Geochronological investigations in the Oppdal area, central Norway

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The isochron ages obtained have been grouped in four geological time periods: 1700–1750 m.y. (dioritic gneisses, Gråhø/Tronfjell Complexes), 1450–1500 m.y. (augen gneisses and intrusives, Gråhø/Tronfjell Complexes), ~1050 m.y. (Basement Complex and Flagstone Group), and ~400 m.y. (minerals). The Caledonian influence in the area seems to be smaller than previously assumed since it has only caused a resetting of the isotopic system between minerals. The isochron ages of ~1050 m.y. are thought to reflect secondary events during the Sveconorwegian Cycle. The time of deposition/intrusion of the rocks of the Basement Complex and the Flagstone Group is thought to be earlier than 1450–1500 m.y. One extensive metamorphism has been recognized, and 1450–1500 m.y. is considered to be a minimum age for this event.

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The Oppdal area is situated in southern Trøndelag (Fig. 1). Geologically the area is bordered by Caledonian rocks of the Trondheim Region in the east and Precambrian rocks of the Gneiss Region in the west. The aim of this work has been to date the various rock units in this area and in this way to contribute to a better understanding of the geological evolution of the area.

Geological setting

The geological mapping of the Oppdal area has been carried out by Eggen (1977), Evensen (1977), and Sjulsen (1977). They suggest that there are rocks here both in autochthonous and allochthonous positions. The autochthonous rocks can be divided into two units, the Basement Complex and the Flagstone Group.

The Basement Complex

On the geological map (Fig. 1) Eggen (1977), Evensen (1977), and Sjulsen (1977) have divided the rocks in the Basement Complex into two groups:

The banded gneisses. – The composition and structure of these rocks are very variable and give them a heterogeneous appearance. They consist mainly of dioritic/quartz dioritic gneisses, granitic gneisses and augen gneisses. Eggen (1977) interprets the banded gneisses as metavolcanics. In the southern part of the area the zone of outcrops of the banded gneisses becomes narrower and it ends just south of the area mapped by Eggen (1977), Evensen (1977) and Sjulsen (1977).

The homogeneous gneisses. – These differ from the banded gneisses in having a uniform granitic composition. Eggen (1977) suggests that the rocks represent granites which have intruded the volcanics and later been metamorphosed. Amphibolites appear as concordant layers and as large massifs in the Basement Complex. The latter are interpreted as metagabbros, while the concordant layers can be of intrusive or extrusive origin (Eggen 1977).

The Flagstone Group

The Flagstone Group is stratigraphically above, and has a concordant contact to the Basement Complex. A conglomerate with strongly deformed quartz pebbles occurs locally at this contact. At Morken the conglomerate has a thickness of about 50 metres (Rosenqvist 1941) and in Åmotsdalen, just south of the map, the equivalent conglomerate has a thickness of more than one hundred metres. This conglomerate indicates a geological time interval between the deposition/intrusion of the rocks of the Base-
Fig. 1. Simplified geological map of the Oppdal area (after S. Eggen (1977), J. Evensen (1977), S. E. Sjulsen (1977)) showing sample localities. 1 - Bjørkeng, 2 - Morken, 3 - Slipran, 4 - Vikasætra, 5 - Storhaugfjellet, 6, 8 - Engan, 7, 9, 10, 11 - Gråhø, 12 - Olbu.

The composition of the rocks in the Flagstone Group is very uniform and there are obvious mineralogical differences from the Basement Complex. The content of quartz and white mica is higher in the Flagstone Group, while the content of biotite and plagioclase is lower. Eggen (1977) defines the rocks of the Flagstone Group as meta-arkoses, and, because of the high content of hematite, he proposes a continental to shallow marine environment of deposition.

In spite of the metamorphism which has affected all the rocks in this group, sedimentary features such as cross-bedding are well preserved.

The allochthonous rocks can be divided into three complexes: The Gråhø/Tronfjell Complexes, the Slipran Complex, and the Hornet Complex.

The Gråhø/Tronfjell Complexes

The eastern part of these complexes, the area around Tronfjell, consists of coarse augen gneisses, gneisses, amphibolites, and leucogranites. The augen gneisses are the most typical rocks in the area. The form of the augen varies; it can be rounded, oval or square and the longest axis can be up to 15 cm. The augen consist mainly of K-feldspar and plagioclase with minor amounts of quartz and white mica. The matrix is composed of quartz, feldspar, biotite, and white mica (Eggen 1977). The leucogranites occur within the augen gneisses and vary from small lenses to large bodies up to hundreds of square metres in area. The contact with the augen gneisses is disturbed by tectonic movements, and it was not possible to decide from the field relations whether the granites intruded the augen gneiss complex before or after the formation of the augen (Eggen 1977). Evensen (1977) has studied the rocks at Gråhø, in the western part of the complex. The metagabbros are the most typical rocks in this area. They intrude a complex of gneisses and augen gneisses. In addition to these rocks there are minor intrusions of leucogranites. Both the augen gneisses and the leucogranites are equivalents to the corresponding rocks at Tronfjell.
The Slipran Complex

The nappe complex is built up of rocks from the Hornblende–mica schist Group and the underlying Flagstone Group. This means that rocks of the Flagstone Group are both autochthonous and allochthonous, but no differences have been found in petrology or chemistry of rocks in the two positions. The Hornblende–mica schist Group consists of three different rock units (Eggen 1977, Evensen 1977).

