THE PRECAMBRIAN ROCKS OF THE TELEMARK AREA IN SOUTH CENTRAL NORWAY

V. The Nissedal supracrustal series

BY

ROGER H. MITCHELL

(Department of Geology, McMaster University, Hamilton, Ontario, Canada)

Abstract. The Precambrian metamorphic rocks of the Nissedal supracrustal series, a thick sequence of basic and acidic lavas with associated agglomerates, has been intruded by gabbroic rocks and then been metamorphosed to amphibolite and epidote amphibolite grade by two periods of regional metamorphism. During the metamorphism, basic lavas were converted into amphibolites and the acidic lavas into leptites. The gabbro and its associated pegmatitic phase were metamorphosed to hyperite and ödegårdite respectively. Extensive granitisation accompanied the second metamorphic event causing large amounts of the supracrustal rock to become converted into granite-gneiss. Lesser amounts of banded gneiss, hornblende gneiss and migmatite were also formed from the supracrustal rocks at this time. The occurrence of lamprophyre dykes of Permian(?) age is noted and the Söftestad iron ore deposit is briefly described.

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Introduction and previous work

This paper describes the types of rock occurring within a belt of Precambrian metamorphosed supracrustal rocks in the Nissedal area of Telemark in south Central Norway. The work is presented as a guide to the petrology of the region, and the structure is only briefly considered as this is being dealt with by other workers.

The earliest description of the area was by DAHLL (1861) who produced a simplified geological map. On this map he showed the occurrence of a gabbro and mentioned the presence of grey gneiss, augen gneiss, red gneiss, hornblende gneiss and schist and mica schist. VOGT (1895) described the Söftestad iron ore deposit but did not further elaborate upon the geology of the area. The Nisser quadrangle was mapped in detail, on a scale of 1:50,000, by the late Steinar Foslie. This map was, however, not quite completed and no description of the geology was ever published. DONS (1960) included much of Foslie's information in a geological map of Telemark together with a brief description of the region. KVIEN (1961) surveyed the Söftestad ore deposit and described some of the surrounding amphibolites and gneisses. DONS (1965) described a calcite syenite and associated breccia which occur at Fjone on the west shore of Nisser.

The geological environment — The Telemark granite-gneiss

The Nissedal series are a part of the Precambrian of southern Norway and the position of these rocks relative to the other major divisions of the Precambrian in the region is shown in Fig. 1. (HOLTEDAHL & DONS 1960). From this it can be seen that the Nissedal series are entirely surrounded by the Telemark granite-gneiss. The contacts between the gneiss and the supracrustals are varied in aspect. In the north a fault separates the two; in the south and west there appears to be a gradation from supracrustal gneiss into the granite-gneiss proper. This gradation occurs along a fairly well defined boundary. In the east a similar gradation is found, but here all boundary relationships are much more complex because of the increasing degree of metamorphism and complexity of folding.

The granite-gneiss in Nissedal is a very inhomogeneous body. In colour it varies from white to grey or red. The texture varies from granitic to gneissose. Small areas of homogeneous granite can be found within the gneisses. Large granitic pegmatites are abundant. Within the gneiss are also found frequent occurrences of partially digested supracrustal rock (i.e. mica schist, hornblende schist and amphibolite). The gneiss consists essentially of plagioclase (c. 40%), quartz (c. 30%), microcline (c. 20%), biotite (c. 5%) and hornblende (c. 1–2%). The quartz appears as irregular sutured grains and round pools. Deformation lamellae and undulatory extinction are evidence of post-crystallisation strain of the quartz crystals. The feldspar is a xenoblastic oligoclase (An. 12%). Microcline appears as large xenoblastic crystals and is the only potash feldspar present. It replaces earlier plagioclase and occurs as interstitial crystals and is evidently the last mineral to crystallise in the rock. Myrmekitic intergrowths are developed in some places between the oligoclase and the microcline. The major mafic mineral is biotite (ZY-dark brown, X-light green) which occurs as ragged laths. Alteration of the biotite to chlorite occurs along cleavage planes with concomitant development of a greenish tinge in the mica. The alteration also releases iron from the biotite which recrystallises to idiomorphic crystals of magnetite within the parent biotite crystal. Hornblende (ZY-dark green, X-light green) is present as xenoblastic grains. Minor amounts of apatite and idiomorphic magnetite also occur.

The Telemark granite gneiss can, in this area at least, be described as a synkinematic granite (MARMO 1962). Such bodies typically are inhomogeneous gneisses in which partially granitised metamorphic rocks occur as remnants of the pre-existing terrain which was subjected to the granitisation. Synkinematic granites are formed during the early stages of orogenic cycles.

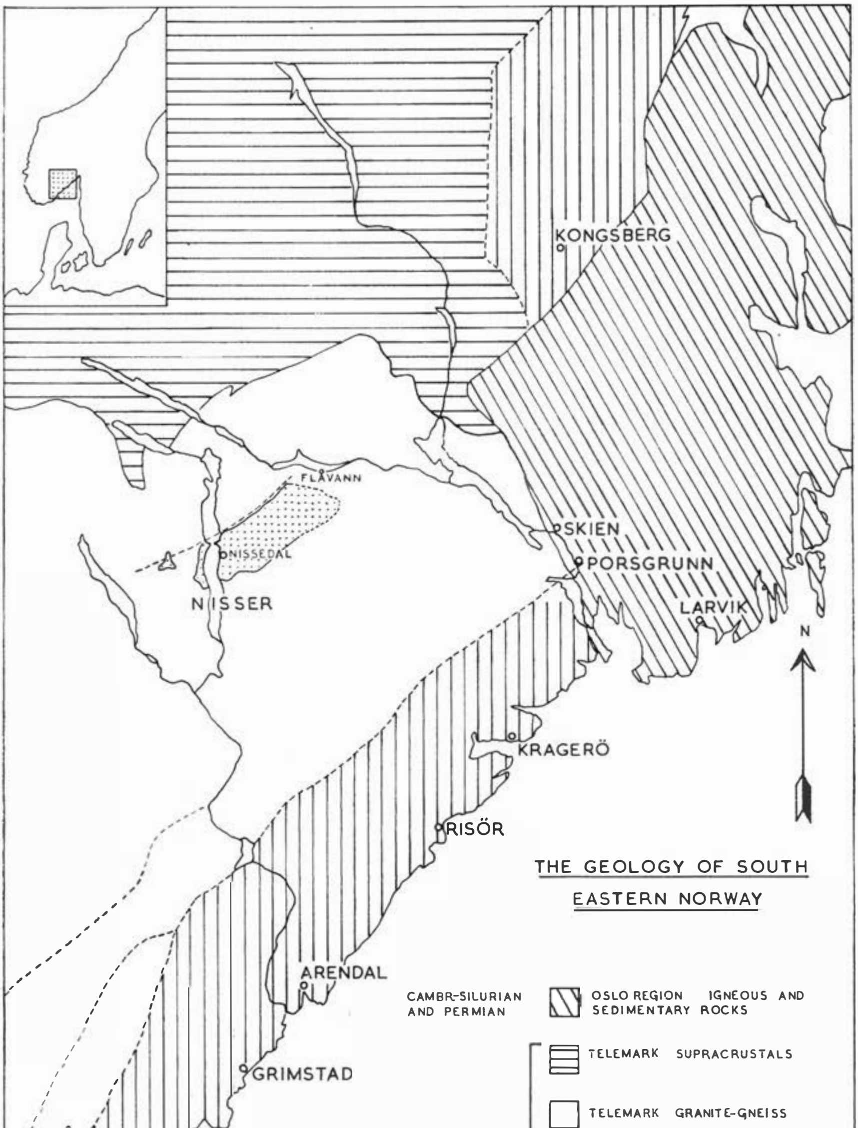


Fig. 1. The Geology of South East Norway. (After HOLTEDAHL & DONS 1960).

The Nissedal supracrustal series

The metamorphosed supracrustal rocks stretch from the west shore of Nisser north–eastwards towards the south shore of Flåvann (Fig. 1). The most important types of rock found within the area are as follows:

Amphibolites, hyperites and gabbroic rocks, leptites, ödegårdites, agglomerates (basic and acidic), quartzo-feldspathic gneisses and schists, migmatites, hornblende schists and gneisses and banded gneiss.

The distribution of the rocks is shown on the geological map of Nissedal (Fig. 2) and the various types are described below.

The structures of the Nissedal series

Three periods of deformation have been distinguished in the Precambrian of southern Norway (WEGMANN 1960). Two of these involved folding and metamorphism, the third involved the production of large shear zones in the recrystallised rocks. These three periods of deformation are also recognisable in Nissedal. The first period of folding produced folds with east–north–east orientated axial plane strikes. The second produced folds with more northerly axial plane strikes. The superposition of the two fold systems has given rise to a system of domes and basins. These are best seen in the northern parts of the area where granitisation has not been very extensive. This second period of deformation in the Bamble area (Fig. 1) was accompanied by intensive granitisation (WEGMANN 1960). It is proposed that the granitisation of the rocks in Nissedal was contemporaneous with the periods of granitisation which occured in the Bamble area. As a consequence of these periods of folding, the supracrustal rocks now appear as a synclinorium. Along the southern edge of the supracrustal area there occurs a large asymetrical anticlinal structure which is overturned towards the south. The core of this structure is occupied by migmatites. The large fault which bounds the area in the north is probably an expression of the third period of deformation. Other large faults of similar strike are found both within the granite-gneiss and the supracrustals.

