Petrography of the Gula Group in Hessdalen, Southeastern Trondheim Region, with Special Reference to the Paragonitization of Andalusite Pseudomorphs

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Al-rich pelites from Hessdalen, SE Trondheim region, Central Norway, belonging to the Cambrian Gula Group, are described petrographically. The schists carry abundant porphyroblasts of staurolite, garnet, kyanite and pseudomorphs after andalusite. X-ray diffraction analysis has shown that the white mica of the pseudomorphic mineral assemblages is paragonite with a little muscovite.

It is proposed that the andalusite pseudomorphs are relics from a contact metamorphic aureole associated with pretectonic to early syntectonic emplacement of deep-seated, sub-surface gabbroic bodies, indicated by geophysical evidence. The subsequent high-pressure metamorphism of lower almandine-amphibolite facies, tentatively correlated with an early fold phase F_1, inverted the andalusite porphyroblasts to aggregates of kyanite. The formation of paragonite occurred during a retrogressive metamorphic phase, as a pseudomorphosis of the kyanite in the altered andalusite porphyroblasts.

P. Bøe, Geologisk institutt, Universitetet i Trondheim, Norges Tekniske Høgskole, N-7034 Trondheim–NTH, Norway

Introduction

The area under consideration is situated in the northern part of Hessdalen, a western tributary valley to the upper Gauldal valley in the county of Sør-Trøndelag (Fig. 1). A recent article on the geology of the Røros district embraces the Hessdalen area (Rui 1972). In this work the stratigraphy of the south-eastern Trondheim region is correlated with that of the Meråker district to the north, following Wolff (1967). It is also shown that the lithostratigraphic sequence is inverted, as is the case in the Meråker area.

The stratigraphic succession in the eastern Trondheim region has been correlated with that occurring in the western part of this rather extensive eugeosynclinal area of the Norwegian Caledonides (Wolff 1967). From various evidence it is now generally accepted that the Gula Group (named Gula Schist Group by Wolff 1967, and Gula Group by Wolff 1973) is the oldest unit of the Lower Paleozoic stratigraphic succession in the Trondheim region; this is followed by the volcanic Støren Group, the Lower and Upper Hovin Groups and the Horg Group (Roberts et al. 1970).