Amphibolites/gabren schists. – These are the dominating rocks, and appear usually as layers of about 1/2 metre in thickness alternating with the other units, but they are also observed with greater thickness.

Garnet-mica schists. – They have a banded appearance with layers of quartz (thickness about 1 cm) alternating with layers consisting of mica, garnet, plagioclase and quartz.

Metapsammites. – They occur as layers varying in thickness from a few cm to about 50 cm. The rock has a gneissic structure and is similar in appearance to a flagstone rich in biotite. No sedimentary structures have, however, been observed in this rock.

The Hornet Complex

In this complex also there are rocks of both the Hornblende–mica schist Group and the Flagstone Group, and, as in the Slipran Complex, the flagstone is apparently identical to its autochthonous equivalent. The characteristic unit in this complex is a rock with a rapakivi texture. In some zones the rapakivi is strongly deformed and one can find transitions to augen gneisses and mylonites.

Metamorphism

Eggen (1977) and Evensen (1977) have studied the metamorphism of the rocks in the area, and have recognized only one extensive metamorphism. All the rock units discussed above appear to have been subjected to this metamorphic event. This was tested by using the K\textsuperscript{Ar}-bio geothermometer developed by Thomson (1976). No variation in metamorphic grade could be detected between the different rock units tested. The temperature indicated by this thermometer is 550°C–600°C, but the pressure has not been determined. Using Winkler’s (1974) subdivision of metamorphic rocks into four grades, the rocks in the area must be placed near the base of ‘medium grade’. There has not been any extensive retrograde metamorphism in the area, but some chloritization of biotite is observed.

Structural geology

Sjulsen (1977) has carried out structural studies and recognized several deformational events. In the first period of deformation (D\textsubscript{1}) there has been isoclinal folding (F\textsubscript{1}) and all the rocks in the area have been folded during this deformation. During D\textsubscript{2} the rocks were strongly deformed and the contacts of the Tronfjell/Gråhø and Slipran complexes were folded at this time (F\textsubscript{2}). These nappes must, therefore, have been in their present position prior to the D\textsubscript{2} deformational period. D\textsubscript{3} is a deformational period during which large recumbent folds were formed. The Hornet nappe complex is a recumbent fold and came into its present position during the D\textsubscript{3}-deformation.

During the last period of deformation (D\textsubscript{4}) a crenulation cleavage was locally developed in the rocks of the Basement Complex and the Flagstone Group.

Previous interpretations

The Oppdal area has been studied by amongst others: Tørnebohm (1896), Bjørlykke (1905), Goldschmidt (1916), Carstens (1925), O. Holtedahl (1938, 1940, 1960), Barth (1938), Rosenqvist (1941, 1942), H. Holtedahl (1949), Gjelsvik (1952), Holmsen (1955), Strand (1960), Oftedahl (1964), and Hernes (1967). Radiometric age determinations on total rock systems have not previously been carried out. However, biotites were analysed from two localities at Lønset and gave K-Ar ages of 370 m.y. and 388 m.y. (Broch 1964).

The rocks of the Basement Complex have been correlated with the gneisses further west in the Gneiss Region. Hernes (1967) correlated these rocks with the Lower Tingvoll Group, and he suggested that they represented an Eocambrian rock unit gneissified during the
Caledonian orogenic period. However, Råheim (1977) has shown that rocks of the Tingvoll Group were formed much earlier in the Precambrian at about 1620 m.y. (recalculated to $\lambda = 1.42 \cdot 10^{-11}$ yr$^{-1}$). O. Holtedahl (1938) and Gjelsvik (1952) also postulated an Eocambrian age for the Basement Complex, while Rosenqvist (1941, 1942) and H. Holtedahl (1949) were of the opinion that the conglomerate at the contact between the Basement Complex and the Flagstone Group was a basal-conglomerate separating rocks of Precambrian and Eocambrian age.

Most geologists (e.g. O. Holtedahl 1938, Barth 1938, Rosenqvist 1941, 1942, Gjelsvik 1952, Hernes 1967) have considered the Flagstone Group in Oppdal to be equivalent to the Eocambrian light sparagmites in southern Norway. Gjelsvik (1952) pointed out that if this was the case and the Basement Complex was a Precambrian rock unit, then the dark sparagmite would be absent in the Oppdal area. He concluded that the Basement Complex was not a Precambrian rock unit, but an equivalent to the dark part of the sparagmite sequence in southern Norway and as such of Eocambrian age.

