx. 50 %) and plagioclase (10–20 %) – show complex recrystallisation into aggregates of small interlocking grains with the development of unusually coarse-grained saussurite and myrmekite. Quartz (approx. 25 %) forms lensoid aggregates between the larger feldspars and consists of smaller grains with a tendency to triple point junctions. Aggregates of small, randomly-orientated biotites, together with minor epidote and occasional small garnets, surround opaque iron ore which has feathery boundaries of reacted appearance. This sample is the most thoroughly retrogressed and recrystallised of the mangerite syenite samples with essentially an amphibolite facies mineralogy and few granulite facies relicts.

RC 560, 561, 562 Mangerite syenites

In hand specimens these rocks resemble RC 558. In section, however, the K-feldspar (up to 50 %) forms very coarse, irregularly-shaped, untwinned grains with undulose extinction. A fine-grained mortar texture composed of feldspar, strained quartz, and some myremekite occurs along mutual grain boundaries. Plagioclase (10–20 %) forms large grains with undulose extinction and bent twin lamellae, mosaic aggregates between these larger grains, and also as small inclusions in K-feldspar. Quartz (10–20 %) likewise forms interlocking mosaic aggregates along the boundaries of larger grains. Small, granular garnet grains form overgrowths between iron ore and both feldspars. Wispy retrograde biotite is closely associated with both garnet and ore and the feldspars near these minerals show saussuritic clouding. Biotite also occurs as separate plates and occasionally as cores to garnet overgrowths. Small amounts of a rather altered, green clinopyroxene are found in association with garnet and ore. In appearance it resembles the pyroxene formed by granulite facies reactions in metabasic pods within the syenite (Lappin 1966) and strongly suggests the one-time presence of the high P granulite assemblage quartz – plagioclase – orthoclase – clinopyroxene – garnet – ore. These sections are noteworthy for the lack of retrogressive saussurisation, extensively developed in RC 558; both feldspars, however, show the metamorphic clouding typical of many granulite facies rocks and caused by patterns of a very fine-grained, needle-like inclusions. A complex history of strain and annealing is suggested by undulose extinction, mortar textures and mosaic aggregates. The larger K-feldspar grains seem to be relicts of an early stage in textural development.

RC 563 Mangerite syenite

In hand specimen this sample resembles RC 558. In thin section, however, the feldspathic areas

(50–60 %) consist of aggregates of smaller grains with complex interfingered boundaries probably representing annealed granulation. Individual grains and grain boundaries are marked by varying degrees of metamorphic clouding due to both fine needle-like and opaque ore phases. Quartz (up to 20 %) occurs as lensoid aggregates of grains with complex sutured grain boundaries and also as larger grains with undulose extinction. Most of the garnet (up to 20 %) forms small granules as overgrowths around iron ore, although larger garnets (3 mm diameter) of independent origin occur. Quartz also occurs as cores to some garnet overgrowths and as small inclusions in garnet. Quartz is produced during garnet-forming reactions between early pyroxenes and feldspars in metabasic rocks from the mangerite syenite. Most of biotite and minor amphibole form wispy, retrogressive plates or laths at garnet or iron-ore boundaries but some independent biotite plates occur and in places incipient saussuritisation within the feldspars seems to grade into areas of metamorphic clouding.

The garnet overgrowth textures are best preserved in this sample though the granulation/annealing processes within the feldspars seem to be more extreme as does the degree of metamorphic clouding which resembles in proportion the saussuritisation of RC 558.

RC 567, 568, 569 Sheared mangerite syenites

In hand specimen these samples have a platy, banded appearance. In thin section they consist of very fine-grained microcline, oligoclase and quartz with a strain-free, triple-point texture and occasional coarser, ribbon-like areas of oligoclase and quartz. Biotite and muscovite form small plates within the fine-grained, triple-point-textured areas and define a foliation. Occasional larger, sieved muscovite porphyroblasts also occur.