AMPHIBOLITES

Amphibolites are the most abundant type of supracrustal rock within the region. They occur as thick layers between thin layers of leptite

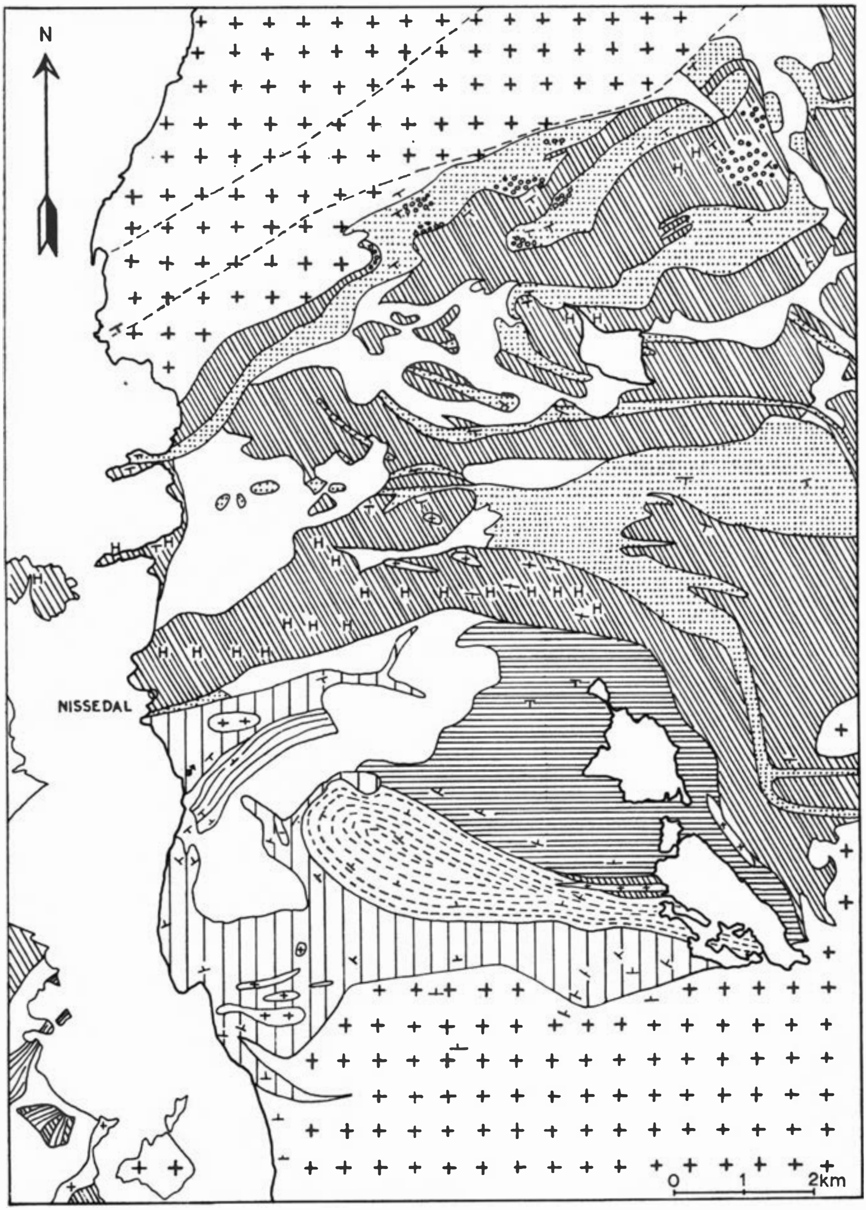
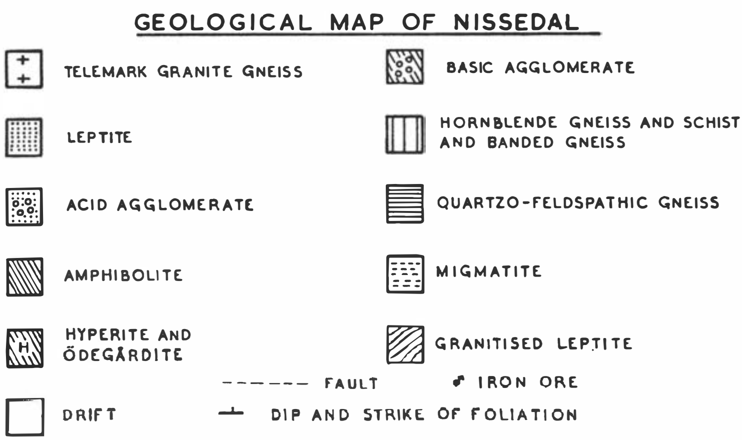


Fig. 2. Geological map of Nissedal (After Foslie with own observations 1965).

(Fig. 2). Such alternating bands of amphibolite and leptite make up a large part of the series. Contacts between the amphibolites and the leptites where seen are sharp. The two rock types lie conformably to each other. Amphibolites are best seen in the northern part of the synclinorum where granitisation has not been strong enough to convert the rocks into hornblende gneisses or schists.

Where recrystallisation and metamorphism have not been too extreme, perhaps as a consequence of the recrystallisation of the surrounding rocks which then acted as an insulating shield and prevented the flow of metasomatic fluids, amphibolites which present an igneous aspect can be found. Such rocks occur at Skarvås, Nutstölnut, and near Nissedal post office. They are dark grey rocks which are very fine grained with small (5–10 mm.) laths of feldspar being visible in hand specimens. The rocks consist essentially of plagioclase (50–60%), hornblende (35%) and pyroxene (5%). The feldspar (labradorite, c. An. 65%), occurs as long sub-idiomorphic laths which give rise to a relict ophitic texture. The laths are intensely corroded. The corrosion involves the formation of a symplectite between a clear untwinned plagioclase and a very pale green hornblende. The plagioclase of the symplectite has a higher refractive index than that of the associated lath and is thus more calcic (Fig. 3). The symplectite is considered to have formed during the metamorphism of the rock (SEDERHOLM 1916). The major mafic mineral in these amphibolites is a xenoblastic hornblende (ZY-blue green, X-light green) which occurs between the feld-



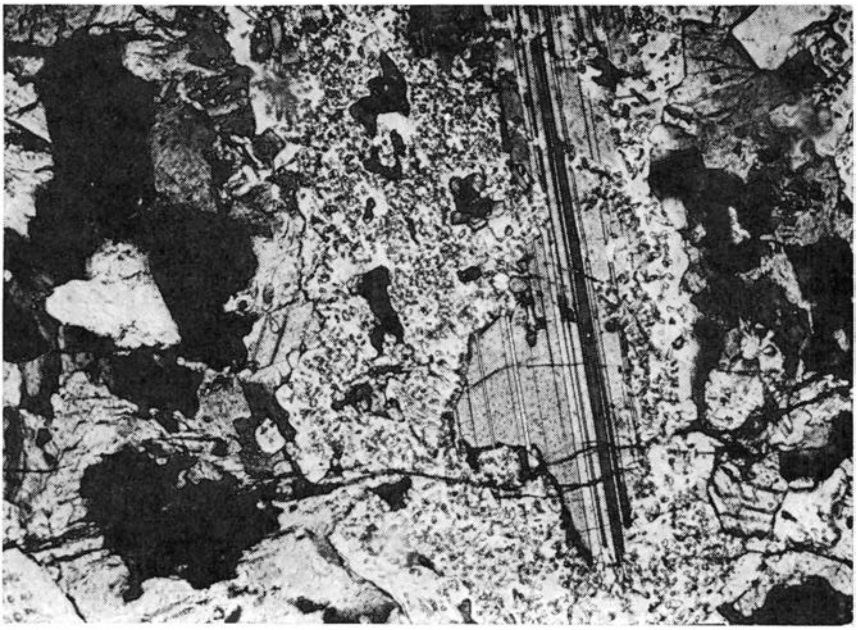


Fig. 3. Hornblende-plagioclase symplectite in meta-volcanic rock. Relict clinopyroxene (black) within xenoblastic hornblende can be seen at the lower left hand edge of the photograph. Nissedal village. Magnification 10 ×.

spar laths. Within many of the hornblende crystals are cores of a very irregularly shaped colourless clinopyroxene (augite) (Fig. 3). Furthermore, adjacent pyroxenes which are not connected physically are in optical continuity. This suggests that they once formed large continuous ophitic sheets which have now been broken up by recrystallisation and conversion of the pyroxene to hornblende. Magnetite is plentiful (c. 5%) as irregular masses. Associated with the magnetite is a little green spinel (pleonaste). The spinel forms rims around the magnetite and was probably formed by reaction between the iron ore and aluminium and magnesium, which were either introduced into the rock or released from the other minerals during metamorphism. These amphibolites to judge from their relict texture and mineralogy were originally basic igneous rocks. The stratiform outcrop between bands of leptite (which was originally a lava, see below) indicates an igneous origin and it is proposed that the basic rocks were extruded as lavas.

Associated with and grading into the amphibolites described above are massive and foliated amphibolites. The degree of foliation depends upon the amount of preferentially oriented biotite or hornblende present in the rock. The amphibolites are not banded and the colour varies from black to dark green. In some amphibolites, angular inclusions of coarse grained amphibolite occur within a fine grained amphibolitic matrix. In others, small (2 cm) lensoi dacidic inclusions are found lying with their greatest dimension parallel to the strike of the foliation of the host rock. Typically the rocks consist of plagioclase (An. 22–30%) and hornblende (ZY-blue green, X-light green) in approximately equal amounts (40%). The plagioclase occurs as xenoblastic grains which show faded albite twin lamellae and which are often highly sericitised. No zoning was seen in any of the crystals. Some alteration of the feldspar to scapolite occurs in areas close to occurrences of ödegårdite or hyperite. Hornblende typically forms xenoblastic crystals but a few idioblastic crystals can also be found. Biotite (10%, ZY-yellow brown, X-light yellow) forms ragged laths arranged in sub-parallel fashion. Pleochroic haloes around zircon inclusions in the biotite are common. Sphene (up to 5%) is a characteristic mineral in these rocks. It forms rounded and drop shaped pinkish-brown crystals. Idiomorphic crystals are rare. Epidote is often abundant in these amphibolites.

The amphibolites described above are highly recrystallised rocks and no trace of the original mineralogy or texture is preserved, thus it is difficult to ascertain the nature of the original rocks. In view of the association of these rocks with the meta-volcanic rocks mentioned above, it seems quite probable that they too were originally basic lavas.