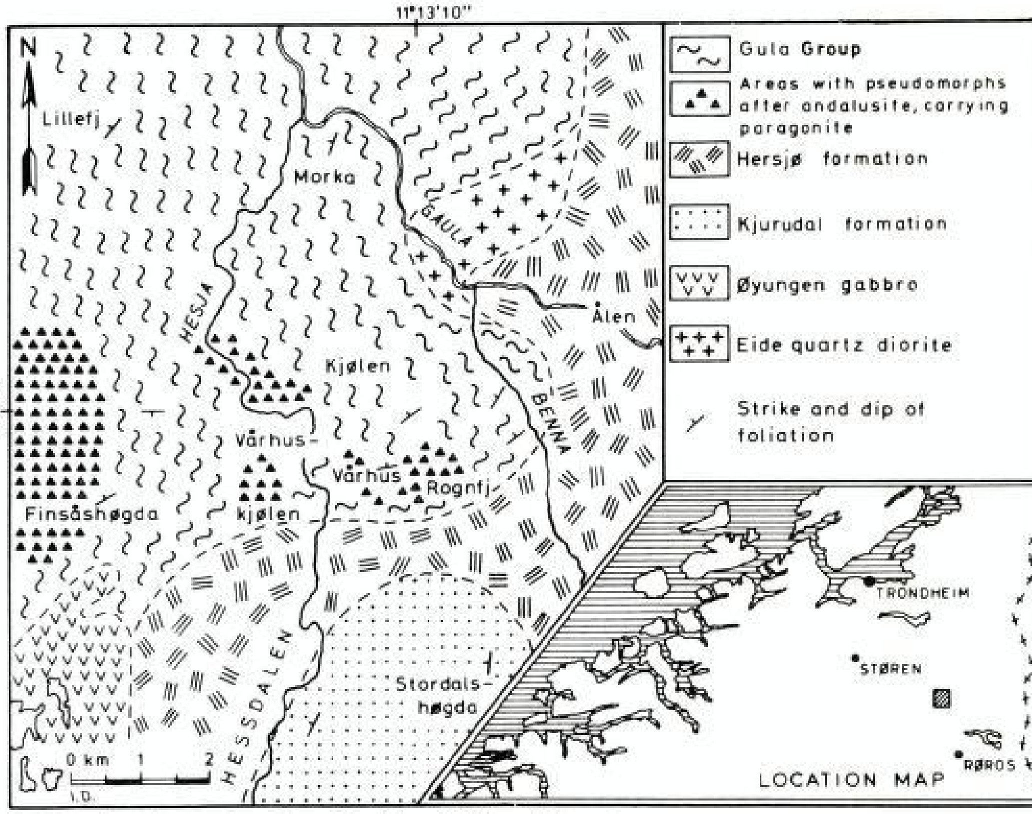

Fig. 1. Geological map of northern Hessdalen, SE Trondheim region.

Geological setting

In Hessdalen the metasediments of the Gula Group constitute the youngest part of this group, which occurs extensively in the central part of the Trondheim region. Volcanic rocks of the Hersjø formation, a supposed Støren Group equivalent, are lying tectonically below the mica schists of the Gula Group. The Hersjø formation is itself overriding the Kjurrudal formation, which is regarded as a Hovin Group equivalent (formation named after Rui, 1972). The Al-rich schists in Hessdalen, with numerous occurrences of staurolite and Al_2SiO_5-polymorphs, form a southern continuation of the so-called Drøya schists in Haltdalen, a few kilometres to the north in Gauldalen (Vogt 1941). Further to the north they are probably represented by the Heinvola zone in Tydal (Kisch 1962) and the zone with 'Selbu millstone' (Carstens 1929). To the south of the studied area similar rocks are found on the mountain Hersjøfjell (Birkeland 1967).

The occurrence of andalusite and andalusite pseudomorphs in Hessdalen has long been known. In 1868 Th. Kjerulf's co-worker Knut Hauan recorded andalusite on the western banks of the river Hesja, and in 1873 he found the mineral at Vårhus (diaries of Knut Hauan, NGU archives). It may be assumed that the reported crystals of andalusite actually were pseudomorphs of the mineral with their orginal shape unchanged. Hauan also observed glacial striae on these pseudomorphs partly weathered out of the schist in the Vår-hus-Rognfjell area.

Tectonic structures

The folding deformation in the Hessdalen area seems to be divisible into two main episodes. An early fold phase, F_1, probably folded the sediments and volcanics in tight or isoclinal folds overturned to the east, with the formation of a distinct axial plane foliation. The schists split along this foliation, which mostly coincides with primary bedding on a mesoscopic scale. The F_1, foliation originally had a general NNE-strike with westerly dip, as seen in southern Hessdalen outside the present map area (Birkeland 1967, Bøe 1971). There are few mesoscopic folds of this episode to be seen in Hessdalen.

A later folding phase F_2 has refolded the earlier folds and foliation along east-west axes. The later phase is especially well marked in northern Hessdalen by the eastward extension of the Gula Group on Rognfjell, in the shape of a large and fairly open synform (Fig. 1). Lineations belonging to this second episode, defined chiefly by crenulations but also by mineral orientations and mullions, have directions within the sector 285°–315°, using a 400° scale. Axes of mesoscopic folds from the Hersjø and Kjurrudal formations in the southern part of the map (Fig. 1) have directions within the same sector, with a concentration around 310°.

Description of the mica schists

Mica schists of the Gula Group within the present area are brownish grey and usually fine-grained with an indistinct lamination. Small segregations of quartz of syntectonic origin are common, but not numerous. On weathered surfaces the schists have a rusty appearance, probably a result of disseminated sulphides. Graphite is observed in some places. Porphyroblastic minerals are common, and up to 3–4 cm in size. The porphyroblasts give a knotted appearance to the foliation surfaces.

The texture of the schist matrix is typically lepidoblastic, usually with biotite defining the foliation. In thin-sections, the schists may display microfolds, sometimes with the development of fracture cleavage and strain-slip cleavage. Some modal compositions, based on volumetric analysis of selected specimens, are given in Table 1.

Quartz and sodic *plagioclase* are completely recrystallized to granoblastic grains, which are slightly elongated within the foliation. Both these minerals have a fresh appearance with even extinction. The plagioclase lacks twinning.

Table 1. Modal analyses of mica schists of the Gula Group from Hessdalen, Sør-Trøndelag.