RC 564 Grey gneiss

In hand specimen the rock is medium grained with a regular, but gradational, colour banding due to subtle variations in the amount of ninerals present. In thin section it consists of rather irregular, lensoid, largely untwinned plagioclase (about 50 %), quartz grains or aggregates of quartz (about 20 %) of similar shape showing undulose extinction, and minor amounts (about 5 %) of finer-grained microcline associated with myrmekite. Biotite (about 10 %) and hornblende (5–10 %), like the lensoid quartz or feldspar grains, define the foliation. Large grains of epidote (5–10 %), some with random inclusions of biotite others zoned and cored by lower relief, low birefringence, yellow-brown allanite tend to lie in more random orientation relative to the foliation. Apatite and sphene are abundant accessories. Apart from very minor sericitic alteration of the plagioclase the rock is extremely fresh.

RC 565 Grey gneiss

This sample resembles RC 564 in texture though hornblende is absent and quartz and plagioclase are more abundant. Somewhat larger amounts of microcline and myrmekite are also present.

RC 583 Grey gneiss

In thin section largely-untwinned plagioclase is the most abundant mineral (50–60 %) and forms large (up to 2 mm), irregular grains with smaller strained quartzes (20–30 %) as inclusions or along feldspar grain boundaries. Microcline is present as antiperthite and also as small grains associated with quartz. The biotite fabric (biotite forming about 10 %) is complex suggesting more than one foliation surface. Large zoned epidotes (2 mm long) are associated with biotite-rich elements of the fabric. Apatite and sphene are common. Minor sericitic alteration of plagioclase occurs.

Eltevik

All the specimens were collected within 50 m of the southeast entrance to the small road tunnel between Borgund and Eltevik, Stadlandet almost 2 km southeast of the latter village (Fig. 1 and 1:50,000 map Vanylven Blad 1119 111).

RC 532 Grey gneiss

In hand specimen the Eltevik grey gneisses are all rather similar medium-grained rocks with a fine-scale colour banding and limited quartzofeldspathic segregation. In thin section this sample contains well twinned plagioclase (approx. 50 %), aggregates of strained, lensoid quartzes (between 20 and 30 %), microcline

(2–5 %) forming largely independetn grains but also antiperthite. Biotite (5–8 %) and muscovite (about 3 %) have a planar orientation. The muscovite, however, seems to be late. 1–2 % of epidote and minor amounts of apatite, carbonate, and iron ore also occur. The feldspar and epidote show minor amounts of dusty alteration.

RC 534, 535, 536, 537 Grey gneisses

These samples are almost identical to RC 532 except for minor variations in the amounts of constituent minerals, particularly microcline and associated myrmekite varying from about 5–10 % and occurring both as independent grains and as antiperthite. RC 537 shows a greater degree of dust-like alteration in feldspar.

Hoddevik

All the samples except RC 576 and 577 were collected from the grey gneisses and quartzites on the shore within 100 m of Hoddevik pier, Stadlandet (Fig. 1, 1:50,000 map, Stad 1019 11). RC 576 and 577 were collected above 250 m northwest of the pier on the shore section.

RC 553 Quartzite

This sample consists largely of quartz (approx. 80 %) with an elongate, lensoid form, complex, sutured margins, and undulose extinction. Plagioclase (up to about 5 %) forms aggregates of smaller, often-untwinned crystals and microcline (approx. 5–10 %) forms both lensoid grains similar in grainsize to quartz and smaller grains which, together with myrmekite, are often associated with plagioclase. Muscovite and biotite (5–10 %) form large plates elongate in the foliation and show a limited alteration to chlorite. Allanite and iron ore are accessory minerals. Alteration is limited to the minor development of chlorite and to slight dusty alteration in feldspars.

RC 579, 582 Quartzites

These samples are essentially similar to RC 553 except that both have larger plates of primary muscovite. Both show limited alteration.

RC 580 Grey gneiss

This contains about 40 % of quartz forming irregular grains with sutured boundaries and undulose extinction. Twinned plagioclase (5–15 %), and microcline (10–15 %) occur, the latter mineral as antiperthite and independent grains. Biotite (5–10 %) forms a complex planar fabric wrapping around lensoid felsic aggregates and associated with granular, zoned epidote (5–10 %). Apatite and sphene are common accessories and minor secondary muscovite occurs. The feldspars are fresh. Sparse garnets are seen in hand specimen.