The amphibolites described above are quantitatively the most important types; lesser amounts of other but equally important amphibolites can be seen at Framnes and at Espeliheie.

At Framnes there is found a very light green schistose rock which is interbedded with and grades into dark green massive amphibolite. At the contact between the two, parallel bands of schist alternate with bands of massive amphibolite. The banded zone is about 2 metres in width, the width of individual bands is very variable. The width of the outcrop of the schist is narrow (50 m) but the rocks can be traced along the direction of strike of the foliation eastwards almost to Frovatn (5 km). Large (5 mm) idiomorphic octahedra of magnetite are scattered throughout the rock. The schist is composed principally of hornblende (70%, ZY-blue green, X-pale green). The hornblende forms xenoblastic crystals which typically contain droplike inclusions of magnetite. Chlorite (20%) occurs as either small lath shaped crystals which show well developed polysynthetic twinning or as large xenoblastic plates which are untwinned and fibrous. The twinned chlorite has formed after the growth of the fibrous plates. The chlorite laths also penetrate the hornblende crystals. The chlorite is a clinochlore (ZY-colourless, X-very pale green). Biotite (5%, ZY-light brown, X-colourless) occurs as short stout laths closely associated with the hornblende. Plagioclase is very rare in these rocks and only a few highly sericitised untwinned xenoblastic crystals occur. Magnetite and a little apatite are accessory minerals. The magnetite occurs as very long thin crystals within the fibrous chlorite plates and as irregular masses in addition to the idiomorphic crystals and droplike inclusions noted above.

At Espeliheie, to the west of Holmevatn, there is found a highly schistose medium grained dark green rock consisting of biotite (c. 45%), hornblende (c. 45%) and iron ore (c. 10%). The schist is interbedded with and grades into biotite rich amphibolites. The biotite in the schist occurs as large laths (ZY-light brownish yellow, X-colourless) and is generally of a coarser grain size than the associated hornblende. Hornblende (ZY-bluish green, X-light green) occurs as small xenoblastic crystals. Some of the crystals occur within the biotite laths. Magnetite occurs as large irregular masses spread throughout the rock and as small globules within the hornblende crystals. The magnetite has been altered in many places to an orange red hydrated iron oxide. Small veins of this mineral run between the mineral grains of the whole rock and also penetrate down the cleavage planes of the biotite. The alteration seems to be a consequence of metamorphism and not weathering as the alteration persists in unweathered samples. Feldspar is absent in these rocks.

It is proposed that the amphibolites at Framnes and Espeliheie are the representatives of metamorphosed ultramafic rocks. Reasons for this conclusion are that the rocks present a different modal composition when compared with closely associated meta-volcanic rocks of the same metamorphic grade and also because of the general lack of feldspar in these rocks. The occurrence of a chlorite which is rich in mag-

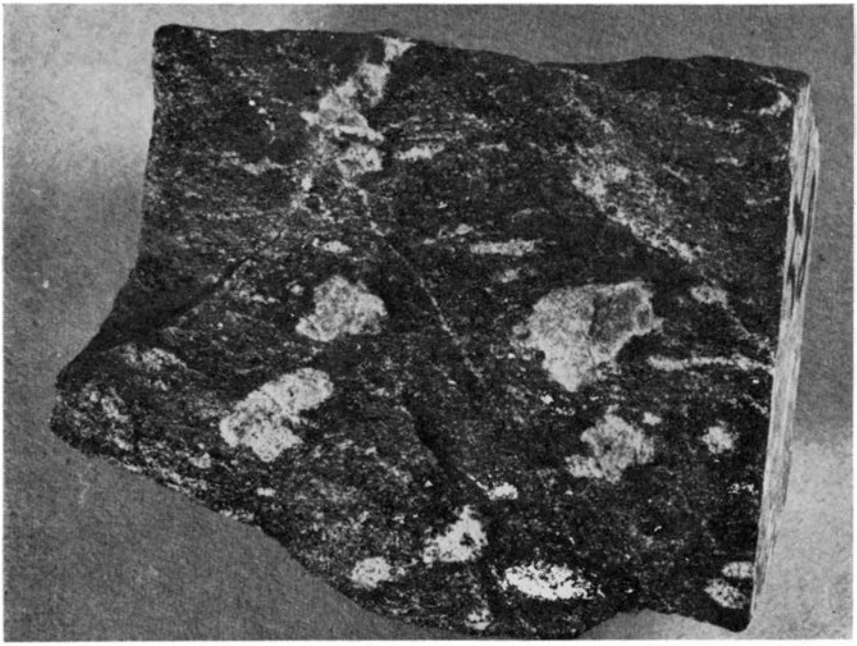


Fig. 4. Amphibolite with irregular feldspar patches. Tveitane. Magnification 1 ×.

nesium is perhaps indicative of an early differentiate of a basic magma. The rocks may represent the lower parts of thick lava flows enriched in early formed minerals; intrusion of thick sills is, however, a possibility that cannot be ruled out.

An amphibolite which is of minor quantitative importance but which is somewhat unusual is found at Tveitane, Vik and just to the west of Bulia. The rocks are fine grained and dark grey in colour. They contain numerous white, large (1 cm) irregular patches (Fig. 4). The patches sometimes have a yellow core. They often weather out prominently. The zone of patches is small and when traced across the strike of the foliation they die away rapidly, the rocks becoming typical foliated amphibolites. Along the strike direction the patches persist for long distances. The patches consist of aggregates of large plagioclase crystals. The feldspar is a xenoblastic andesine (An. 36%), the yellow tinge seen in hand specimens is imparted by a high degree of sericitisation. Chequerboard twinning due to a high degree of pericline twinning associated with albite twinning is well developed in many of the crystals. The ground mass minerals form embayments into the felsic areas. Small idiomorphic crystals of hornblende and iron ore occur in the felsic patches. The ground mass itself is a typical xenoblastic amphibolite composed of nearly equal amounts of plagioclase and hornblende (ZY-blue green, X-light yellow). The plagioclase is of similar composition to that of the feldspar aggregates. Epidote and sphene are absent in these rocks. The original nature of the rocks is difficult to decide upon; the gradation into meta-volcanic rocks indicates a possible volcanic origin. The persistence of the feldspar aggregating along the direction of the strike of the foliation may reflect an original feature of the rock if the foliation coincides with original horizons (e.g. several thin lava flows) within the rock. If so, the feldspars may have been phenocrysts of a glomero-porphyritic type, the present character being a consequence of metamorphism. If the aggregates are not of primary igneous origin then they may represent a type of porphyroblastic growth or metamorphic segregation.

In conclusion, the Nissedal amphibolites can be said to be meta-igneous rocks on the evidence of the relict textures and minerals occurring in some of them. That they might be volcanic lavas is indicated by the general stratiform outcrop of the amphibolites between thin beds of leptite (which is of volcanic origin, see below) and by the association of some of the rocks with agglomerates. Some of the amphibolites appear to be meta-ultramafic rocks. Thus the amphibolites are considered to be ortho-amphibolites produced by the regional metamorphism of basic volcanic lavas.

HYPERITES AND GABBROIC ROCKS

Hyperites outcrop mainly in the region to the north and north-east of Nissedal village, i.e. at Sundsodden, Lauvdalsfjell Hesten and Stemmefjell. Similar rocks can also be found around Måvatn and at Juvåsen. The hyperites form prominent ridges and high rounded hills. The hyperites are entirely surrounded by amphibolites but in no place could an intrusive contact be seen between the two. Gradational contacts caused by metamorphism and recrystallisation are often seen. At Nystökleivane slightly foliated hyperites are found alternating with schistose amphibolites in sharply defined layers. The observed occur-

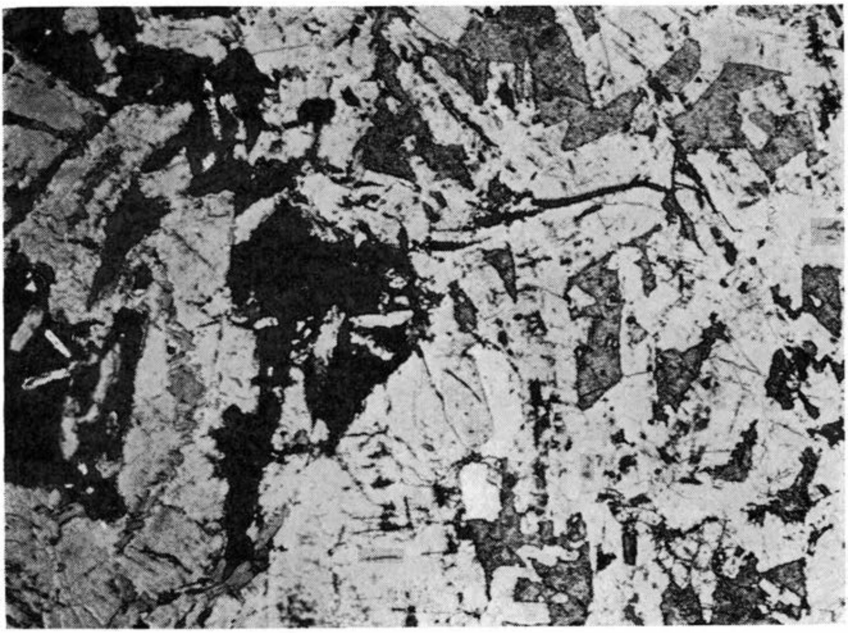


Fig. 5. Hyperite. Colourless feldspar laths surrounded by 'ophitic' plates of hornblende (grey) and magnetite (black). Sundsodden. Magnification 10 ×.

rences indicate that there are two main lens shaped masses of hyperite with smaller occurrences at Måvatn and Juvåsen (Fig. 2). The hyperites are in many cases quite strongly foliated. The grain size varies from medium to very coarse grained types. All the rocks in hand specimens characteristically show large feldspar laths set in a dark green finer grained matrix. The feldspars are typically dark in colour and have a purple sheen. The rocks are often cut by irregular veins of pure coarsely crystalline hornblende or by veins of hornblende and quartz.

