POLYPHASE METAMORPHISM IN THE GRANULITE FACIES TERRAIN OF THE RISØR AREA, SOUTH NORWAY

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The tectonic and metamorphic evolution of this Pre-Cambrian complex is discussed in terms of field relationships and petrofabrics. Events are summarized in tabular form and correlated with those in the Amphibolite facies terrain immediately to the north.

Doleritic sheets, originally intruded into metasediments, now form a 'Pyribolite Series' showing a variety of assemblages inherited from successive metamorphisms. An 'Arendalite Series' of charnockitic, enderbitic and more intermediate lithologies is thought to have formed by Granulite facies alteration of pre-existing metasediments and migmatites. This metamorphism produced a complex of Pyribolites, Arendalites and metasediments which were subsequently intruded by basic rocks and underwent prolonged Amphibolite facies alteration. Regional granitisation converted many of the metasediments to rocks of general granitic aspect and obliterated most major structures.

It is suggested that the Granulite facies metamorphism was part of an orogenic episode pre-dating the Sveconorwegian Regeneration which produced the late granitisation: radiometric work appears to lend some support to this hypothesis.

X-ray diffractometry and microscope studies demonstrate the disequilibrium state of potassium-rich feldspars in the granitised rocks and the Arendalites.

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Introduction

The Granulite facies rocks south of Risør represent the northern limit of Bugge's 'Arendalite Series' or 'Arendal Charnockites' (Bugge 1940, 1943, 1960). Recently isolated occurrences of 'Hornblende Granulite' assemblages have been described from the Vegårshei district, to the northwest (Touret 1967a) and from eastern Bamble, to the northeast (Morton et al. 1970).

The metamorphic history of the present area is complex and the distinct Granulite facies character of rocks studied by Bugge in the Arendal region has here been partially overprinted by later metamorphism and granitisation. A large normal fault along Sandnesfjorden (Fig. 2) separates the present area from Amphibolite facies rocks to the north: the latter have a similar metamorphic history which is less dramatically revealed, since it involved the overprinting of successive maxima of Upper Amphibolite grade (Starmer 1969a).
Bugge’s investigations (1940, 1943) suggested an ‘Arendalite Series’ which was subdivided into ‘acid’, ‘intermediate’ and ‘basic’ divisions. The ‘acid division’ consisted of ‘quartz-hypersthene diorites, charnockites and biotite – or hornblende granites’. The ‘intermediate division’ included ‘quartz norites, quartz-hypersthene diorites and different mangeritic and monzonitic rocks’ and in particular included the type ‘arendalite’ (s.s.) a ‘quartz-hypersthene diorite with acid antiperthitic plagioclase’. The ‘basic division’ consisted of gabbros, norites, hornblende norites and amphibolites. The whole series was thought to result from in situ transformation of pre-existing lithologies with the preservation of relict structures.

Within the present area an ‘Arendalite Series’ corresponds to rocks of Bugge’s ‘acid’ and ‘intermediate’ divisions. This group of lithologies includes charnockitic and enderbitic types but the term ‘Arendalite’ has been retained because they are fundamentally different to charnockitic rocks from many other regions. As de la Roche (1967) concluded in his study of charnockitic suites, ‘la nomenclature spécifique reste préférable à une nomenclature systématique’.

The basic lithologies form a distinct group, sometimes occurring as remnants in the Arendalites. Migmatisation effects have, however, produced intermediate rocks and to this extent the whole series is represented. The basic lithologies formed from intrusives emplaced before the development of the Arendalites and probably corresponding to Bugge’s older hyperites. They are now represented in general by plagioclase – hornblende – pyroxene assemblages which have been termed ‘pyribolites’ in other metamorphic
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Potassium feldspar studies

The obliquity (Δ) and disorder in potassium-rich feldspars of the Arendalites and Granitised Series are seen to reflect a state of disequilibrium in many of the rocks.

X-ray diffractometry studies were performed on hand-picked crystals and on several parts of larger porphyroblasts and augen. Fig. 3 shows a few selected diffractograms of these feldspars.

There is a great variation in obliquity but most are near-maximum microcline (Δ > 0.75) or low obliquity forms (Δ < 0.2) with few intermediate

Fig. 2. Structural map of the area.
types. Many are perthitic or cryptoperthitic with lattice angles indicative of low-albite as the perthite phase.