Gee (1975a, 1975b, 1978) correlated the Flagstone Group with the rocks of the Risbäck Group in Jämtland, and he supposed that they represented metasediments deposited late in Precambrian time. The rocks of the Hornblende-mica schist Group have been proposed to be of Cambro-Silurian age (Rosenqvist 1941, 1942, H. Holtedahl 1949), and H. Holtedahl (1949) correlated them with the Röros Group. Later Råheim (1977) carried out isotopic analysis of schists belonging to the so-called Röros Group in the Surnadal syncline, and concluded that they were metamorphosed in Precambrian time, probably about 1700 m.y.

Rosenqvist (1941, 1942) considered the metagabbros and the granites to be intruded and metamorphosed during the Caledonian orogenic period. He also connected the formation of the augen gneisses in the Oppdal area with Caledonian events, while Tørnebohm (1896) and Carstens (1925) suggested a Precambrian age for these rocks.

Several geologists (e.g. O. Holtedahl 1938, H. Holtedahl 1949, Holmsen 1955) have recognized that the rocks in the Oppdal area occur in a nappe system, and they have connected the thrusting of the nappes with the Caledonian orogenic period.

Analytical procedure

Most of the samples were collected from road cuts, where it was not difficult to get fresh samples. Between 5 and 10 samples of the same rock type were collected at each locality within a distance of about 10 metres. The weight of each sample was between 3 and 10 kg.

At Gråhø it was difficult to obtain fresh samples. In this case the average weight of each sample is smaller, and fewer samples were collected at each locality.

The rocks were first crushed in a steel jaw-crusher and then milled to powder in a steel swing mill. Rb and Sr were determined by X-ray fluorescence spectrography. Mass spectrometry was performed on a V6 Micromass 30 mass spectrometer. Variable mass discrimination in $^{87}$Sr/$^{86}$Sr was corrected by normalizing $^{86}$Sr/$^{88}$Sr = 0.1194 (Faure & Hurley 1963). The $^{87}$Rb decay constant used was $1.42 \cdot 10^{-11}$ yr$^{-1}$.

Regression lines were calculated using the technique of York (1969). As discussed by Brooks et al. (1968), 2.5 as a value of the quality of fit number (MSWD) has been used as a cutoff level for a straight line where the scattering of the datapoints about the best fit line is only due to experimental errors.

The assigning error to the regression points, the coefficient of variance for $^{87}$Rb/$^{86}$Sr, is taken as 1\%, and the standard deviation for $^{87}$Sr/$^{86}$Sr as $1 \cdot 10^{-4}$. All errors quoted in this paper are two sigma errors.

Results

A summary of the ages obtained is given in Table 1. The data which form the basis for this and Figs. 2–8 are available from Mineralogisk-geologisk museum, Oslo.

The Basement Complex

Samples from two localities (Bjørkeng (loc. 1) and Morken (loc. 2)) were analysed, but only the samples from Bjørkeng give an isochron (Fig. 2 a). Here five of the six samples define an isochron age of 1055 $\pm$ 70 m.y. (MSWD = 1.05) and an initial $^{87}$Sr/$^{86}$Sr of 0.7078 $\pm$ 0.0005. Sample A is excluded from the calculation.

The samples at Morken were collected close to the contact with the overlying conglomerate which separates the Basement Complex from the
Fig. 2 a-b) Isochron diagrams for total rock samples from the Basement Complex. In 2a, sample A is not included in the age calculation.

c) $^{87}\text{Rb}^{86}\text{Sr}$ versus model age for total rock samples from the Basement Complex. Model ages use an assumed initial $^{87}\text{Sr}^{86}\text{Sr}$ of 0.7078, the value obtained from loc. 1 (Fig. 2a).

Flagstone Group. In Fig. 2 b the data from Morken and Bjørkeng are plotted together. The considerable scatter of the datapoints shows clearly that most of the samples analysed have a disturbed isotopic system. This is also demonstrated in Fig. 2 c, which illustrated that total rock ages for most of the samples are dependent on the Rb/Sr ratio. It is clear that samples with higher Rb/Sr have more disturbed isotopic systems and give younger apparent ages. The same phenomenon has been pointed out by Page (1978) and Bell & Blenkinsop (1978) in their studies of rocks in metamorphic terrains.

Plagioclase, K-feldspar, and biotite were separated from sample B. The minerals and the total rock together give an isochron age of 396 ± 8 m.y. (Fig. 3). The value of the MSWD factor is 1.98.

The age of 396 ± 8 m.y. is in agreement with the ages reported by Broch (1964), who referred K/Ar-ages ranging from 370 m.y. to 388 m.y. on biotites from the Basement Complex. This is also well within the range of Rb-Sr and K-Ar ages of minerals reported from other parts of the Caledonian orogenic belt, the majority of which lie between 420 and 380 m.y. (Brueckner et al. 1968, Strand 1969, Bryhni et al. 1971, Brueckner 1972, Wilson 1972, Wilson & Nicholson 1973, Råheim 1977).

The data from the Basement Complex show clearly that this is a Precambrian rock unit influenced by Caledonian events. The influence has not been sufficient to reset the isotopes in the total rock samples completely, but the disturbance of the isotopic system in the samples from Morken may be attributed to this.