Localities: 1. Vårhus; 2. Vårhus; 3. Vårhus; 4. Morka; 5. Finsåhøgda; 6. Rognfjell; 7. Finsåhøgda; 8. Finsåhøgda

	Mica schist	Staurolite-mica schist				Andalusite-mica schist		
	1	2	3	4	5	6	7	8
Staurolite porphyroblasts	–	8	5	7	9	3	–	–
Andalusite pseudomorphs	–	–	–	–	–	18	27	30
Quartz	51	28	21	33	33	37	22	19
Plagioclase		8	14	9	8	–	22	13
Biotite	44	49	50	46	43	39	33	32
Muscovite	x	x	9	2	5	x	1	1
Chlorite	1	5	x	–	x	1	4	4
Garnet	–	–	x	2	x	x	–	–
Kyanite	–	–	x	x	x	x	–	x
Tourmaline	–	x	x	x	x	x	x	x
Apatite	–	–	x	x	x	x	x	–
Orthite	x	x	x	x	x	–	–	x
Rutile	x	x	x	x	–	x	x	x
Zircon	x	x	x	x	x	x	x	x
Opaques	x	x	x	x	x	x	x	x
	100	100	100	100	100	100	100	100
An-content of plagioclase			25–28	28		25–30		25

The contents of quartz listed in Table 1 were determined by means of DTA-analyses.

Biotite forms small parallel-oriented flakes with irregular outline. The darkest absorption colour is yellowish brown. The refractive index measured on flakes is: $n_y \sim n_z = 1.624$. Maximum interference colour is green of the 3rd order.

White mica appears in small amounts in the matrix, usually parallel to the foliation, but it is also seen growing across this regional foliation. A third occurrence is that within pseudomorphs after andalusite (see below). The white mica of the matrix seems to have a higher maximum interference colour (transition 2nd to 3rd order) than that in the andalusite pseudomorphs. In all probability the white mica in the groundmass is a muscovite.

Chlorite may be present in quite appreciable amounts, though the mineral is generally an accessory. Fan-shaped aggregates are seen, together with individ-

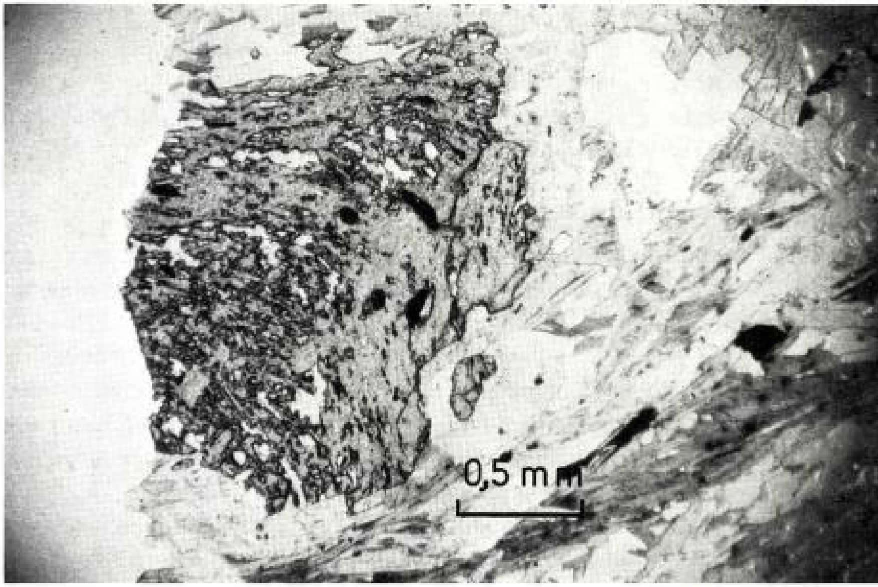

Fig. 2. Rotated syntectonic porphyroblast of staurolite. Plane polarized light. Vårhus.

ual flakes, often in intimate intergrowth with biotite. The chlorite is biaxial, is:$2V_Z \sim 15°:n_X \sim n_Y = 1.675$. Optical data indicate an Mg-rich ripidolite (Trøger 1971, p. 118).

Orthite, partly metamict, is usually the only epidote mineral present. In a few specimens, however, orthite occurs within fresh clinozoisite. *Tourmaline* may be present as small idioblastic prisms, with yellow-green absorption colours along the ω direction. *Apatite* is likewise observed as very small idioblastic grains. Opaque minerals in the schists comprise sulphide and oxide ore minerals, as well as graphite.