Most crystals show some degree of 'random disorder' (Christie 1962) giving diffuseness from domains of variable obliquity rather than sharp intensity peaks. The least severe effects are the production of an 'RD' background and broadening at the bases of the $131/1\bar{3}1$ peaks. Some are 'RD' feldspars composed of small domains of varying obliquity and producing diffuse reflections in the 2.8–3.1 Å range. Many have small $131/1\bar{3}1$ peaks superimposed on this diffuse background with twin reflections indicating a dominance of high obliquity domains – RD(M) types, and single peaks showing a dominance of low obliquity domains – (O)RD types. RDM and ORD types are also common with a diffuse RD background but more distinct $131/1\bar{3}1$ peaks or a single peak, respectively.

Highly ordered, low obliquity orthoclase (type O) has not been found. Maximum or near-maximum microcline (type M, $\Delta > 0.75$) is common, giving twin $131/1\bar{3}1$ peaks and an insignificant RD background. In Arendalites and the Granitised Series, late replaceive crystals ($2\nu = 75–80^\circ$) are always of this type and have well-developed grid-twinning.

Feldspars of types RDM and RD (M) characteristically have irregularly developed, diffuse and shadowy tartan effects within single crystals. Undulatory extinction is also common. There is evidence that some RD(M) microcline in the Arendalites has inverted from crystals with uniform low obliquity (probably of types ORD or O) but there is no reason to suppose that all were originally of this type, and many may have initially been replaceive RD forms.

Details of the potassium-rich feldspars are discussed with the lithological descriptions, but in general they show great variability and appear to have been 'frozen' in a metastable state, partly induced by their replacement origins. The variation, often within a single crystal, is thought to result from local differences in microscopic environment, particularly in chemical conditions and fluid concentration. The type M rims on some crystals reflect a higher degree of ordering associated with adjacent recrystallisations and late fluid activity.

Descriptions of lithologies

*The Intrusive 'Hyperites'*

Intruded into the metamorphites are a series of troctolitic-noritic-gabbroic bodies which have developed corona growths and amphibolite. They are part of a regional differentiation series recently described by the author (Starmer 1969b) and only a few relevant features will be summarized here.

The large coronite mass at Laget is a troctolitic gabbro grading to olivine gabbro in its eastern end and in a small eastern satellite. In contrast with similar bodies in areas to the north, amphibolite on the margins is extremely thin but has developed adjacent to pegmatites and in a series of N-S trending
shears. A rutile vein to the west of the main body is genetically related to it and a late, somewhat sheared, olivine-free gabbro emplaced on its western flank has produced an adinole. (Augen gneisses and aplitic granites have been altered to a gneiss of quartz, andesine, antiperthite, rutile and sphene with minor magnetite, biotite and diopside.)

Exposures of noritic troctolite coronite to the southeast (map 1910, 2528) are more heavily amphibolitised and seem to have been discordant dikes now surrounded and broken by augen gneisses. Similar dikes on the northern shore of Risøya (map 4058) and to the northeast (map 5241) contain a small amount of primary augite; they show only limited amphibolitisation but have developed late biotite as a series of minute crystals aligned in the plagioclase cleavages. To the southwest of Laget, olivine-norite rocks have formed larger, discordant masses which have been heavily amphibolitised, and show a similar set of orientated inclusions (Rodwell 1968).

The Metasedimentary Series

Metasediments occur in the north and to a limited extent in the east, but elsewhere the same rocks are found as remnants in the Arendalites and the Granitised Series. Several distinct types are recognisable and a few modes are presented in Table 1.

Most of the metasediments have a late biotite fabric associated with the early stages of regional granitisation: the mica may be disorientated or strongly lepidoblastic and accompanied by form-orientated quartz. Granitisation caused the development of potassium feldspars in the metasediments. Effects were of variable intensity and 'granitic' gneisses often contain remnant bands of metasediment or layers rich in quartz, biotite, sillimanite or graphite.

A green, fine-grained calc-silicate horizon runs through Laget and along the shore of Sandnesfjorden. Quartz, diopside and subordinate magnetite, with or without plagioclase (An34–48) form a granoblastic mosaic which has been overprinted by a quartz-actinolite – (plagioclase) fabric and later phlogopitic biotite (Plate 2; A–D). The original, static mosaic was very fine-grained (often < 0.2 mm) but diopside was sometimes larger and poikiloblastic, enclosing small crystals of quartz, magnetite and plagioclase (Plate 2; A). Apatite and sphene are common accessories and certain layers contain orthopyroxene or grossularite.