The Flagstone Group

This group has been sampled at several localities. Six of the seven samples from a quarry at Kleivan about 5 km south of Engan define an isochron age of 1035 ± 94 m.y. (MSWD = 0.89) with an initial ratio of 0.7110 ± 0.0019 (Fig. 4 a). This locality is situated outside the area mapped by Eggen (1977), Evensen (1977) and Sjulsen (1977), (Fig. 1), but there is no doubt that it is a part of the Hornet Complex (Eggen pers. comm. 1979).

About 1.5 km west of Slipran (loc. 3) 11 samples were collected and analysed from the autochthonous part of the Flagstone Group. If they are regressed together they do not define any isochron age. However, five of the sam-
samples lie on a straight line with a best fit slope corresponding to an age of 1052 ± 43 m.y. (MSWD = 0.95) and initial 87Sr/86Sr of 0.7104 ± 0.0011 (Fig. 4 b). There is no significant difference between these data and the data obtained from the samples at Kleivan. When data from the two isochrons are regressed together they define a linear array; a best fit line gives t = 1037 ± 31 m.y. (MSWD = 0.87) and I = 0.7109 ± 0.0007.

The samples collected at Vikasætra (loc. 4) and Storhaugfjellet (loc. 5) south of Gråhø (the authochthonous part of the Flagstone Group) show too much scatter to define an isochron (Fig. 4 c). In Fig. 5 a all the datapoints from the Flagstone Group are plotted together, and, as in the case of the Basement Complex, few of the samples fall on the isochron. The disturbance of the isotopic system is also demonstrated in Fig. 5 b which illustrates that samples with high Rb/Sr show younger apparent ages than samples with low Rb/Sr.

The Gråhø/Tronfjell Complexes

The Gråhø and Tronfjell Complexes have similar tectonic positions (Eggen 1977, Sjulsen 1977) and the results of analyses from the two complexes will therefore be discussed together.

Augen gneisses. – Samples of augen gneisses have been collected at Engan (loc. 6, The Tronfjell Complex), Gråhø (loc. 7, the Gråhø Complex) and Stekern. The locality at Stekern is about 2 km west of the area mapped by Eggen (1977), Evensen (1977), and Sjulsen (1977), but the augen gneisses here are equivalent to those at Tronfjell and Gråhø (Eggen pers. comm. 1979). Isotopic studies of nine samples from Engan define an approximate isochron age of

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Fig. 4. Isochron diagrams for rocks from the Flagstone Group a) Kleivan. The locality is situated 6 km south of loc. 8 (Fig. 1). Sample plotted as open circle is not included in the age calculation. b) Loc. 3. Samples plotted as open squares are not included in the age calculation. c) Loc. 4 and loc. 5. The isochron obtained from Kleivan is shown as a reference isochron.

Fig. 5. a) All the analyzed samples from the Flagstone Group are plotted. The isochron obtained from Kleivan is shown as a reference isochron. b) 87Rb/86Sr versus model age for total rock samples from the Flagstone Group. Model ages use an assumed initial 87Sr/86Sr of 0.7110, the value obtained from Kleivan.
Ten samples from Stekern indicate an age of 1347 ± 225 m.y. (MSWD = 29.7) and initial 87Sr/86Sr of 0.7098 ± 0.0082. If samples A and B are excluded from the regression analysis, the age is increased to 1443 ± 120 m.y., the initial ratio is 0.7080 ± 0.0040, and the isochron fit improves (MSWD = 26.4). There is, however, no obvious reason for rejecting any of the data as the freshness and degree of the alteration of the samples are uniform. Brueckner (1979) points out, however, that rocks can act as open systems to the migration of rubidium and strontium without showing any obvious textural or mineralogical signs of this behaviour either in thin section or in hand sample.

When the samples from Engan and Stekern (excluding A and B) are regressed together, the age is 1463 ± 68 m.y. (MSWD = 24.8) and the initial 87Sr/86Sr is 0.7076 ± 0.0028 (Fig. 6 a). The high value of the MSWD factor (> 2.5) obtained from the analyses of the augen gneisses at Engan and Stekern implies that the scatter of the datapoints about the isochrons cannot be solely due to experimental error, but must also reflect geological disturbance. The most likely explanation is that the total rock Rb-Sr isotopic systems have been disturbed during later metamorphic/deformational periods, the Sveconorwegian (~ 1000–1100 m.y.) and/or the Caledonian (~ 400 m.y.).

Biotite, K-feldspar, and plagioclase have been separated from sample C. Together with the total rock sample they give an approximate isochron age of 392 ± 21 m.y. (MSWD = 6.2) (Fig. 6 b). This result is consistent with the mineral age obtained from the Basement Complex.

At Gråhø there are augen gneisses of the same type as at Stekern and Engan. The samples at Stekern and Engan were taken from new roadcuts and were therefore fresh. At Gråhø it was not possible to obtain samples of equivalent quality. Nevertheless, ten samples from locality 7 have been analysed and eight of them give an apparent age of 1129 ± 302 m.y. (MSWD = 5.9), and an initial ratio of 0.7177 ± 0.0084 (Fig. 7 a).