Staurolite, garnet and kyanite occur as porphyroblasts. In addition, andalusite was very likely initially developed as single-crystal porphyroblasts.

Staurolite occurs as idioblastic dark brown prisms up to 2 cm in size, which occasionally weather out on the exposed surfaces of the schist. Penetrative cross twins are fairly common. The staurolite prisms usally lie within the F_1 foliation planes. Under the microscope, staurolite is seen to be markedly poikiloblastic, the inclusions (mostly quartz) making up 50% or more of the crystal volume. The included grains are of distinctly smaller size than the present groundmass grains, but the textural relations between porphyroblasts and matrix are obscured by a later deformation of the matrix. It seems possible that this later small-scale deformation may have rotated the staurolite porphyroblasts somewhat after their growth. In two specimens, staurolite porphyroblasts possess curved inclusion trails indicating probable syntectonic growth (Fig. 2). In some sections, the staurolite gives the appearance of pushing aside the matrix foliation. Summing up, these various observations would seem to point to the conclusion that staurolite had a rapid, early F_1, syntectonic growth.

Measurements of refractive indices and axial angle indicate that the mineral is an Fe-rich variety (Trøger 1971).

Garnet is generally present as idiomorphic poikiloblasts, less than 0.5 cm in size. Only in one small area, at Morka, have larger garnets (2 cm) been found. Curved trails of inclusions are occasionally seen within the garnet porphyroblasts. Staurolite is sometimes included in these garnets. In most cases, garnet has grown by volume replacement, cutting the matrix foliation, though sometimes the porphyroblasts appear to push aside the matrix foliation to some degree. According to Misch (1971), where porphyroblasts are cutting the foliation and at the same time pushing it aside, this is an indication of late syntectonic to post-tectonic growth.

A garnet from Morka has been analysed chemically. This is shown to be a pyralspite with the following computed molecular composition: 63% almandine, 20% grossularite, 10% spessartite, and 7% pyrope.

Kyanite is found in several forms, indicating different modes of formation. Om Rognfjell, lenticular segregations occur (10–15 cm in length) containing approximately equal amounts of quartz and ice-blue kyanite, the latter in 2–3 cm-long prisms. Some paragonite has been indentified in these lenses by its X-ray diffraction pattern. In addition, the lenses carry a little staurolite, and occasional crystals of green apatite. These lenses are probably of hydrothermal origin, the necessary components for the mineral formation having been derived from some distant source.

A second type of kyanite occurrence is that of pseudomorphs after what is presumed to have been andalusite, especially the larger ones. This kyanite, present as slightly bent, unorientated needles, sometimes arranged in a dendritic pattern, is the result of polymorphic inversion from andalusite. A third type of kyanite is present as scattered porphyroblasts in the schist, and was possibly formed at the expense of biotite.

A particular occurence of kyanite from Finsåhøgda deserves special mention. Here the kyanite is consentrated in small (0.5 cm) aggregates in intimate intergrowth with sillimanite of fibrolite type. A few kyanite grains are completely pseudomorphosed to sillimanite mats, this clearly being a prograde replacement feature. Most of the kyanite growth is regarded by the writer as syntectonic with respect to the F_1 fold phase.

Lime-silicate rocks

Interbedded in the pelitic schists are lenses and thin layers of lime-silicate rocks. The texture of these rocks is either massive or banded with alternating