Actinolite developed from diopside throughout a rock, or in layers and patches. It formed aggregates, subhedral crystals or poikiloblasts (occasionally also of hornblende) which contain a fine quartz-diopside-magnetite mosaic. When effects were extreme, the rocks acquired a new, granoblastic or lepidoblastic fabric of actinolite, quartz (plagioclase) and magnetite; the result of prolonged alteration which was sporadically dynamic. Late phlogopitic biotite grew from actinolite and diopside with some resorption of magnetite. Where it formed a strongly lepidoblastic fabric, this was often oblique or even perpendicular to earlier actinolite growths (Plate 2; D).
Table 1. Typical modal analyses.

| Specimen          | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 |
|-------------------|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| Plagioclase       |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Antiperthite      |    |    |    |    |    |    |    | 12.7| 10.1|   |    |    |    |    |    |    |    |    |
| Myrmekite         |    |    |    |    |    |    |    | 3.3 | 4.1 |   |    |    |    |    |    |    |    |    |
| K-feldspar        |    |    |    |    |    |    |    |    | 27.6| 10.  |   |    |    |    |    |    |    |    |
| Perthite          | 38.0| 30.6|    |    |    |    |    | 17.9| 27.6| 31.2|    |    |    |    |    |    |    |
| Quartz            |    |    |    |    |    |    |    |    |    | 4.7  |    |    |    |    |    |    |    |
| Orthopyroxene     |    |    |    |    |    |    |    |    |    |    | 13.1|    |    |    |    |    |    |
| Clinopyroxene     | 21.6| 22.1|    |    |    |    |    | 13.0| 22.1|    |    |    |    |    |    |    |
| Hornblende        |    |    |    |    |    |    |    |    |    |    |    | 12.7|    |    |    |    |
| Biotite           |    |    |    |    |    |    |    |    |    |    |    |    | 4.3  |    |    |    |
| Iron ore          | 6.6 | 5.5 |    |    |    |    |    |    |    |    |    |    |    | 1.0 |    |    |
| Garnet            | -  | -  | 6.7 |    |    |    |    |    |    |    |    |    |    |    | 0.5 |    |
| Actinolite        |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    | 2.0 |    |
| Sillimanite       | -  | -  | 15.6| -  |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Cordierite        | -  | -  | 22.6| -  |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Muscovite         | -  | 0.8 | -  | -  |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Apatite           | tr. | 0.3| 0.3 | 0.8| 0.5| 1.2| 0.8| 0.2| 0.3| 0.2|    |    |    | 1.2 |    |
| Zircon            | tr. | tr. | tr. | tr. | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  |

Total            | 100.0| 99.9| 99.9| 100.0| 100.0| 100.0| 99.9| 100.0| 100.0| 100.0| 100.0| 100.0| 99.9| 100.0| 99.9| 100.0| 100.0|

Metasediments 1-4, Pyribolites 5-9, Arendalites 10-16, Granitised Series 17-19. 1 Calc-silicate with phlogopitic biotite. 2 Calc-silicate with almost complete alteration of diopside to actinolite and biotite. 3 Slightly granitised biotite quartz-cordierite-sillimanite gneiss, south of Laget. 4 'Border migmatite' from islands SE of Akvåg-garnetiferous quartz-plagioclase-biotite gneiss with potassium feldspar. 5 Two-pyroxene granulite with a little hornblende. 6 Orthopyroxene-granulite. 7 Pyribolite (s.s.). 8 Pyroxene amphibolite with garnet, biotite and quartz. 9 Biotite-amphibolite with quartz. 10 Granoblastic charnockitic Arendalite with little retrogression. 11 Garnetiferous charnockitic Arendalite with biotite. 12 Retrogressed charnockitic Arendalite. 13 Retrogressed enderbitic Arendalite. 14 Garnetiferous quartz-enderbite (Arendalite). 15 Quartz-hypersthene syenite. 16 Quartz-hypersthene diorite. 17 Quartz-monzonitic augen gneiss. 18 Granoblastic granitic gneiss. 19 'Basic facies' gneiss of the Granitised Series.
A variable series of medium-grained biotite-quartz schists and gneisses, containing varying amounts of plagioclase, occur along the Sandnesfjorden and Skagerrak coasts and as remnants in the central granitised district. Good marker horizons are provided by thin quartzitic, sillimanitic and graphitic layers. Many contain garnet and/or cordierite, the presence of one or both being controlled by the Fe/Mg ratio of the rock. The garnets are almandine-pyrope varieties containing 59–72% Alm. and 12–31% Pyr. Purple-pink crystals, particularly diagnostic of sillimanitic and graphitic rocks, are characteristically poor in calcium relative to red-brown types which may contain 2.5–5.6% And. and 2.5–8.6% Gross.