The isochron age is not well defined. This can be due to the sampling problems at Gråhø. After the cleaning (cut by saw) the final sample size here was very small. Such samples place even stronger limitations on allowable minor movements of Rb and Sr during the superimposed deformational and/or metamorphic events.

There is no geological reason to suggest that the augen gneisses at Gråhø are younger than those at Engan and Stekern and the most likely interpretation is that the ‘age’ of 1129 m.y. is a mixed one and as such has no geological meaning.

Augen from the augen gneisses. – Seven augen from the augen gneisses have been separated and analysed. Two samples were collected at Stekern and five samples at Engan (loc. 6). The scatter of the datapoints exceeds experimental uncertainties (MSWD = 20.9) and results in a best fit solution with an age of 1372 ± 145 m.y. and an initial 87Sr/86Sr of 0.7119 ± 0.0060. If samples A and B are excluded from the regression analysis, the age is 1459 ± 84 m.y., and the value of the MSWD factor decreases significantly to 4.2. The initial ratio is 0.7095 ± 0.0032 (Fig. 7 b).

Samples A and B weighed only 100–150 grams and were smaller than the other samples (ca. 200–300 gram). They would, therefore, be more sensitive to minor movements of Rb and/or Sr during the superimposed events. This can be the reason for the poor fit to the isochron.

Taking the uncertainty of the data into consideration, there is no significant difference between the age of the augen and of the augen gneisses. The implication of this for the general history of the rock will be discussed later.

Granitic intrusion at Engan. – Ten samples of the granitic intrusion at Engan (loc. 8) give an approximate isochron age of 1489 ± 116 m.y. (MSWD = 28.9). The initial ratio is 0.7036 ± 0.0116 (Fig. 7 c).

The high value of the MSWD factor indicates a disturbance of the isotopic systems as in the case of the augen gneisses.

Two samples are excluded from the regression analysis. They both have a relatively high Rb/Sr, and, as discussed earlier, such samples tend to have more disturbed isotopic systems than those with low Rb/Sr.

The low value of the initial 87Sr/86Sr may suggest a mantle origin of the magma. However, the data are so uncertain that this cannot be confirmed.

The intrusions at Gråhø. – Ten samples have been collected and analysed from one of the small granitic intrusions at Gråhø (loc. 9). The scatter of the data exceeds experimental uncertainties (MSWD = 14.5), and results in a best-fit
solution of $1455 \pm 97$ m.y. and an initial $^{87}\text{Sr}/^{86}\text{Sr}$ of $0.7171 \pm 0.0124$ (Fig. 7d).

Metagabbro is the dominant rock type in the Gråhø Complex. It forms intrusions of various sizes, and samples were collected from two of these (loc. 10, 11). Eight samples were analysed. Seven of them give an approximate age of $1271 \pm 163$ m.y. (MSWD = 243.0). The initial ratio is $0.7036 \pm 0.0019$ (Fig. 7e). The very high value of the MSWD factor implies considerable disturbance of the isotopic systems.

If samples A and B are excluded from the regression analysis, the value of MSWD decreases to 104.3, while the age increases to $1646 \pm 323$ m.y. The initial $^{87}\text{Sr}/^{86}\text{Sr}$ will then be $0.7024 \pm 0.0015$.

The data leave considerable uncertainty as to the age of the metagabbro at Gråhø. However, the field relations in the area do not indicate any time difference between the formation of the gabbro and granites. Therefore, the ages of 1271 m.y. or 1646 m.y. do not seem to be geologically significant. From the other results from the area, an age between 1450 m.y. and 1500 m.y. seems more likely. It is interesting to note that the two samples with the highest Rb/Sr (A, B) are those which deviate most strongly from a linear array.

The low value of the initial $^{87}\text{Sr}/^{86}\text{Sr}$ of the metagabros indicates a mantle origin of the magma whereas the adjacent granites have a considerably higher initial ratio indicating a crustal origin. This is in good agreement with the conclusions reached by Evensen (1977).

Dioritic gneiss, Stekern. – As discussed earlier the rocks at Stekern are thought to be a part of the Gråhø/Tronfjell Complexes.

A dioritic gneissic rock rich in biotite has been dated. This rock unit can probably be correlated with the gneiss horizons in the Gråhø/Tronfjell Complexes described by Eggen (1977) and Evensen (1977). Because of the complex folding of the rocks at Stekern it was not possible to determine the relation between the gneiss and the surrounding granites and augen gneisses.

Eight samples were analysed and six of them form a roughly co-linear array and define an isochron age of $1734 \pm 106$ m.y. (MSWD = 3.3) and an initial $^{87}\text{Sr}/^{86}\text{Sr}$ of $0.7017 \pm 0.0012$ (Fig. 7f).

This is the highest 'age' obtained from the rocks in the Oppdal area, and the very low initial ratio indicates that the rock cannot have had a long crustal history prior to this time.

The Slipran Complex

Six samples of a garnet-mica schist (belonging to the Hornblende – mica schist Group) were collected near Olbu (loc. 12), but the datapoints do not fall on an isochron (Fig. 8a). The reason for the scatter probably lies in the fact that the samples were penetrated by narrow veins of
quartz which may have disturbed the isotopic systems.