RC 581 Grey gneiss

This sample is similar to RC 580 except for the rather greater amount of epidote, somewhat finer grainsize and minor dust-like alteration of the feldspars.

RC 554 Grey gneiss

This was collected closest to the quartzite boudins at Hoddevik within a zone which seemed transitional between the quartzite and the surrounding grey gneiss. Like the quartzite it is relatively enriched in ^{87}Sr and ^{87}Rb (Fig. 3) compared with the other grey gneisses. In thin section biotite (about 5 %) and epidote, forming very large, allanite-cored grains are less abundant than in RC 580 though their textural relationships are similar. Microcline is notably more abundant, forming, as in the quartzites, large, perthitic, augen-shaped grains often with complex myrmekitic intergrowths along grain boundaries. Minor, dusty alteration of the feldspars is present though some of the large microclines show a limited amount of sericitic alteration. Minor, secondary muscovite is also associated with biotite. Sparse garnet was recorded in hand specimen.

RC 576 Garnet-mica schist transitional to grey gneiss

This sample is composed of equigranular quartz (approx. 40 %), plagioclase (approx. 40 %), somewhat elongate in the foliation, garnular, zoned epidote together with xenoblastic garnet, biotite, and minor muscovite. Some dusty sericitic alteration is seen in the plagioclase. In the field this specimen is gradational into RC 577.

RC 577 Garnet-mica schist

In hand specimen this is a medium-grained schist breaking along muscovite-rich foliation surfaces. In thin section, quartz (approx. 50%) forms large (up to 3 mm long), elongate, strained grains with complex, sutured boundaries. Plagioclase occurs only in small amounts whilst muscovite (up to 40%) occurs as plates some 3 mm long. Biotite (5–10%) forms smaller laths intergrown with muscovite or along the edges of larger muscovites. Allanite, unusually without epidote overgrowths, is the dominant assessory. Sparse garnet was seen in hand specimen. All minerals are virtually unaltered.

Selje

The samples from this subarea can be split into two geographical groups (Fig. 1 and 1:50,000 map Vanylven, Blad 1119 111). Firstly banded gneisses, augen gneisses and associated grey gneisses (RC 602, 590, 591, 593) collected from the peninsula on which the old village is built and from the area to the south in the vicinity of the boat factory. Secondly a series of grey gneisses and garnet-mica schists (RC 597, 598, 599, 600, 601) collected over a limited distance (30 m across strike) some 40 m north of a prominent orthopyroxene eclogite lens described by Eskola (1921), Lappin (1966), Green (1969), and occurring near the locality given in older maps as Grytingvåg. The locality is 250 m north-northwest of Selje kirke.

RC 590 Augen gneiss

This specimen contains abundant, elongate, sheared augen (up to 5 cm long) of K-feldspar. In thin section microcline is dominant (between 50 and 60%) though the augen consist of aggregates of 1 mm long, subhedral, perthitic microclines with occasional quartz grains and myrmekite along grain boundaries and as inclusions. Quartz (up to 30%) forms elongate aggregates of crystals with irregular boundaries and undulose extinction. Small amounts of somewhat zoned plagioclase (5–10%) are present and also biotite (about 5%). Sphene has reaction rims of ilmenite and the latter partial rims of allanite. The feldspars show fine dusty alteration occasionally recognisable as sericite. Some biotites show alteration to sericite or chlorite.

RC 591 Grey gneiss

This specimen is a grey gneiss with some K-feldspar augen found as an enclave with the augen gneiss (RC 590). In thin section it is similar to RC 590 except that there is more plagioclase and biotite and rather less microcline. All phases are of rather fresher appearance.