The plagioclase (An_{38-44}) has frequently developed patch antiperthite and myrmekite, especially in granitised lithologies. Magnetite and apatite are constant accessories and graphitic horizons contain pyrite.

Sporadically throughout the area, biotite-quartz-plagioclase gneisses, which carry a little orthopyroxene, tend towards the assemblages found in biotite-rich enderbitic rocks of the Arendalite Series.

Granitised biotite-quartz-cordierite-sillimanite gneisses are enclosed by 'granitic' augen gneisses in a valley southeast of Laget (map 0228). To the northeast, this horizon occurs only as remnant lenses and nebulites but reappears to the west of Hope (map 3711) and grades into quartzitic variants. Similar gneisses through Laget (map 0315) carry plagioclase instead of sillimanite. In all of these rocks, pinitised cordierite, sericitised plagioclase and sillimanite (where present) are enclosed in a quartz mosaic with later phlogopitic biotite partly derived from cordierite.

The 'border migmatites' of Bugge (1943) are represented on islands south of Akvåg (map 5353). Here garnetiferous plagioclase-quartz-biotite gneisses have developed potassium feldspar and grade into charnockitic rocks containing hornblende and biotite in addition to the typomorphic pyroxene. A sublepidoblastic to granoblastic mosaic of quartz, plagioclase (An_{38}), RD(M) feldspar and garnet is overprinted by a lepidoblastic biotite-quartz fabric. The biotite, some of which has developed from garnet, cuts plagioclase but is eroded by a phase of late, replaceive quartz and microcline commonly found in the Arendalites.

The Pyribolite Series

In the central area, Pyribolites occur as major bands alternating with granitised rocks: in the metasediments they occur as layers which are generally concordant to the segregation banding and lithological variation, but also show cross-cutting relationships. Thin-section and field observations suggest they were originally basic intrusives rather than interstratified sedimentary layers.

Essentially the Pyribolites consist of dark-coloured, plagioclase-pyroxene-hornblende lithologies in which the felsic minerals and segregations have a characteristic green or green-brown coloration. The locally variable intensity of a number of metamorphic recrystallisations has produced a somewhat
random distribution of pyroxene-granulites, pyribolites (s.s.) pyroxene-bearing amphibolites and quartz-biotite amphibolites. Magnetite and apatite are constant accessories (a few modal analyses are presented in Table 1).

Pyribolites are cut by both Arendalites and granitic rocks and occur as nebulites, xenoliths, layers and broken fold-hinges in these lithologies (Plate 1; A). Towards the contact with Arendalites the basic enclaves frequently show a marked increase in the modal proportions and sizes of orthopyroxenes. Contamination by xenoliths and xenocrysts of Pyribolite led to some hybrid, intermediate rocks of quartz-hypersthene diorite composition.

Late granitisation produced augen gneisses rich in hornblende and biotite and caused some Pyribolite bands to thin along the strike.

Coronite textures are locally well-preserved (e.g. in the broad Pyribolite band west of Akvåg – map 3730) and show that the original intrusives were gabbroic or doleritic with augites and labradorite laths of about 3 mm size. The primary pyroxenes were subhedral with schiller and exsolution lamellae and some had simple twins. In contrast to the later ‘hyperite’ coronites (Starmer 1969b) these rocks have the characteristic coloration of the Pyribolite Series and the primary augites were replaced by aggregates or elongate fingers of ortho- and clino-pyroxene (with associated magnetite resorption) before the growth of enclosing hornblende coronas (Plate 2; E, F). Rarely orthopyroxenes have partially or completely pseudomorphed primary augite twins. (Later green-brown hornblende developed from both primary and secondary pyroxenes and caused internal replacements, particularly along cleavages. Around magnetite a little biotite grew before being surrounded by similar hornblende. Primary labradorite laths tended to recrystallise to granoblastic andesines. Where laths persisted they developed myrmekite and patch quartz during hornblende growth.)

Specimens collected from a conformable Pyribolite band in a metasediment sequence at Hope (map 4812) have been dated by O’Nions et al. (1969). Amphibole K-Ar determinations yielded ‘ages’ of 994 ± 31 m.y. for an amphibolitised ‘hornblende-plagioclase gneiss’ (SN 70) and 970 ± 30 m.y. for less altered patches of ‘metagabbro’ (SN 71). The latter rock contained relict augite with incipient chloritisation and partial conversion to hornblende; it had a ‘palimpsest igneous texture’ and was described as ‘an incompletely amphibolitised pre- or synkinematic gabbro’ (O’Nions et al. 1969, p. 186).