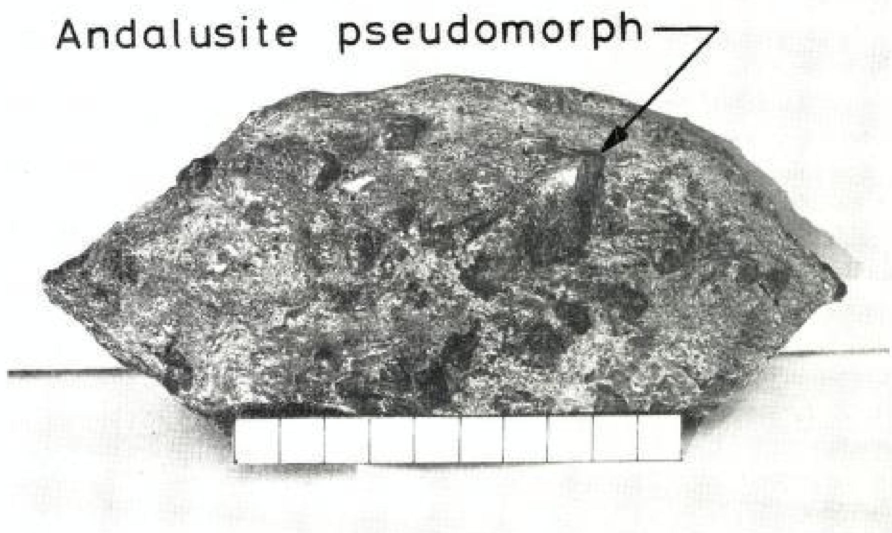

Fig. 3. Specimen of schist from the Gula Group showing one well-preserved andalusite pseudomorph, together with several staurolite idioblasts (dark bodies). Length of scale is 10 cm. From Vårhus.

biotite-rich and amphibole-rich bands. The mineral assemblages consist of plagioclase, scapolite, actinolitic amphibole, diopsidic pyroxene, clinozoisite, orthite (mostly included in clinozoisite), sphene, rutile, biotite and calcite.

The banded lime-silicate rocks conform petrographically to the lime-silicate gneiss described from the Gula Group by Goldschmidt (1915, pp. 8–21). These rocks are regionally metamorphosed calcareous sediments.

Pseudomorphs after andalusite

Pseudomorphs presumed to be after andalusite are a characteristic feature of the Al-rich pelites of northern Hessdalen. The pseudomorphs, of 1–2 cm average size, have been found in several areas (Fig. 1). They are generally light grey, with a darker brownish or bluish colour on fracture surfaces. The shape, and even the colour, of the bigger ones with sharp prismatic forms and rhombic or square cross-sections resemble that of idioblastic andalusite. In the present writer's view there can be little doubt that these light-coloured pesudomorphs were once individual andalusite crystals (Fig. 3).

Microscopic examination has shown that the andalusite is generally completely transformed to different mineral assemblages, in spite of good preservation of andalusite morphology in many cases. The pseudomorphs are easily seen within the schist matrix, with sharp borders between pseudomorphs and matrix. The foliation of the schist is in most cases wrapping around the pseudomorphs; only in a few cases is there a partial deflection of the schistosity with truncation of especially the biotite. It would appear that the andalusite formation was pretectonic to early syntectonic. This is in agreement with evidence found by Birkeland & Nilsen (1972).

Rognefjell and Vårhus are the localities where the largest pseudomorphs have been found. Locally these are quite abundant, and on Rognefjell the writer has found pseudomorphs projecting up to one cm out of the schist as a result of postglacial weathering. The largest pseudomorph measures 5 cm in length, though its prismatic shape is somewhat deformed.

In upper Gauldalen, pseudomorphs have been found containing some relict andalusite. Andalusite crystals showing little alteration have also been reported from this district (Birkeland & Nilsen 1972). In the river Hesja the writer found an erratic boulder of schist with pseudomorphs containing patches of relict andalusite. In the collections at the Geological Institute, Norges Tekniske Høgskole, Trondheim, there are specimens of brown schist with partly pseudomorphosed andalusite. Some of the specimens were found as erratics by J. H. L. Vogt in the Holtsjøen area, some 10 km to the north-east of the present area. One specimen is from Hessdalen, collected by R. Jakobsen Sørby.

It is clear that, in upper Gauldalen, the andalusite shows different degrees of alteration from very litle change to complete replacement. In Hessdalen, however, the impression is that the andalusite crystals are all completely altered to multiphase, multicrystal pseudomorphs (classification according to Spry 1969, p. 91).

The pseudomorphs in the three modal-analysed specimens (Table 1, Nos. 6–8) all show complete alteration. In these particular specimens the pseudomorphs, which are about 0.5 cm in size, have elliptical outlines and sharp borders against the matrix. The dominant replacive minerals are white mica (ca. 50%, mainly paragonite) and chlorite (30–40%); some individual grains of quartz are present as well as the accessories biotite, apatite, tourmaline and ore minerals. It is likely that quartz and some of the accessories are primary inclusions in the originally poikiloblastic andalusite. The micas show no directional growth and display a mesh-like texture.