The hyperites are composed of plagioclase (c. 55%), hornblende (c. 35%), pyroxene (c. 5%) and iron ore (c. 5%). The plagioclases in thin section are seen to be large sub-idiomorphic laths (An. 38–45%). The laths are clouded and cracked, iron ore fills the cracks. The cloudiness is due to sericitisation and to the occurrence of parallel rows of small round pale green inclusions. These rows are parallel to the trace of the (010) cleavage, and are composed of hornblende which has grown in the feldspar during metamorphism. Scapolitisation is always present to some degree, the feldspars being altered to aggregates of scapolite crystals. The laths are corroded and embayed by the ground mass minerals. Development of hornblende 'rosettes' within feldspars is common. These are small circular areas of hornblende prisms with a radial arrangement. The feldspar only occurs as laths and does not occur as xenoblastic grains in the ground mass. The ground mass in many cases shows an 'ophitic' texture towards the laths. The 'ophitic' mineral here, however, is hornblende (Fig. 5), which often exhibits patchy extinction. Not all the hornblende occurs in this manner, it is also present as small xenoblastic crystals which show uniform extinction. In some cases the large plates of hornblende are seen to contain irregular areas of a colourless non-pleochroic clinopyroxene (augite). A few of the xenoblastic grains also have cores composed of this mineral. Adjacent crystals of the augite not connected physically are in optical continuity. The augite is in fact being replaced by the hornblende and the large plates of hornblende represent areas of now-replaced pyroxene, which at one time formed ophitic plates about the feldspar laths. Later the replaced plates broke down into aggregates of xenoblastic hornblendes. The patchy extinction is the first sign of the breakdown. The 'ophitic' texture now observed is thus a relict texture as the pyroxene is now replaced by hornblende. Iron ore occurs as large plates enclosing feldspar laths (Fig. 5), as large irregular masses and as small globules within hornblende crystals. Minor amounts of biotite (ZY-yellow brown, X-colourless) as small laths together with large prisms of apatite make up the remainder of the rock.

The hyperites also show two other important textures. The first of these is a corona texture, which consists of a central core of interlocking xenoblastic hornblende crystals surrounded by a rim of finer grained radially arranged prismatic hornblende crystals of the same type. The radial hornblende are usually perpendicular to nearby feldspar laths. Augite in rare cases can be seen at the centre of the structure.

The second texture is a symplectite which occurs between plagioclase and hornblende. Large hornblende crystals are surrounded by an irregular zone of clear untwinned plagioclase which contains small globules of hornblende of a similar type to that which occurs in the centre of the structure. Twinned plagioclase laths surround the whole. The plagioclase of the symplectite has a higher refractive index than that of the andesine laths and is thus more calcic. In some cases a connection between the rows of inclusions in the feldspar laths and the hornblende of the symplectite can be traced.

Since the first descriptions of corona and symplectite textures by SEDERHOLM (1916), many other workers, notably BRÖGGER (1934), have discussed the origin of such features. The general opinion is that the textures are of metamorphic origin. A similar origin can be proposed for the textures described above, as the hornblende is the typical metamorphic hornblende found throughout the region. Further original minerals (augite) are seen to be replaced by this hornblende. Additional evidence for a metamorphic origin is that the associated unmetamorphosed gabbro (see below) does not contain such textures. Where replacement of pyroxene can be seen, a reaction of the type shown below has possibly occured: —

$$\text{augite} + \text{andesine} = \text{hornblende} + \text{labradorite}$$

However, it is extremely unlikely that no introduction of material from other sources occured. Such introductions may have been instrumental in bringing about the reactions. The hornblende 'rosettes' present evidence of a mobile phase as no pyroxene is found at the core of the structure and it develops in the centres of feldspar laths.

To complete the picture and to provide evidence regarding the original nature of the hyperites reference must be made to the occurrence of unmetamorphosed gabbro. Only one exposure of the gabbro is found, this being along the north shore of Måvatn. The gabbro consists of plagioclase (c. 60%), pyroxene (c. 20%) and olivine (c. 10%). The plagioclase andesine (An. 46–50%) forms laths which are dusty and cracked. The olivine occurs as clusters of colourless rounded crystals which are much cracked; the cracks are filled with iron ore. No serpentinisation of the olivine is found. A brownish augite having only slight pleochroism forms poikilitic plates about the olivine and fills interstices between the feldspar laths. Alteration of the augite to biotite is seen in places. The only other mineral present is iron ore which forms large interstitial plates. The occurrence of unmetamorphosed gabbro in a region of high metamorphic grade can be attributed to the shielding effect of the recrystallised rocks surrounding it.

The hyperites of Nissedal are thus considered to represent metamorphosed gabbroic rocks. The metamorphism involved the following events; the ophitic plates of augite were transformed into hornblende (presumably olivine was likewise converted into hornblende but no evidence of this has been found in these rocks), the 'ophitic' hornblende plates were then recrystallised into aggregates of xenoblastic crystals. Coronas and symplectite were developed. With an increasing degree of metamorphism all relict minerals and textures were destroyed and coronas and symplectites became less common; corrosion of plagioclase laths and attendant sericitisation increased together with the amount of biotite.

Hyperites which are similar to those found in Nissedal have been described from the nearby Kongsberg–Bamble area (BRÖGGER 1934). The Nissedal rocks differ from the Bamble rocks in that in the latter area olivine and garnet are typical minerals, especially in corona structures. Hornblende is not the dominant mineral that it is in Nissedal. Such differences can be attributed to initial differences in the composition of the primary gabbro and also to the differing grades of metamorphism in the two areas. Many parts of the Bamble area are of granulite facies whilst the Nissedal region is dominantly of amphibolite facies. Gabbroic rocks similar to the Nissedal gabbros were also found in the Telemark area (WYCKOFF 1933). It cannot yet be stated whether the intrusion of the gabbro in the three areas was contemporaneous or not. It is interesting to note that the Nissedal hyperites have experienced two periods of folding, whereas the period of hyperite intrusion in the Kongsberg–Bamble area is placed after the first period of folding which affected this latter area (BARTH 1963).

ÖDEGÅRDITES

Ödegårdites or hornblende-scapolite rocks (BRÖGGER 1934) are found at Nissedal village, Sundsodden, Juvåsen and on the southern slopes of Lauvdalsfjell. The rocks possess a characteristic green and white appearance (Fig. 6), and are often well foliated. The scapolitic areas are sometimes replaced by a pale yellow epidote. Large bluish-silvery masses of magnetite are present in quantity together with a little pyrite. The rocks are veined by many cross-cutting veins of pure hornblende which is very similar to that which occurs in the ödegårdite. The ödegårdites are very closely associated with the hyperites and in fact they grade into them by an increase in the content of feldspar.

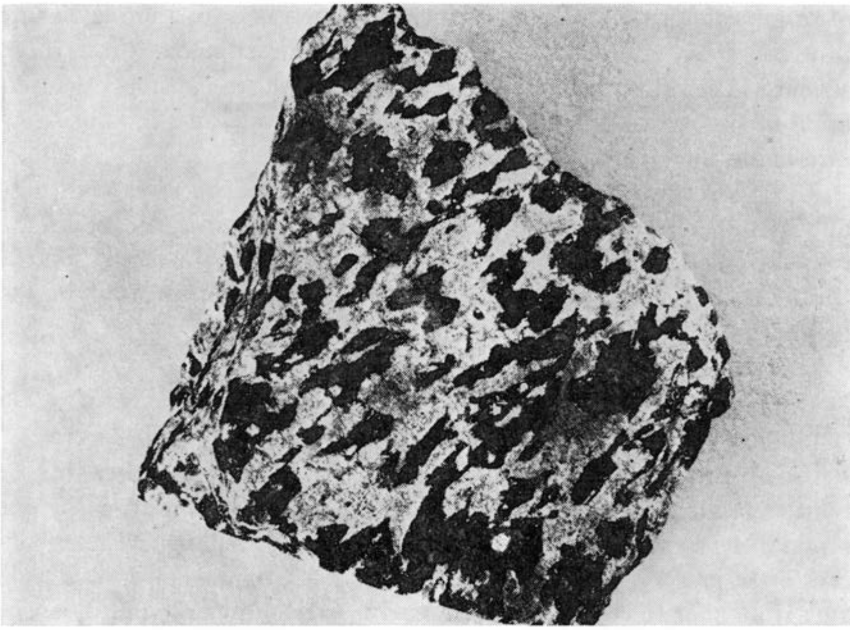


Fig. 6. Ödegårdite. Hornblende (black) and scapolite (grey). Sundsodden. Magnification 0.75 ×.

The associated hyperites are very coarse grained, almost pegmatitic, rocks. The ödegårdites are composed of about equal amounts of hornblende and scapolite (c. 45%) together with some magnetite. The large areas of colour seen in the ödegårdites (Fig. 6) are xenoblastic aggregates of either scapolite or hornblende (ZY-bluish green, X-light yellow green). Each mineral forms areas which are essentially monomineralic. The scapolite has been formed by the alteration of feldspar, as rare remnants of unaltered feldspar remain. Magnetite is found as irregular large masses and as small globules within hornblende crystals. A small amount of biotite is present as thin laths.

Ödegårdites have been described from the Kongsberg–Bamble area by Brögger (1934); these were proved by him to have been formed from the hyperites and gabbroic rocks by secondary pneumatolytic processes. The association of the Nissedal ödegårdites with rocks which were of a pegmatitic nature indicates that the ödegårdites prior to alteration were also of a pegmatitic nature. If this is so, then alteration of original feldspars by fluids which were confined to the pegmatitic zone could have taken place. Thus the scapolitisation might have been a deuteric effect with later regional metamorphism causing the alteration of pre-existing mafic minerals to hornblende and thus bringing into being the hornblende-scapolite rocks now seen.