The rocks of the Hornblende–mica schist Group are stratigraphically above the Flagstone Group, but there is probably no great time difference between the deposition of these two units since there is no metamorphic or structural break between them.

The Hornet Complex

The analytical results from the flagstone in the Hornet Complex have been discussed together with the autochthonous part of the Flagstone Group.

Samples of the rapakivi granite were collected about 6 km south of Engan which is outside the area mapped by Eggen (1977), Evensen (1977) and Sjulsen (1977). It is obvious, however, that this locality is a part of the Hornet Complex.

The datapoints do not define an isochron (Fig. 8 b). It was impossible to get fresh samples and this is probably the reason for the scatter of the datapoints.

**Fig. 7.** Isochron diagrams for total rock from the Gråhø/Tronfjell Complexes. Samples plotted as open circles are not included in the age calculation.

a) Augen gneisses from loc. 7.
b) Augen from Engan (loc. 6) and Stekern.
c) Granitic intrusive from loc. 8.
d) Granitic intrusive from loc. 9.
e) Metagabbro from loc. 10 and loc. 11.
f) Dioritic gneiss from Stekern (3 km west of loc. 3).

**Fig. 8.** a) Hornblende–mica schist from Olbu (loc. 12). No isochron can be defined.
b) Rapakivi from Tøftan. The locality is situated about 8 km south of loc. 8. No isochron can be defined.
Table 1. Rb-Sr isochron regression results for total rock and minerals + total rock from the Oppdal Area. For sample locality, see Fig. 1.

<table>
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<th>Locality</th>
<th>Rock type</th>
<th>No. of samples</th>
<th>MSWD</th>
<th>Age (m.y.)</th>
<th>Initial (^{87}\text{Sr}/^{86}\text{Sr} )</th>
<th>Total rock/minerals + total rock</th>
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<td><strong>Basement Complex</strong></td>
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<td>1055±70</td>
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<td>396±8</td>
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<td>minerals + total rock</td>
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<td>Flagstone</td>
<td>11</td>
<td>0.87</td>
<td>1037±31</td>
<td>0.7109±0.0007</td>
<td>total rock</td>
</tr>
<tr>
<td><strong>Gråhe/Tronfjell Complexes</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Engan</td>
<td>Augen gneiss</td>
<td>9</td>
<td>19.7</td>
<td>1468±103</td>
<td>0.7078±0.0056</td>
<td>total rock</td>
</tr>
<tr>
<td>Stekern</td>
<td>Augen gneiss</td>
<td>8</td>
<td>26.4</td>
<td>1443±120</td>
<td>0.7080±0.0040</td>
<td>total rock</td>
</tr>
<tr>
<td>Engan + Stekern</td>
<td>Augen gneiss</td>
<td>17</td>
<td>24.8</td>
<td>1463±68</td>
<td>0.7076±0.0028</td>
<td>total rock</td>
</tr>
<tr>
<td>Engan</td>
<td>Augen gneiss</td>
<td>4</td>
<td>6.2</td>
<td>392±21</td>
<td>0.8707±0.0033</td>
<td>minerals + total rock</td>
</tr>
<tr>
<td>Gråhe</td>
<td>Augen gneiss</td>
<td>8</td>
<td>5.9</td>
<td>1129±302</td>
<td>0.7177±0.0004</td>
<td>total rock</td>
</tr>
<tr>
<td>Engan</td>
<td>Augen</td>
<td>5</td>
<td>4.2</td>
<td>1459±84</td>
<td>0.7095±0.0032</td>
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</tr>
<tr>
<td>Engan</td>
<td>Granite</td>
<td>10</td>
<td>28.9</td>
<td>1489±116</td>
<td>0.7036±0.0016</td>
<td>total rock</td>
</tr>
<tr>
<td>Gråhe</td>
<td>Granite</td>
<td>10</td>
<td>14.5</td>
<td>1455±97</td>
<td>0.7171±0.0024</td>
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</tr>
<tr>
<td>Gråhe</td>
<td>Gabbro</td>
<td>6</td>
<td>104.3</td>
<td>1646±323</td>
<td>0.7024±0.0015</td>
<td>total rock</td>
</tr>
<tr>
<td>Stekern</td>
<td>Gneiss</td>
<td>4</td>
<td>3.3</td>
<td>1734±106</td>
<td>0.7017±0.0012</td>
<td>total rock</td>
</tr>
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</table>

**Discussion**

**The age of the augen gneisses**

It is important to know how the augen gneisses formed when interpreting the age obtained. Several theories about this have been put forward.

An anatectic origin of augen has been proposed by Mehnert (1968). This cannot, however, be the case in the Oppdal area, because the metamorphic grade has not been high enough to form a melt (Eggen 1977). Furthermore, augen formed by anatectic melting should have a granitic composition (Mehnert 1968), which the augen in the Oppdal area do not have.

Rosenqvist (1941) suggested that the augen gneisses in the Oppdal area were formed by potassium metasomatism which took place on a regional scale during the Caledonian Orogeny.