RC 593 Grey gneiss

A medium-grained rock composed of plagioclase (approx. 20–30%), somewhat elongate quartzes with sutured boundaries (approx. 40–50%), abundant, orientated biotite (about 20%), granular epidote cored by allanite (about 5%) and minor hornblende (< 1%). Apatite is a common accessory and alteration of feldspars is minimal. Microcline was not seen in section.

RC 602 Banded gneiss

This is a typical banded gneiss with felsic layers (with biotite selvages) 1–2 cms thick showing pinch and swell structures separated by thinner biotitic foliae. In thin section microcline predominates (approx. 50%) and forms aggregates of subhedral crystals which are elongate within the foliation and which, together with plagioclase (about 20%) and intervening myrmekite, form feldspar-rich layers of lenses which alternate with lensoid aggregates of strained quartz (about 30%). Biotite is present in small amount (< 5%) and apatite, zircon, and magnetite are accessory minerals. Slight clouding of the feldspars is noted.

RC 597 Garnet-mica schist

This sample contains abundant, large (up to 3 mm long) muscovite plates (approx. 30%) which, together with intergrown biotites (10–15%), define a strong foliation. Mica-rich layers alternate with layers rich in sutured, strained quartz (20–30%), and plagioclase (approx. 10%). Subideoblastic, inclusion-free garnets (10–20%) occur in both layers and large apatites and rutiles are characteristic accessories. The latter mineral is fresh when found in garnet but is partially altered to ilmenite in the groundmass. Alteration is limited to minor chlorite forming after biotite and to slightly dusty alteration of plagioclase.

RC 599 Kyanite-garnet-mica schist

Contains coarse, lensoid aggregates of quartz with interlocking boundaries surrounded by a mica-rich foliae with finer-grained quartz (50–60 % in all) and some plagioclase (5–10 %). Biotite (20–30 %) occurs on quartz/plagioclase grain boundaries and tends to form a net-like fabric. Muscovite is virtually absent. Xenoblastic garnet (5–10 %) is present, as is kyanite (1–2 %). The latter mineral forms small, elongate, randomly-orientated laths generally found within the micaceous foliae. Rarely it has a resorbed appearance. Colourless chlorites occur within the foliation near some garnets and may be primary or secondary. Rutile, zircon and large apatites are dominant accessories. Alteration is limited.

RC 601 Kyanite-garnet-mica schist

Similar to RC 559 although richer in muscovite. Some garnets show evidence for late rim growth. Kyanites enclosed in plagioclase have a resorbed appearance and very small amounts of fibrolite lie on a quartz grain boundaries adjacent to such areas. K-feldspar was not seen. Plagioclase shows minor dusty alteration and rutile is largely replaced by ilmenite.

RC 598 Garnet-mica schist somewhat transitional to grey gneiss

A rather extreme variant of the garnet-mica schist group in which garnet (< 1 %) and plagioclase (< 10 %) are sparsely developed but biotite (20–25 %) and muscovite (15–20 %) are abundant together with quartz (approx. 50 %). The micas have a complex fabric with large plates of muscovite of varied orientation suggesting two foliation surfaces. Biotites are intergrown with the large muscovites but within quartzofeldspathic parts of the fabric are present as indenpendent plates along quartz–feldspar boundaries. Biotite has the brown to green-brown pleochroism more typical of the grey gneisses. Quartz forms complex, sutured, strained aggregates. Large apatites, zircon, rutile, and iron ore are accessory minerals. The abundance of large platy muscovites, and the limited amount of feldspar, suggest that the specimen belongs to the garnet-mica schist group.

RC 600 Garnetiferous grey gneiss somewhat transitional to garnet-mica schist

The specimen contains abundant garnet (approx. 20 %), plagioclase (20–30 %), quartz (30–40 %), and biotite (approx. 20 %). The absence of muscovite, the abundant plagioclase, and the green-brown pleochroism of the biotite suggest closer affinities with the grey gneiss group, though the abundant garnets suggest a transition towards the garnet-mica schists. The garnets are large (up to 5 mm), fresh, and contain a few inclusions of rutile and quartz. Biotite together with finer-grained quartz and plagioclase forms a net-like fabric. Coarser-grained aggregates quartz are also present. Apatite, iron ore, and rutile are accessories. Plagioclase is largely unaltered.