An important difference between the Bamble ödegårdites and those of Nissedal is that the Bamble rocks typically contain rutile whilst the Nissedal rocks contain neither rutile nor sphene; thus most of the titanium in the Nissedal ödegårdites must be concentrated in the magnetite or the hornblende.

LEPTITES

Leptites, that is, quartzo-feldspathic rocks which have a xenoblastic texture 'which has originated through the recrystallisation of the original dense ground mass' (MAGNUSSON 1936), but in which phenocrysts are preserved, are found at Viksodden, Stemmehei, Lauvnetten and Holmane. It is possible that leptites were also originally present in the southern parts of the region but here the metamorphism has been so extensive that recrystallisation and alteration to gneiss has caused them to lose their original identity. In north Nissedal the rocks are gently folded into domes and basins, outcrops being traceable as low lying areas between ridges of amphibolite. In the east in Tördal the leptites are more strongly folded into isoclinal structures. Numerous occurrences of agglomerate are closely related to the leptites (see below). Exposed contacts between the leptite and amphibolite are sharp, and no chilled border facies is preserved due to the high degree of recrystallisation. No igneous brecciation was seen. The leptites are very fine grained and are either pinkish or light grey in colour. Phenocrysts are small and are rarely seen in hand specimens. The leptites are often well foliated; this is particularly well seen at Lauvnetten where there are found long pavements of foliated rock which show the effects of several periods of deformation by the occurrence of 'eyed folds' (RAMSAY 1962). When examined under the microscope at least five different types of leptite are discernable. Three of these are very similar in mineralogy and vary only in the amount of phenocrystal material present and in feldspar composition; They are, however, stratigraphically distinct units. They are composed of irregular feldspar

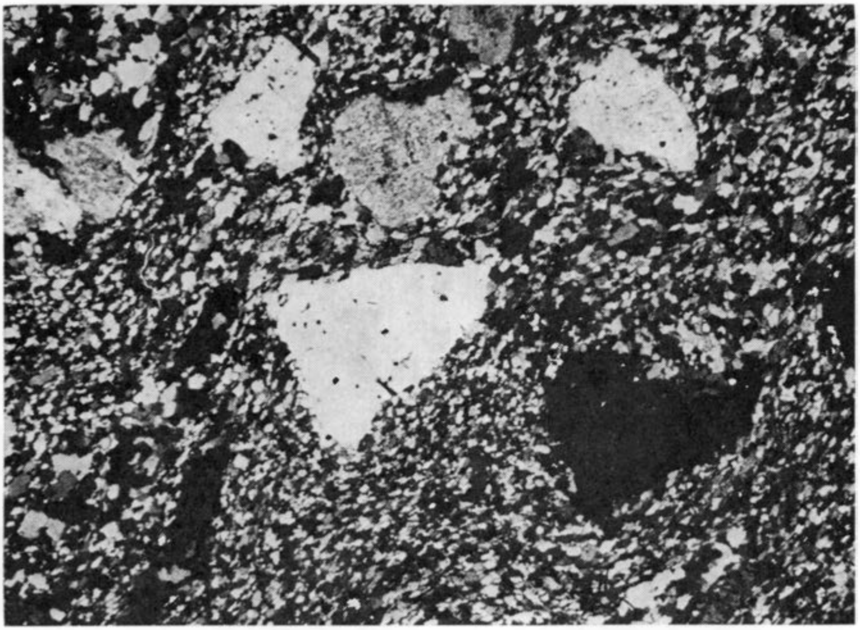


Fig. 7. Leucocratic porphyry. Irregular phenocrysts of oligoclase set in a quartz-oligoclase-magnitite ground mass which shows indications of a flow texture. Holmane, Tördal-Steane Road. Magnification 10 ×.

phenocrysts (An. 20–28%) set in a fine grained ground mass of xenoblastic feldspar (An. 12–25%), quartz, and hornblende (ZY-blue green, X-light yellow green). The irregular shape of the phenocrysts is due to embayment of the crystals by the ground mass minerals. No flow texture was seen around any of these phenocrysts because of the extensive recrystallisation. Large xenoblastic crystals of microcline occur in the ground mass and also as irregular patches and veins replacing the phenocrysts. Small amounts of biotite which is now almost completely altered to chlorite occur together with sphene, magnetite and apatite as accessory minerals. Epidote is seen in some specimens.

The other leptites are somewhat different in character. At Holmane there is found a leucocratic porphyry which consists of large white phenocrysts (5 mm) set in a fine grained white matrix. The phenocrysts are irregular feldspar crystals (An. 13–15%) and the ground mass is composed of a xenoblastic aggregate of plagioclase (An. 10–12%) and quartz. Indications of a flow texture can be seen in the ground mass

(Fig. 7). This is thought to be a relict igneous flow texture, perhaps enhanced by metamorphism, as the large feldspars are considered to be phenocrysts and not porphyroblastic crystals. The porphyry is almost devoid of mafic silicates; only a little metamorphic hornblende being present. Angular magnetite crystals, however, make up about 5% of the rock.

The remaining type of leptite is found forming the northern edge of the supracrustal area in the region to the northwest of Hönnfjell. It is conformable to the gneiss which lies beneath it to the northwest and to the amphibolite to the southeast which lies above it. The rock is very fine grained and is slightly banded, being pinkish and grey in colour. The principal minerals present are quartz (c. 30%), plagioclase (c. 40%), microcline (c. 10%) and magnetite (c. 15%). The large amount of magnetite is an important feature of this rock; it occurs as euhedral crystals spread throughout the mass of the rock. The most important feature is, however, the texture of the rock; large parts of it have a xenoblastic texture, but others are found in which the quartz and plagioclase form long curved crystals which in many cases are reminiscent of the shards seen in recent tuffs. The plagioclase is a clear untwinned oligoclase. The quartz shows undulatory extinction and deformation lamellae which are evidence of postcrystallisation strain of the quartz. The texture suggests that the rocks were originally tuffs but a metamorphic origin for the texture cannot be ruled out. Within the curved feldspar crystals microcline can later be seen replacing the feldspar along cleavage planes, the microcline forming flame-like structures (Fig. 8). The microcline may have been introduced into the rock during the metamorphism or it may have been formed by the redistribution of the original components during metamorphism.

In conclusion it is proposed, on the evidence of the porphyritic nature of the leptites and the general stratiform outcrop, that the leptites are in fact metamorphosed acidic lavas. From the petrographic and field occurrences it is also proposed that at least four different lavas occur, each representing different periods of extrusion as they are separated from each other by thick units of amphibolite. In addition a metamorphosed tuff may be present.

The porphyritic leptites are in all cases examined feldspar porphyries, the feldspar being oligoclase. This is an important difference between the Nissedal leptites and the leptites which are found in the Telemark

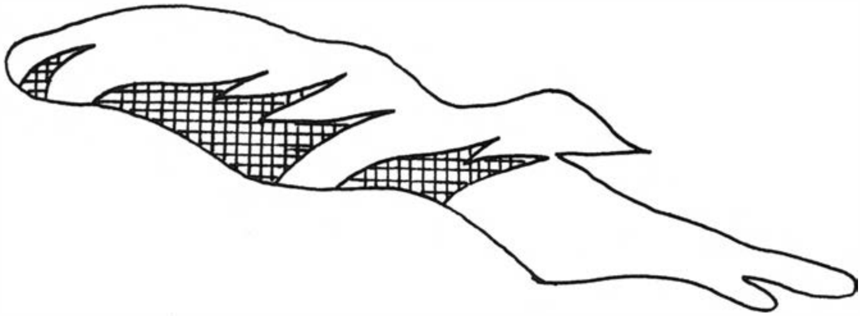


Fig. 8. Oligoclase crystal with curved outlines being replaced along cleavage planes by 'flames' of microcline. Hönnfjell, Tördal-Steane Road. Magnification 50 ×.

series, where quartz, microcline and plagioclase phenocrysts are typical (Dons 1960). Thus it may not be possible to link up any of the Nissedal leptites with corresponding leptites in the Telemark series to the north.

AGGLOMERATES

Examples of both basic and acidic agglomerates are to be found within the Nissedal region.

Basic agglomerates

Basic rocks which are recognisable as agglomerates occur at only two places; these are both situated along the northern border of the area. The largest and most important exposure is between Juvåsen and Grasdalsbekk. The other is within a thin amphibolite band just to the south east of Steitjern; this occurrence is like the main one in most respects and will thus not be further mentioned.

The most typical exposures of agglomerate are found at Juvåsen where there occur large (15–30 cm) angular and square blocks of quartzite together with lesser amounts of fine grained pinkish to white inclusions of quartzo-feldspathic rock set in a dark green fine grained amphibolitic matrix. In addition to these large inclusions there also occur a large number of small (up to 2.5 cm) purple or green inclusions which are often highly elongated in the direction of strike of the rock's foliation. The smaller quartzitic fragments are sometimes distorted in a similar manner. As one climbs up the ridge to structurally higher parts of the agglomerate, the number of quartzite and acidic rock fragments decreases until only the small purple or green inclusions are present.

A section through the agglomerate is visible between Jordet and Holmane along a small stream. The agglomerate can be divided roughly into three parts. The highest and largest is to be seen around Jordet. Here there is found a dark green fine grained rock which contains purple inclusions of widely varying size (up to about 2 cm). The inclusions are sub-angular to ellipsoidal in shape and can be seen to be breaking up and merging with the ground mass, which itself is very variable, parts being areas of very dark green pure hornblende and parts being lighter coloured and amphibolitic. These rocks pass into rocks which are very similar but which in addition contain various types of metamorphic segregation. Three types of segregation are discernable: —

1. Small (2 cm) ellipsoidal patches typically with a thin layer of pink feldspar (microcline) enclosing an olive green core of hornblende and epidote.

2. Ellipsoidal types up to 7 cm long having three distinct zones. The outer is a very thin layer of pink microcline, this encloses a thicker layer of hornblende and epidote which in turn enclose a core of pink microcline.