The size of the white mica is on the average 200 μ, maximum 400 μ. Shapes are rather irregular, with a tendency to elongated flakes. The chlorite, of similar size, is pale green with a faint pleochroism. Its optical properties include $2V_z = 15°$; $n_{xy} = 1.616$; normal interference colours. It is probably the same phase of chlorite growth as that occurring in the matrix. The size of quartz and other mineral grains is in the range 10–100 μ.

Thin-sections of the above-mentioned 5 cm-sized pseudomorph from Vårhus exhibit a different mineral assemblage. Andalusite is again lacking, but on the other hand kyanite is present, irregularly distributed. In some places kyanite occurs in a dendritic pattern as slightly bent needles, while in other areas of the thin-sections kyanite is observed as scattered grains embedded in white mica (Fig. 4). White mica is quantitatively (50%) the most important mineral besides kyanite. Chlorite is absent, and the amount of quartz is less

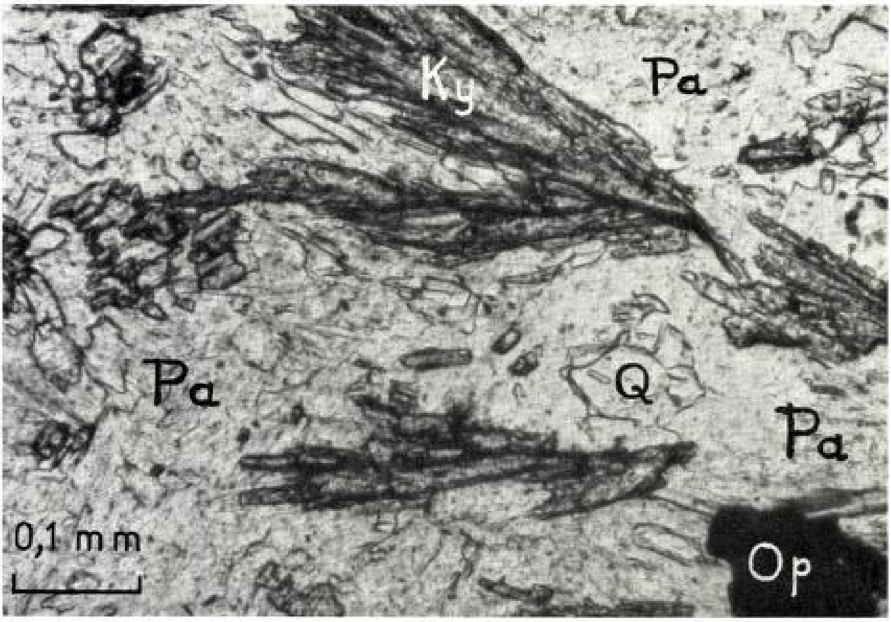

Fig. 4. Photomicrograph of part of a 5 cm long pseudomorph from Vårhus. Kyanite (Ky) is partly altered to a uniform mixture consisting mostly of paragonite (Pa) with a little muscovite. Q and Op are grains of quartz and opaque minerals, respectively.

than 10%. The mutual kyanite-white mica relationship seems to indicate that white mica replaces the kyanite. This presumed formation of the white mica, i.e. paragonite, from kyanite is more advanced in some parts of the pseudomorph, however, than in others.

Kyanite may be detected with the naked eye in hand specimens of some pseudomorphs. As a general rule the larger pseudomorphs carry kyanite.

Examination of paragonite

The larges pseudomorph found (described above) has been crushed and the white mica separated, with a rather poor result. This material, together with unseparated material from other pseudomorphs, has been analysed by X-ray diffraction, using CuKα-radiation. The goniometer was manually operated, with fixed time countings of impulses. The results are given in Table 2. Specimen 1 is poorly separated material, and specimens 2–6 unseparated. The four strongest and best defined reflections obtained in all runs are the basal reflections shown by specimen 1. There is practically no difference in the basal spacing of paragonite from different localities as shown by the d (002) values, indicating a constant Na-content of paragonite from the area. Specimens 2–6 all have clear, well defined reflections for the other three planes, (004), (006) and (0010), with values in very close agreement with those from specimen 1.

Table 2. X-ray diffraction data for paragonite from pseudomorphs after andalusite. For three specimens d (002) data for co-existing moscovite are listed.