Appendix 2. Brief zircon descriptions

RC 537 Grey gneiss

Grains vary from prisms with rounded faces and blunted terminations to oval-shaped and almost spherical grains. A few grains have irregular shapes. A number show central constrictions (Jocelyn & Pidgeon 1974). Outgrowths were seen on a few grains. Many grains are clear except for localised concentrations of dust-sized inclusions or bubbles. Others appear to be more complex consisting of cores of rounded, light-brown, slightly-cloudy zircon surrounded by rims of clear zircon.

RC 558 Mangerite syenite

Zircons vary from rounded, stocky prisms, many with faceted and irregular outlines, to almost spherical grains. L/B ratios rarely exceed three. Grains are generally clear except for rare, small inclusions or bubbles. No zircon cores were observed. The extreme rounding of these zircons suggests the suite has undergone severe chemical corrosion.

RC 602 Banded gneiss

Zircon forms are irregular and vary from prismatic forms to more rounded and faceted grains. High order pyramids frequently terminate tabular grains though often these are blunted. Approximately 5 percent of grains are completely clear. The rest show varying degrees of cloudiness culminating in rare, almost opague grains. The increasing cloudiness is due to accumulations of opaque inclusions and the presence in many grains of cores of brown, rounded and fractured zircons, which contain a high proportion of dust-sized inclusions and are encased by rims of clear zircon.

Appendix 3. Analytical procedures

Rb-Sr and U-Pb isotopic measurements were made on an A.E.I., G.E.C. MS12 mass spectrometer using a Faraday collector and a 10'' ohm resistor. The output signal was fed to a Data General Nova computer.

Rb-Sr

Whole rock powders were dissolved in hydrofluoric and perchloric acid in platinum dishes. Rb and Sr concentrations were determined by isotope dilution using 82 percent enriched ^{84}Sr and 99.2 enriched ^{87}Rb spike solutions. Aliquoting was performed by weighing, and Rb and Sr were separated on cation exchange columns. Strontium was loaded as a phosphate on a single rhenium filament and Rb was run as a triple filament chloride. The normalised (to $^{88}Sr/^{86}Sr$ of 8.375) $^{87}Sr/^{86}Sr$ of Eimer and Amend $SrCO_3$ (Lot 492327) over the period of the measurements was 0.70811 ± 0.00007 (1σ). Rb-Sr isochrons were calculated using the method of York (1969) and a ^{87}Rb decay constant of $1.42\ 10^{-11}y^{-1}$. Uncertainties used in these calculations were $^{87}Rb/^{86}Sr = 0.7$ percent and $^{87}Sr/^{86}Sr = 0.04$ percent.

U-Pb

Zircon fractions were boiled in 1:1 nitric acid and then 'subboiling' distilled water before analysis. Analytical techniques followed Krogh (1973). Samples were dissolved in hydrofluoric acid in teflon bombs, dried, taken up in 3N hydrochloric acid, carefully equilibrated, and aliquoted for spiking with a mixed ^{235}uranium/^{208}lead spike. Lead and uranium were separated on one cubic centimetre anion exchange columns and loaded on single rhenium filaments with silica gel-phosphoric acid (Pb) and tantalum oxide – phosphoric acid (U). The common lead correction used in the calculations was $^{206}Pb/^{204}Pb = 18.1$, $^{207}Pb/^{204}Pb = 15.5$, and $^{208}Pb/^{204}Pb = 36.8$. This composition was estimated from measurements of the blank lead. The error introduced through uncertainty in the actual composition of the common lead correction is insignificant as the concentration of common lead, indicated by the $^{206}Pb/^{204}Pb$ ratios in Table 2, are generally less than 2 percent of the total lead. The overall uncertainties in the isotopic ratios are estimated at within ± 0.3 percent for the $^{207}Pb/^{206}Pb$ ratio and ± 0.5 percent for the two lead to uranium ratios.

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