3. The commonest type are irregular mixtures of the pink and green material.

The second section of the agglomerate follows after this zone of segregations. A typical example is shown in Fig. 9. The large inclusions are being broken down and spread throughout the ground mass by means of recrystallisation and replacement. Whilst the rocks in this area are not very disturbed there occur in places zones of intense distortion. In these zones inclusions of the type seen in the undisturbed rocks are so highly elongated that the rock takes on a banded appearance. The zones represent a series of parallel shear zones. The remaining third part of the agglomerate is characterised by the incoming of quartzite blocks. The quartzite blocks are often distorted into ellipsoidal shapes. They are also smaller in size (up to 8 cm) than those which are found at Juvåsen just to the north. Large numbers of the green and purple inclusions are also present.

It is proposed that the distribution of the inclusions is of strati-

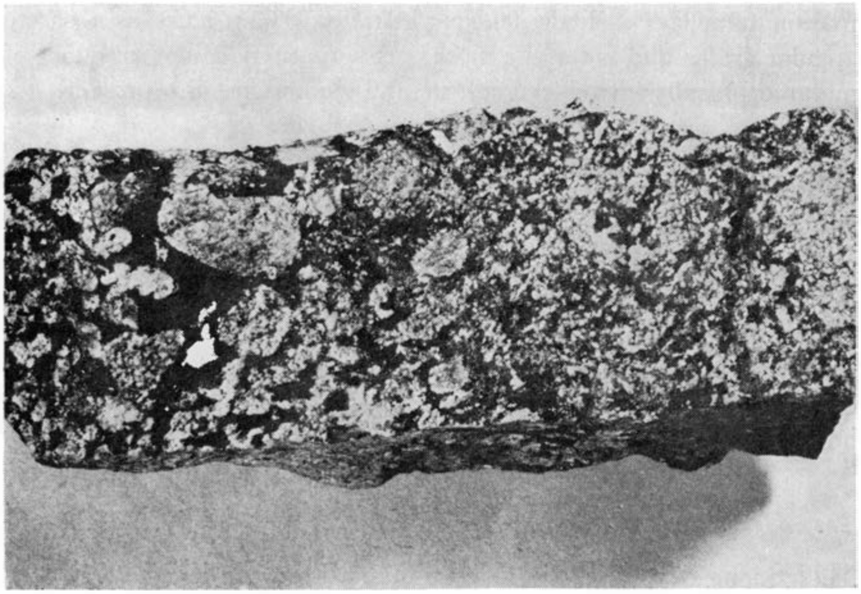


Fig. 9. Meta-agglomerate. Quartzo-feldspathic inclusions set in an amphibolitic ground mass. South east of Jordet. Magnification 0.75 ×.

graphical significance, the number and size of quartzite inclusions decreasing in the structurally and stratigraphically higher parts of the agglomerate.

The mineralogy of the ground mass of the agglomerate is amphibolitic. It consists of widely varying amounts of xenoblastic hornblende (ZY-blue green, X-light yellow) and oligoclase. Large monomineralic areas are common. A brownish sphene is the dominant accessory mineral; it forms irregular aggregates and bands of rounded crystals. Magnetite and apatite also occur in small quantities. The mineralogy of the inclusions is as follows: —

Quartzite inclusions

The quartz grains are angular and are surrounded interstitially by hornblende of the same type as that which occurs in the amphibolitic ground mass. This has been introduced into the quartzite during the metamorphism. The quartz shows undulatory extinction and deformation lamellae. A little feldspar (An. 8–10%) occurs as discrete angular grains and is for the most part sericitised. Minor amounts of metamorphically introduced sphene and epidote are also present.

Pink acidic inclusions

These inclusions are porphyritic, the phenocrysts being oligoclase (An. 12–15%). The phenocrysts are embayed by the ground mass minerals which consist of a xenoblastic aggregate of oligoclase (c. 70%) and quartz (c. 20%). The feldspar is commonly sericitised and the quartz shows undulatory extinction. The inclusions are very leucocratic; the only other minerals present being a little euhedral magnetite and a few xenoblastic crystals of epidote.

Purple inclusions

These inclusions are composed of xenoblastic oligoclase (c. 70%) and quartz (c. 20%). The inclusions are non-porphyritic, the feldspar is often altered to sericite or scapolite and the quartz shows undulatory extinction. Metamorphic hornblende and epidote make up the remainder of the inclusion together with minor amounts of sphene, magnetite and apatite. The green inclusions mentioned above always occur in association with the purple inclusions and they are in fact derived from the purple types. The green colouration is caused by a high content of metamorphic hornblende and epidote due to a greater degree of alteration during metamorphism.

Features common to all the inclusions are that they vary in shape from sub-angular to ellipsoidal forms, that they all do not present sharp margins towards the ground mass when examined microscopically and that they all contain minerals which have grown in them during metamorphism. The rounding and blurring of the inclusion margins is due to deformation and recrystallisation during metamorphism. It is also important to note that the purple inclusions decrease in size down to microscopic dimensions. Thus some of the rocks should really be termed tuffs. Whether the original basic ground mass of the agglomerate was also of a tuffaceous nature is uncertain as the rocks are now so highly recrystallised.

As regards the origin of this agglomerate two important features must be noted. Firstly, the agglomerate lies comformably to the amphibolites which lie above and below it. Secondly, there seems to be a distribution of the quartzite blocks such that they are concentrated in the lower parts of the agglomerate sequence. The quartzite also shows a tendency to decrease in size upwards through the agglomeritic body and also to the south east i.e. down the dip of the foliation of the agglomerate. These features can be explained if the agglomerate was produced by an eruption of the Vulcanian type. In this type of eruption the bedrock is brecciated and ejected from the crater to a distance which is largely dependent on the size of the fragments (ANDERSON 1933). This produces asize distribution of ejecta around the crater. As the eruption progresses the amount of bedrock included in the ejecta will decrease, the products of the eruption being largely primary volcanic products such as tuffs or lavas. Thus the quartzite and acidic inclusions are interpreted to be fragments of bedrock ejected early in the volcano's history.

The provenance of the quartzite inclusions raises interesting problems as no occurrences of quartzite have been found within the supracrustal area. The nearest known outcrop of quartzite is near Vrådal 13 km to the north (SYLVESTER 1964), but here only an insignificant quantity is found. However, large amounts of quartzite of sedimentary origin are found in the Seljord district further to the north and it is tempting to propose that this quartzite originally extended as far south as Nissedal. Unfortunately as yet no criteria can be found which would enable a correlation to be made between the quartzite inclusions and the Seljord quartzite. If such a correlation could be made it would then be possible to place the Nissedal series in their correct stratigraphical position relative to the Telemark series. If the inclusions are in fact derived from the equivalent of the Seljord quartzite, then it must lie at a deeper level within the Nissedal region and is consequently not exposed. Outcrops may now also be present in a highly granitised condition within the granite-gneiss to the north. The acid rock inclusions, more easily accounted for as large amounts of leptite, lie stratigraphically below the agglomerate; thus derivation from these is possible. It is also interesting to note that whilst amphibolites lie below the agglomerate only a few inclusions of this rock were found.

It is thus suggested that a volcanic centre was situated in this region from which fragments of the disrupted bedrock were ejected along with primary volcanic products. Judging by the distribution of the quartzite blocks, the centre must have lain to the north of Juvåsen beyond the present margin of the supracrustals; no trace of this centre has yet been found. Supporting evidence for the existence of such a centre is the occurrence of several north-south striking basic dykes now metamorphosed to amphibolite. These dykes cut the agglomerate discordantly; thus they are younger than the agglomerate but are older than the metamorphism. They may represent a late dyke phase of volcanic activity in this district.

Acidic agglomerates

This type of agglomerate is best seen to the south of Nordalstjern where it forms a continuous ridge running north east towards Tryte. Similar rocks can also be seen to the west of Haglitjern. In the Nordalstjern region the agglomerate lies conformably upon the Telemark granite-gneiss, but further to the north east the deep valley of Barlinddalen marks a fault line between the two. Amphibolites and the basic agglomerate lie conformably upon the agglomerate. The agglomeritic rocks are highly banded due to variations in the content of the minerals which compose them. They are pinkish-grey in colour and are strongly foliated; weathering emphasises the foliation and causes resistant inclusions to stand out prominantly. The inclusions are of two types, quartzitic and acidic rock. Basic inclusions are very rarely seen. The inclusions, especially the quartzite, exhibit a wide size range. At Trytetjerne, large squarish blocks (30 cm) are the dominant type. These can be either crowded together or spread widely apart. Thin epidote veins commonly occur in the blocks. The ground mass is a fine grained pink acidic rock with sporadic patches and veins of hornblende. The rocks are cut by irregular basic dykes now metamorphosed to amphibolite. Along the ridge to the south west the character of the rock changes; the large quartzite blocks are gradually replaced by smaller (5 cm) quartzite inclusions and by the acidic quartzo-feldspathic inclusions. All these small inclusions are distorted into ellipsoidal forms by the later deformation of the rock.

Examination of the quartzite inclusions shows them to consist of highly deformed quartz crystals (c. 99%). The crystals are about four times as long as they are wide. They exhibit undulatory extinction and have complex sutured margins. A little magnetite, epidote and hornblende also occur in the inclusions.

The acid inclusions have a high quartz content (c. 20%) the quartz being deformed in a similar manner to that of the quartzite inclusions. The feldspar is a highly sericitised oligoclase. This has not deformed like the quartz but has tended to recrystallise into aggregates of xenoblastic crystals. Hornblende (ZY-blue green, X-yellow green) occurs in widely varying amounts. Epidote, sphene and magnetite are accessory minerals. The epidote and hornblende are of metamorphic origin.