Spec.nos.	Localities	hkl	Paragonite d	Muscovite d
1	Vårhus	002	9.65	10.07
		004	4.82	
		006	3.21	
		0010	1.92	
2	Rognfjell	002	9.65	10.09
3	Rognfjell	002	9.64	
4	Finsåhøgda	002	9.65	
5	Vårhuskjølen	002	9.63	10.06
6	Vårhus	002	9.64	

In some specimens muscovite has been detected, chiefly by the (002) reflection, this showing a somewhat larger basal (002) spacing than paragonite (Fig. 5). There is reason to believe that small amounts of muscovite are always present in association with the paragonite.

Axial-angle measurements on specimen 1 have been carried out on a U-stage, giving 2V values in the range 46°–48° (10 measurements). This is a higher angle than reported earlier (Harder 1956, Neathery 1965, Deer et al. 1966).

Metamorphism

The porphyroblastic growth of andalusite presents a problem of its own, recently discussed by Birkeland & Nilsen (1972). These writers connect the andalusite growth in upper Gauldalen with contact metamorphism associated with gabbro intrusion.

The gabbro body situated closest to the present area is the Øyungen gabbro, with a surface outcrop of about 45 km², a few kilometres to the south-west (Fig. 1). The distance from the nearest contact of this intrusion to the areas with the most intensive andalusite formation at Vårhus and Rognfjell is 5 km. It does not seem very likely that the thermal influence of the Øyungen gabbro should have such a profound effect at this distance from the intrusion border. Any possible thermal effects from the Eide quartz-diorite may be discounted, as this is not a homogeneous intrusion but rather a concentration of quartz-diorite sills and dykes (Flatebø 1968).

If one considers the growth of andalusite in the Hessdalen area to be a contact metamorphic phenomenon, then one must necessarily postulate the subsurface presence of instrusive bodies. Geophysical evidence does, in fact, indicate the location of a deep-seated magnetic body in the area between

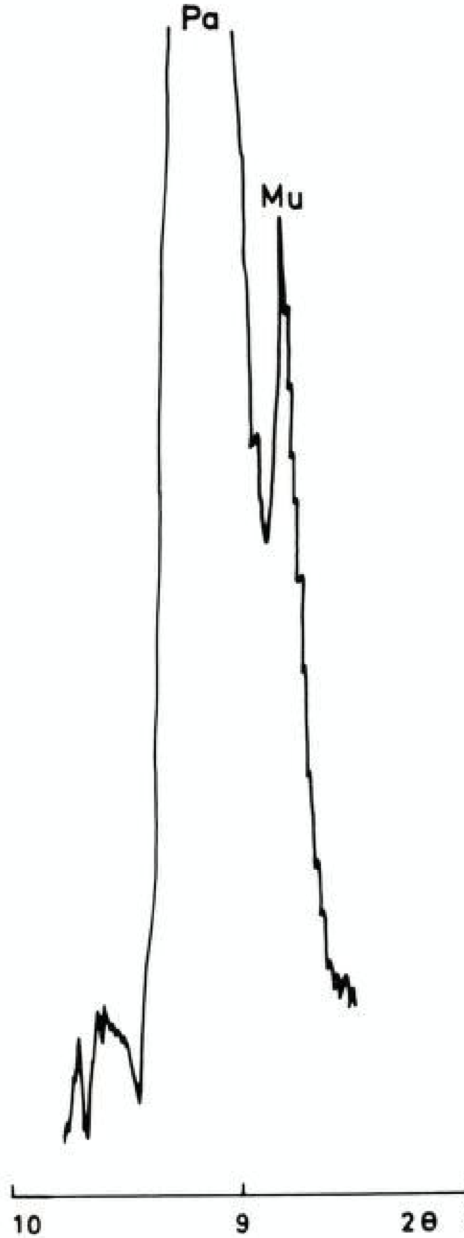

Fig. 5. Diffractometer traces over (002) peaks for co-existing paragonite and muscovite, using CuKα-radiation. Same specimen as in Fig. 4.

Finsåhøgda and Rognfjell (K. Åm, pers. comm.) The aeromagnetic map Haltdalen, issued by the Geological Survey of Norway, shows the presence of a marked but somewhat subdued magnetic anomaly along the eastern side of Hesja (Fig. 6). The cause of this magnetic anomaly is most likely a subsurface gabbroic instrusion carrying magnetite.