Strømberg (1962) proposed that augen can be developed during strong deformation of rocks. First a migration of ions takes place during deformation and then during post deformation crystalloblastesis the augen can be formed. Eggen (1977) suggested that the augen gneisses in the Oppdal area had been formed in this way, but unlike Rosenqvist he did not think that the migration of ions had taken place on a regional scale.

The isochron of the augen gneisses in the Oppdal area could represent the age of the 'parent rock'. This could mean that when the augen were formed, say during the Caledonian Cycle, the migration of ions was on such a small scale that it did not disturb the isotopic systems of the total rock samples. The data obtained on separated augen give the same age as the total augen gneisses. This implies that if the augen gneisses were formed by the processes suggested by Strømberg (1962) and Eggen (1977), this must have taken place at least 1450–1500 m.y. ago. It is most reasonable to correlate these events with the strongest deformational period (D2) in the area.

**The thrusting of the Hornet Complex**

The Hornet Complex is tectonically higher than the Slipran Complex. It is a large recumbent fold with the fold axis in the N-S direction. It has been thrust after the D2 deformational period since the nappe borders are not folded by F2. The rapakivi forms the central parts of the fold, and zones of the rapakivi and the surrounding flagstone have been strongly deformed and mylonitized during the folding and thrusting of
the complex. A recrystallization has occurred in the mylonitic parts of the rapakivi.

The mylonite is dated by A. Krill (pers. comm. 1979) to 1500–1600 m.y. This age can be interpreted in two ways; either it reflects the time of the intrusion of the rapakivi (primary age) or it reflects the time of mylonitization (secondary age).

That resetting of isotopic systems occurs during mylonitization has been demonstrated repeatedly in other parts of the world (e.g. Odom & Fullagar 1970, Abbot 1972, Russell 1976, Gabrielsen et al. 1979).

The most reasonable interpretation of the age of the mylonite is therefore that it reflects the time of mylonitization.

Taking the uncertainty of the data into consideration there is no significant difference between the data obtained on the mylonite (1500–1600 m.y.) and the augen gneisses of the Tronfjell/Gråhø Complexes (1463 ± 68 m.y.). The age of the augen gneisses is correlated with the strong F2 folding and this implies that the thrusting of the Hornet Complex (Da) must have taken place just after this folding. It is therefore most reasonable to look at D2 and Da as two events in the same orogenic period.

The time of metamorphism

Only one extensive metamorphism is observed in the area, and all rocks show the same metamorphic grade (Eggen 1977, Evensen 1977).

An opinion common to many geologists working the Oppdal area (e.g. Rosenqvist 1941, 1942, O. Holtedahl 1938, H. Holtedahl 1949, Oftedahl 1964) is that the rocks were metamorphosed during the Caledonian Orogenic Cycle. The new results, however, indicate that the metamorphism occurred in Precambrian time. A correlation in time between the extensive metamorphism and the considerable deformation and folding during D2 and D3 seems probable. This means that the main metamorphic event took place at about 1450–1500 m.y.

The chloritization of biotite may be connected with events during the Sveconorwegian (~1050 m.y.) or Caledonian (~400 m.y.) Cycles.

The age of the Basement Complex and the Flagstone Group

The rocks of the Basement Complex and the Flagstone Group show ages of about 1050 m.y. while the superimposed rocks in the area give higher ages. An obvious question is whether this age represents the time of the deposition/intrusion of the rocks or reflects a secondary event. The latter interpretation seems to be the most probable one.

The fact that 1450–1500 m.y. is a minimum age for the main metamorphic event in the area excludes the possibility that the ages obtained from the Basement Complex and the Flagstone Group reflect the time of intrusion/deposition of these rocks. Furthermore, the thrusting of the Hornet Complex is determined to ~1450–1500 m.y., and since it is thrust above the Basement Complex and the Flagstone Group, these rocks have to be older.

If it is postulated that the age of ~1050 m.y. reflects secondary events it is necessary to explain resetting of Rb and Sr in these rocks only and not in the adjacent granites and augen gneisses. The cause of the resetting is probably to be found in the structural conditions in the area. Råheim & Compston (1977) and Black et al. (1978) have demonstrated that development of a crenulation cleavage can lead to a reequilibration of Rb and Sr in rocks because it opens the rock to fluids and to a migration of Rb and Sr. A crenulation cleavage occurs at some localities in the Oppdal area. It is best developed in the flagstone, but it also occurs in the basement (Sjulsen 1977). It is developed at Bjørkeng where the 1055 m.y. isochron of the basement is defined. The cleavage does not appear to be developed in the metagabbro, granites, and augen gneisses (Sjulsen 1977). It is the youngest structural element in the area and formed during the last deformational period (D4).

Comparisons with other results from the Gneiss Region

The rocks and minerals analysed are grouped in four geological time periods: 1700–1750 m.y., 1450–1500 m.y., ~1050 m.y., ~400 m.y. Only the augen gneisses and the metagabbro of the Gråhø Complex fall outside one of these periods. However, the uncertainty in the data is rather high, and as discussed previously there is no reason to suggest that these rocks are younger than the granites at Gråhø and the augen gneisses at Engan and Stekern (1450 m.y. – 1500 m.y.).