The matrix of the agglomerate has a variable composition due to the variation in the amount of metamorphic hornblende present. It is very fine grained and consists of oligoclase, quartz and hornblende (ZY-blue green, X-yellow green). The ground mass quartz is of two types. One is a highly deformed type like that of the inclusions and is in fact derived from them by their breakdown and subsequent merging of their components with the ground mass. The other is a xenoblastic type; this type is dominant, being a primary constituent of the ground mass and not derived by breakdown of inclusions. The feldspar is highly sericitised; rare large crystals occur which give the rock a slightly porphyritic appearance. There also occur rare phenocrysts of a very finely perthitic feldspar. Sphene is abundant as idiomorphic crystals and as aggregates of rounded crystals. Magnetite, apatite and epidote are present as accessory minerals which are often concentrated into bands parallel to the foliation of the rock. Occasionally there is found a pale green augite which is for the most part altered to hornblende. This augite is a relict igneous mineral and is not of metamorphic origin as it is unstable in these rocks, which have never been metamorphosed to any degree of metamorphism higher than the amphibolite grade. The hornblende and the epidote of the agglomerate tend to be concentrated near the borders of the inclusions; the rest of the ground mass is quite leucocratic. It is proposed that the ground mass of the agglomerate represents a metamorphosed quartzo-feldspathic igneous rock; whether this was originally a lava or a tuff is impossible to state because of the high degree of recrystallisation.

The agglomerate has some features in common with the basic agglomerate, notably the occurrence of quartzite and acidic inclusions of similar type. Moreover, there is a tendency for there to be a size distribution of the quartzite blocks. If a similar genesis is proposed i.e. a Vulcanian eruption, the size distribution points towards a volcanic centre in the same general region as that indicated for the basic agglomerate. As regards the provenance of the inclusions the conclusions reached for those found in the basic agglomerate are valid.

QUARTZO-FELDSPATHIC GNEISSES AND SCHISTS

Fig. 2 shows the distribution of these rocks. At Skårnetten are found coarse and medium grained rocks of either a pink or grey colour. Slight banding due to the variation in the amount of biotite present occurs. The gneisses grade northwards into finer grained more compact grey gneisses and schists in the Ervetjern–Langmyrtjern region. The rocks are all similar in their mineralogy but wide variations in the amount of mafic minerals occur. Thus rocks can be found which have up to 15% biotite with little or no hornblende whilst in others the reverse is the case. Hornblende rich rocks are however not typical. In general the mineralogy is as follows. Quartz (10–15%) occurs as xenoblastic crystals showing undulatory extinction. A little quartz is also found as small round 'pools' which for the most part do not exhibit undulatory extinction. The interpretation of this feature is that there are two generations of quartz present. The xenoblastic quartz being primary recrystallised quartz and the 'pools' of quartz being quartz which was either introduced during metamorphism or was formed by the recrystallisation of mobilised primary silica produced during metamorphism. Plagioclase is the most abundant mineral (c. 70%). It shows a wide variation in composition (An. 15–38%) but is for the most part oligoclase. It forms large xenoblastic crystalswhich are commonly sericitised. Faded albite twin lamellae occur. Biotite (ZY-dark green, X-light green) is the principal mafic mineral. Alteration along cleavage planes to a light yellow chlorite is characteristic. The hornblende (ZY-blue green, X-light yellow green) when present is the typical metamorphic hornblende of the region. Microcline is quite abundant in these rocks, it occurs intersticially and replaces earlier plagioclase. Sphene is the major accessory mineral; it forms aggregates of droplike brownish crystals or rims around iron ore crystals. A non-pleochroic pale green augite is a rare constituent of these rocks; this is largely altered to hornblende. A little epidote is sometimes present.

On the evidence of their mineralogy, i.e. quartz and feldspar with very few mafic minerals, the quartzo-feldspathic gneisses and schists are interpreted to be metamorphosed silica rich igneous rocks which have been thoroughly recrystallised and slightly granitised. Prior to recrystallisation they were originally leptites. Quartz and microcline may have been introduced into the rocks during metamorphism. These gneisses and schists represent the northernmost limit of the granitisation phenomena which occur along the southern borders of the supracrustal series.

MIGMATITES

Migmatites are found to the south of Skårnetten in the Litveitfjell–Holmevatn area (Fig. 2). The migmatites occupy the core of an anticline which is overturned towards the south. The rocks are very strongly foliated, the foliation being defined by mica and by thin parallel bands of granitic material. The metamorphic component of the migmatites is a coarse grained grey biotite gneiss. This is veined by granitic material. Finer grained more schistose types of migmatite are found in the southern parts of the region where they grade into hornblende schists. The grey gneiss is composed of oligoclase and brown biotite together with a little muscovite and quartz. The granitic component is composed of albite, oligoclase quartz and muscovite with a little brown biotite. The granitic veins are very irregular in width and length; many of them swell out into augen which weather out prominently. They can in many cases be traced back into granitic pegmatites lying either concordantly or discordantly to the gneiss. These pegmatites are composed of quartz, albite, oligoclase,muscovite and andradite garnet. The granitic component of the migmatite was derived from these pegmatites. The rock which was migmatised was probably amphibolitic; the planes of foliation in such rock would allow easy introduction of the granitic material. During the process the hornblende of the amphibolites was converted into biotite.

The migmatites are also cut by ptygmatic veins; these veins are of granitic composition and they have sharp contacts with the surrounding gneiss. Biotite in the gneiss lies parallel to the contacts. The veins are often associated with small drag folds, the veins following the style of the folds (Fig. 10). From this association it is deduced

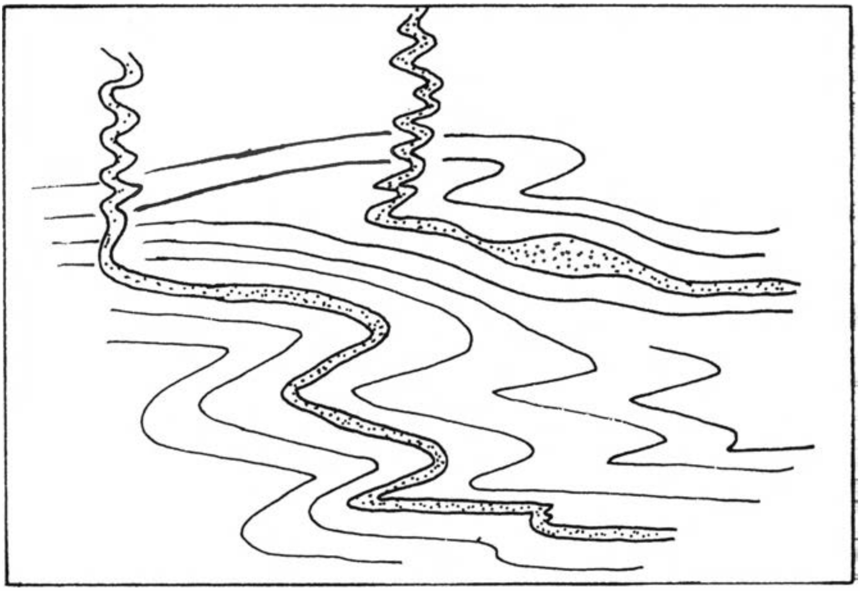


Fig. 10. Drag folds and ptygmatic veins in migmatite.
Findrotjern. Magnification. 0.25 ×.

that some of the ptygmatic veins were produced by the deformation of a thin planar granitic vein which in places was parallel to the pre-existing foliation and in others was cross-cutting.

HORNBLENDE GNEISSES AND SCHISTS

To the south of a line joining Söftestad and Holmevatn are found hornblende gneisses and schists which represent amphibolites which have been slightly granitised. The degree of granitisation is variable and is weakest in the northernmost parts of the area. In the south in the Trågedokk region, gradation into granite-gneiss takes place firstly by a decrease in the amount of hornblende together with the conversion of much of the hornblende into biotite. Secondly an increase in the amount of quartz takes place. The gneisses are typically dark grey rocks in which veins and patches of hornblende occur which has segregated out from the body of the rock during metamorphism. In the area around Nesbukta, feldspar augen are common. Where the rocks have been completely granitised, nebulitic biotite rich streaks serve to define the original structure of the replaced schists. Large and small granitic pegmatites are abundant in this region; they replace and vein the gneisses. The gneisses are composed of a xenoblastic hornblende (ZY-blue green, X-light yellow green), oligoclase (An. 18–26%) and biotite (ZY-brown, X-light yellow) in widely varying amounts depending upon the degree of granitisation. In the schists which lie close to the southern edge of the supracrustal region quartz is common as rounded 'pools' and sutured grains. Accessory sphene forms rounded droplike crystals together with a little magnetite.

BANDED GNEISS

Lying to the south of Lauvvika and up to the Telemark granite-gneiss proper is a small outcrop of banded gneiss. The banding is very well defined, the individual bands varying in width from 1–20 cm. The bands are either light grey or dark grey in colour. The banding reflects the composition of the bands, the dark grey bands being hornblende rich. The mineralogy of the bands is similar, only the amounts of the constituents varying. The hornblende (ZY-blue green, X-light yellow green) is xenoblastic. The plagioclase is an oligoclase (An. 10–14%) which is often replaced by microcline or is sericitised or saussuritised. Quartz occurs as rounded 'pools'. Minor amounts of epidote, magnetite and apatite occur as accessory constituents.

Ellipsoidal granitic pegmatite masses lie parallel to the banding of the gneisses; they are also cut by pegmatite veins. Discordant pegmatites frequently send offshoots out along the planes of foliation of the gneiss. Much biotite is developed adjacent to these offshoots.

When traced to the south the banded gneiss shows a decrease in the amount of mafic minerals and an increase in the amount of quartz and microcline. This change is observable across the foliation of the banded gneiss, the attitude of which remains constant throughout. Eventually the banded gneiss becomes a granite-gneiss with a faintly discernable foliation. Nebulitic biotite rich remnants of the banded gneiss can also be seen.

Because the banded gneiss has close association with and very similar mineralogy to the hornblende gneisses, it is regarded as a derivative of these gneisses. The exact mode of formation cannot as yet be stated but chemical redistribution of the components during granitisation appears to have taken place.