Exposed gabbros in the eastern Trondheim Region are known to have different magnetic properties. The Øyungen gabbro shows no magnetic anomalies,

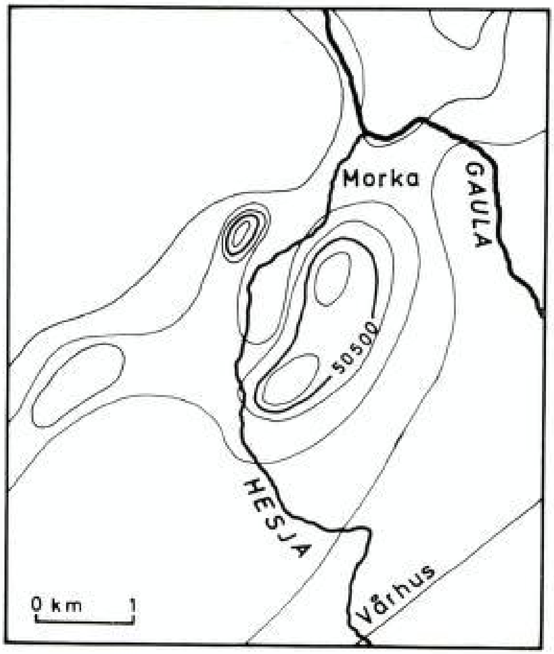

Fig. 6. Part of the aeromagnetic map Haltdalen (1620 I) showing the location of two magnetic anomalies on either side of the river Hesja. Intervals between isomagnetic curves are 100 gamma.

while the large Fongen gabbro lying some fifty kilometres to the north of the investigated area is markedly magnetic.

From the available evidence, it thus appears probable that the andalusite growth occurred in the contact aureoles of gabroic bodies, this perhaps giving some of the clues to the intensive andalusite porphyroblastesis. The relatively large size of the andalusite crystals suggests that a situation of steady heat flow may have occurred in the schists. The schists with pseudomorphs after andalusite thus seem to represent parts of a former contact aureole of hornblende–hornfels facies presumably lying above a zone of high-grade K-feldspar-cordierite-hornfels facies (Birkeland & Nilsen 1972). The vertical distance down to the presumed deep-seated gabbro could be 2–3 kilometres.

The contact, low-pressure metamorphism which is here proposed to be associated with gabbro emplacement at depth, was pretectonic to early syntectonic with respect to the F_1 deformation phase. This locally restricted metamorphism was followed by the regional high-pressure metamorphism broadly synchronous with the F_1 phase. The progressive regional metamorphism terminated in most parts of the area in the staurolite-almandine subfacies. In one part, Finsåhøgda, the sillimanite-almandine-orthoclase subfacies was probably imposed on the staurolite-almandine subfacies by a partial rise of temperature in the post-F_1/pre-F_2 static phase, the confining pressure remaining constant.

The paragonitization

The disorientated growth pattern of paragonite, sometimes in intimate intergrowth with chlorite, is indicative of a post-F_2 static formation of the mineral. The chlorite of the andalusite pseudomorphs is probably of the same type as that in the matrix, where chlorite certainly is a retrograde phase. It is very likely therefore, that even the white mica, including paragonite, crystallized during diaphthoresis.

Paragonite occurs either together with, or without, kyanite. A few thin-sections of schist from outside the investigated area containing preserved primary andalusite display white mica; however, X-ray analysis has revealed this to be mainly muscovite, possibly with a little paragonite. Some kyanite is also observed, and it seems most likely that paragonite has formed at the expense of kyanite and not directly from andalusite. This means that, in general, andalusite in the first place inverted to kyanite as a response to prograde metamorphism. The formation of paragonite then proceeded as a transformation of kyanite during the waning phase of regional metamorphism. The pseudomorphs have thus acquired their present mineralogy by a two-stage transformation process. The formation of andalusite with subsequent pseudomorphosis to kyanite and later on to paragonite is thought to have progressed as a broadly continuous process during the main Silurian phase of the Caledonian orogeny.

It is the impression from the present investigation in the Hessdalen area that paragonite is exclusively connected with aluminium-rich milieux, deriving its sodium from matrix plagioclase. This appears to be valid for the pesudomorphs, as well as for the kyanite lenses on Rognfjell, and shows that the chemical conditions were not suitable for the formation of paragonite in the schist groundmass.

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