Ages between 1650 m.y. and 1750 m.y. have been reported from several parts of the Gneiss
Region. Råheim (1977) dated gneisses at Surnadalen at $1671 \pm 63$ m.y. and Pidgeon & Råheim (1972) obtained an age of $1672 \pm 60$ m.y. from gneisses in the Kristiansund area. Gneisses from Hareidland are dated by Mysen & Heier (1972) at $1646 \pm 70$ m.y. Brueckner (1979) has carried out isotopic analysis of augen gneisses at Tafjord and obtained an age of $1672 \pm 63$ m.y. All of these data are recalculated to the new decay constant for $^{87}\text{Rb}$ ($1.42 \cdot 10^{-11}$ yr$^{-1}$).

The augen gneisses and granites in the Oppdal area give ages between 1450 and 1500 m.y. Ages in this interval have previously been obtained in the Gloppen-Eikefjord area where Abdel-Monem & Bryhni (1978) have dated mangeritic rocks to $1479 \pm 64$ m.y. (recalculated to $\lambda = 1.42 \cdot 10^{-11}$ yr$^{-1}$). They conclude that the age must be taken as a minimum age.

The same may be the situation in the Oppdal area, i.e. that the ages between 1450 and 1500 m.y. reflect a secondary event which has not affected the isotopic systems in the rocks dated by Pidgeon & Råheim (1972), Mysen & Heier (1972), Råheim (1977), and Brueckner (1979) either because these rocks have been situated outside the area of influence or because the influences have not been sufficiently strong to cause resetting of Rb and Sr. A problem in this connection is to explain why no re-equilibration of the isotopes has occurred in the dioritic gneiss at Stekern ($t = 1734 \pm 106$ m.y.). A more detailed study of the rock unit may give an answer.

An alternative explanation is that the ages between 1450 and 1500 m.y. do not represent any specific geological event but are mixed ages. As discussed previously in this paper, rocks with high Rb/Sr often show more disturbed isotopic systems and give younger apparent ages than samples with low Rb/Sr. The dioritic gneiss at Stekern which gives an age of $1734 \pm 106$ m.y. has a considerably lower Rb/Sr than the rocks giving ages in the interval 1450–1500 m.y. This may be why the age of 1734 m.y. has been preserved.

In any case the ages between 1450 and 1500 m.y. must be considered as minimum ages for the formation and metamorphism of the augen gneisses, granites and metagabbro in the Oppdal area.

The ages of ca. 1050 m.y. obtained in the area are probably secondary ages reflecting Sveconorwegian events. Ages of this magnitude have also been reported from other parts of the Gneiss Region. Brueckner et al. (1968) have dated gneisses in the Tafjord area at $1058 \pm 150$ m.y. ($\lambda = 1.42 \cdot 10^{-11}$ yr$^{-1}$). Pyroxene from gneisses from Gloppenfjorden was dated by Bryhni et al. (1971) using Ar isotope analysis to $1022 \pm 18$ m.y. Priem et al. (1973) dated the Hestbreipiggan Granite at 1009 m.y. ($\lambda = 1.42 \cdot 10^{-11}$ yr$^{-1}$).

These results indicate that large parts of the Gneiss Region have been affected by the Sveconorwegian events.

**Conclusion**

The time of deposition/ intrusion of the rocks in the Basement Complex and the Flagstone Group has not been determined, but ca. 1450–1500 m.y. is considered to be a minimum age.

No age has been obtained from the Hornblend – mica schist Group but, as discussed previously, there can be no great time difference between the deposition/intrusion of this rock unit and the underlying Flagstone Group since no structural or metamorphic breaks have been observed.

After the deposition/intrusion of these rocks, the Gråhø/Tronfjell Complexes and the Slipran Complex were thrust into their present position ($D_2$, deformational period) and folded ($F_1$).

The formation of the augen gneisses is correlated with the strong $F_2$-folding (minimum age of 1450–1500 m.y.).

The Hornet Complex lies tectonically above the Gråhø/Tronfjell Complexes and the Slipran Complex. The contact of this complex is not folded by $F_2$ as the others, and it must therefore have been thrust into position after the $D_2$ deformational period. The age obtained for the mylonitic parts of the complex (~1500–1600 m.y.) probably indicates the time of thrusting ($D_3$). It is most reasonable to look at $D_1$, $D_2$ and $D_3$ as events in the same orogenic period, and the main metamorphic event should be correlated with this (minimum age of 1450–1500 m.y.).

The ages of ~1050 m.y. probably reflect the development of a crenulation cleavage during the Sveconorwegian Orogenic Period ($D_2$).

The rocks in the Oppdal area have been affected by the Caledonian Orogenic Cycle, but the new data indicate that the influence is smaller than previously thought. A resetting of Rb and Sr has taken place only between minerals. This is consistent with results from other parts of the Gneiss Region.
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