DYKE ROCKS AND PEGMATITES

Basic dykes have already been mentioned in connection with the basic agglomerate. These dykes are now metamorphosed to amphibolite and they are of Precambrian age.

Unmetamorphosed dykes can also be found in the region. These are best seen along the shores of Nisser, where they are intruded into amphibolites. The dykes are lamprophyres in which small (2–3 mm) white phenocrysts are set in a fine grained dark grey ground mass. The phenocrysts are of two types. The predominant type is an euhedral augite of a light greenish hue. Pleochroism is but slight, the crystals are zoned and 'hour glass' structures are commonly seen when the mineral is observed under crossed nicols. The other type of phenocrysts are hexagonal in cross section. The original mineral which formed them has now been completely replaced by a mixture of calcite and chlorite. The original mineral of these phenocrysts may have been biotite which is a typical mineral of many lamprophyres. The ground mass is composed mainly of augite which is of the same type as the phenocrystal augite. The crystals are often idiomorphic and they are set in a matrix of calcite and chlorite. Magnetite is abundant in the rock (c. 10%) as small euhedral crystals and less commonly as dendritic crystals. The alteration of the ground mass of the lamprophyres has been very extensive and it cannot be stated if plagioclase was originally present in quantity. The high calcite content of the rocks may be due to alteration of original calcium bearing minerals by deuteric fluids. The Nissedal lamprophyres are thus possibly augite camptonites. Such lamprophyres are associated with deep seated highly alkaline rocks. The nearest occurrence of such alkaline rocks is at Larvik, to the east, where large volumes of larvikite (augite monzonite) are found. The larvikites are associated with the Oslo Region igneous activity of Permian age, and it is quite possible that the Nissedal lamprophyres represent a dyke phase associated with the intrusion of the larvikites.

Dolerite dykes occur on the western shore of Nisser at Fjone (DONS 1965). Dons suggests that they are also related to the Oslo Permian igneous activity.

Pegmatites are exceedingly common in the Nissedal region. They range in size from a few centimetres to tens of metres. They form either ellipsoidal masses or discordant veins. By far the commonest are granitic pegmatites composed of quartz, microcline, albite, biotite, muscovite and magnetite. Graphic textures are often found. Less commonly found are pegmatites which are composed of amazonite, quartz, albite, biotite and andradite garnet. The colour of the amazonite varies from a very pale green (Nesbukta) to a very bright green (Söftestad, Ervetjern). It is possible that the amazonite pegmatites are related to the important amazonite pegmatite at Skarsfjell in Tördal to the east. This pegmatite occurs in granitised supracrustal amphibolites which belong to the Nissedal series. Age determinations carried out upon microcline and lepidolite from this pegmatite (NEUMANN 1960) indicate that the Nissedal series are older than 910 million years.

ORE DEPOSITS

The most important iron ore deposit in the area is at Söftestad. This is a magnetite-hematite-apatite ore which in places is of a banded variety. The ore lies on the west limb of a north easterly trending syncline. The outcrop is sinuous, due to the effects of the two periods of folding. Numerous other examples of the two deformations can be found within the mine. The country rocks are amphibolites, hornblende gneisses and reddish quartzo-feldspathic gneisses. The ore forms a thin lensoid body within a quartz-plagioclase-biotite gneiss. The lens lies parallel to the foliation of the gneiss. Contacts with the gneiss are for the most part quite sharp though some gradational ones can be found. This suggests that some replacement has occurred but the gradation may, however, be of metamorphic origin and so unconnected with the actual ore genesis. The ore is cut in many places by pegmatites, lamprophyre dykes and by thin calcite and chlorite veins. The ore reached its present condition by the metamorphism of an original magnetite-apatite ore. The magnetite is poor in titanium and rich in vanadium compared with magnetite which is associated with gabbroic rocks. The apatite is rich in rare earths. Other primary minerals found in small quantities are pyrite, chalcopyrite, bornite and chalcocite. Alteration of the ore by invading fluids associated with the metamorphism has led to the alteration of the magnetite to hematite and to the introduction of much hornblende and epidote. Other minerals formed at this time include stilbite, calcite, chlorite, gypsum, anhydrite, phrenite, malachite, azurite and asbestos.

The Söftestad ore is similar to the metamorphosed magnetite apatite ores found at Grängesberg in central Sweden.

The original ore at Söftestad was of the Kiruna type. The genesis of such ores is still a matter of some debate but a magmatic segregation origin is possible. In Nissedal the lack of associated meta-sediments seems to preclude a sedimentary origin.

A titaniferous magnetite ore was formerly worked at the Veneli mine situated on the western slopes of Lauvdalsfjell. This is a very small deposit situated within hyperitic rocks and represents a magmatitic segregation from the gabbroic magma. Numerous other small prospects have been worked for ore of this type or for copper; all of them occur within gabbroic rocks.

Associated with the granitic pegmatites and the phase of granitisation is a period of molybdenite mineralisation. The veins are small in Nissedal and only a few of them have been worked. The mineralisation is probably associated with the more important molybdenite deposits which occur at Kleppe to the east in Tördal.

The metamorphic grade of the supracrustals

The most important mineral assemblages occurring in the rocks are as follows: —

A) Basic rocks:
Hornblende-oligoclase.
Hornblende-oligoclase-epidote.
Hornblende-oligoclase-biotite.
Hornblende-oligoclase-biotite-chlorite.
Sphene is present in all the basic rocks. Relict assemblages with augite, olivine and more calcic plagioclase are also found.

B) Acid rocks:
Quartz-oligoclase-hornblende.
Quartz-oligoclase-hornblende-biotite.
Quartz-oligoclase-hornblende-biotite-epidote.
Microcline and sphene are usually present. Pyroxene is a relict mineral.

The rocks thus lie within the amphibolite and epidote amphibolite facies. The occurrence of chlorite is taken to be an effect of retrograde metamorphism. Such retrograde effects have been described in metamorphosed basic rocks by WISEMAN (1934). The rocks have been subjected to two periods of deformation and thus it is probable that two different metamorphic facies are superimposed, as it is unlikely that temperature and pressure conditions were the same in each period. The time interval between the two events is unknown. The superposition accounts for the occurrence of amphibolite grade rocks intermixed with rocks of the eipdote amphibolite grade. The second period of deformation was associated with granitisation as granitised supracrustal gneisses are the youngest gneisses in the area. The third period of deformation only caused the fracturing of the rigid gneiss block. Thus it is likely that the second metamorphic event caused the retrograde metamorphism of pre-existing amphibolite grade rocks. The evidence for such a sequence of events comes from the fact that granitisation is thought to occur within the temperature range 500–600°C. (MARMO 1962). This is somewhat lower than the temperature proposed for the amphibolite facies, which is 550–750°C (TURNER & VERHOOGEN 1960).

CONCLUSIONS

The Nissedal supracrustal series is a series of metamorphosed acidic and basic volcanic rocks. The rocks for the most part are lavas but pyroclastic rocks are commonly found; these are agglomerates and they are associated with both the acidic and basic volcanic activity. There is also the possibility that some of the rocks thought to be metamorphosed lavas are in fact metamorphosed tuffs. Alternate extrusion of acidic and basic rock has occurred, the basic lavas being predominant. The volcanic sequence has been intruded by gabbroic rocks. After intrusion of the gabbroic rock and cessation of volcanic activity the rocks were folded and metamorphosed to the amphibolite grade. During this period the basic rocks were metamorphosed to amphibolites, the acidic to leptites and the gabbroic to hyperites and ödegårdites. A second period of metamorphism and deformation followed, this caused retrograde metamorphism of the meta-volcanic rocks and was accompanied by extensive granitisation of the leptites and amphibolites. Hornblende gneisses, quartzo-feldspathic gneisses, migmatites and granite-gneiss were formed during this period. The production of a large area of granite-gneiss caused the area to behave as a rigid block towards a third period of deformation, large faults were produced at this time.

The supracrustals are of Precambrian age, but they cannot as yet be related in age either to the nearby Telemark series or to the Kongsberg–Bamble rocks, both also of Precambrian age. Certain contrasts and similarities can be found. The most striking feature of the Nissedal region is the apparent complete lack of sedimentary rocks. This is quite unlike the Telemark series with its extensive quartzites and also unlike the Kongsberg–Bamble area in which all types of sedimentary rock can be found. The only rocks found in Nissedal which could be sedimentary are the quartzite blocks found in the agglomerates. These could be derived from an equivalent of the Seljord quartzite and if this could be proved, the relative age of the Nissedal series to the Telemark series could be fixed. Relating the age of the rocks to any of the rocks in the Kongsberg–Bamble area is as yet impossible. All the three areas have been intruded by gabbroic rocks which are now for the most part metamorphosed to hyperites; it is impossible to say if any of these intrusions were contemporaneous or not. However, the fact that the Nissedal hyperites have been affected by two periods of deformation whilst those of Bamble are reported to have suffered only one (BARTH 1963), seems to indicate that the rocks are not contemporaneous.

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Grid references of place names mentioned in the text.
All places lie on AMS sheet 1613 III.

Barlinddalen	785666	Lauvnetten	792610
Bulia	762611	Måvatn	785632
Ervetjern	770584	Nesbukta	720540
Espeliheie	804572	Nordalstjern	755657
Findrotjern	755557	Nutstölnut	811591
Framnes	714585	Nystökleivane	780600
Frovatn	775598	Skarvås	760645
Grasdalsbekk	700654	Skårnetten	765685
Haglitjern	779650	Steitjern	746649
Hesten	752601	Stemmefjell	765605
Holmane	810654	Stemmehei	770622
Holmevatn	800550	Sundsodden	715604
Hönnfjell	803668	Söftestad	722572
Jordet	806655	Trågedokk	780540
Juvåsen	805660	Trytetjerne	775659
Langmyrtjern	782590	Tveitane	730620
Lauvdalsfjell	730595	Vik	721611
Lauvvika	726535	Tördal	893579
Litveitfjell	745564		

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