Plate 1. Field-relationships and fold styles. A. D3 boudinage and tightening of F2 fold (foreground): Pyribolite in Arendalite (4 cm = 1 m). B. Sharp aplitic contact of augen gneiss (left) and Arendalite (right) with pink feldspars developed in latter (4 cm = 1 m). C. F1 isoclinals with fully penetrative S1 foliation. D. F2 fold picked-out by quartzo-feldspathic layers with S2 axial planar foliation in hinge zone. E, F. F5 folds: E in Arendalite with relict mafic layer. F in biotite-quartz-sillimanite gneiss. G, H. Granitised Series: A few small augen developed in G and larger potassium feldspar porphyroblasts in H. J. Granitic pegmatite vein in Pyribolite with chilled-margin and dilation effects on coarse quartz-plagioclase vein.
The intrusives underwent varying degrees of conversion to pyroxene-
granulites before the Amphibolite facies hornblende growths. A few were
apparently pyribolitic (s.s.) at the metamorphic climax, hornblende forming
part of the granoblastic mosaic with pyroxene and plagioclase: in most the
hornblende developed later.

The pyroxene-granulites had static granoblastic fabrics and contained
calic andesine (An₄₁–₉₀), pyroxenes and magnetite, occasionally with a
little quartz and hornblende (Plate 2; H). Orthopyroxenes were of hyper-
sthene or less common bronzite compositions (En₆₀–₇₄) and clinopyroxenes
were diopsidic augite. Although usually aggregated together, often with a
common hornblende rim, the two pyroxenes sometimes segregated into
layers about 1 cm wide.

The granulite mosaic has yellow veinlets in fine, hair cracks and inter-
granular films, but this phenomenon is not observed in heavily amphiboli-
tised types where the fabric has recrystallised. Similar features occur in the
Arendalites and are discussed in that section.

Some massive, two-pyroxene granulites and rarer orthopyroxene granu-
lites were preserved without significant later alteration (Plate 2; H) but most
rocks were strongly affected by prolonged Amphibolite facies metamorphism
and formed pyribolites (s.s.), pyroxene amphibolites and amphibolites. Or-
thopyroxene was completely replaced before clinopyroxene, an effect fre-
quently observed in composite aggregates. A few rocks containing only or-
thopyroxene probably represent altered orthopyroxene granulites.

Green-brown hornblende grew in the rocks and where effects were in-
tense, resorbed pyroxenes were surrounded by a new mosaic (normally 2–4
mm grain size) of sodic andesine, hornblende, quartz and magnetite. Some-
times hornblende (and less frequently the whole fabric) was lepidoblastic
with larger porphyroblasts elongated in the foliation. Quartz, exsolved dur-
ing hornblende and garnet growth, filled lobate margins, or was irregular
and frequently included in plagioclase, garnet and amphibole.

Garnetiferous amphibolites, some containing a little resorbed diopside,
have only been found between Laget and Sandnes (map 2013–4513). The
garnets, unlike those in the Arendalites, were products of the amphibolitis-
tion and were not Granulite facies minerals. Poikiloblasts enclose quartz,
magnetite and rarely partially resorbed hornblende and pyroxene. They are
often concentrated in certain layers but in some rocks, poikiloblastic garnets
have coalesced as spongy growths over areas of 10 cm², or more, and com-
prience up to 50% of the mode. The static-growth garnets are red, almandine-
pyrope varieties but some have grossularite contents reaching 15–20%.

Sporadically amphibolites were affected by local, but nevertheless intense,
Lower Greenschist retrogressions before the growth of late biotite fabrics.
Hornblende was chloritised to clinochlore (rarely penninite), or was partially
altered to bastite.

Biotite growth from hornblende, pyroxene and garnet, was particularly
marked in the more heavily-amphibolitised rocks (Plate 2; G) The laths
were occasionally mimetic to previous grain boundaries or completely irregular, but frequently lepidoblastic and accompanied by form-orientated quartz. Biotite-rich schists developed along internal shear planes and at the margins of Pyribolite bands, especially adjacent to granitised rocks. Later prehnite growth in biotite cleavages split the laths apart and there was some chloritisation.

The Pyribolite Series shows various stages and processes of granitisation. The recrystallisation of plagioclase to more sodic forms, observed during amphibolitisation, was continued and produced sodic andesines and antiperthites. Myrmekite and quartz reaction rims formed extensively against potassium feldspars and microperthites which now started to grow. The latter sericitised and replaced all stages of the plagioclase recrystallisations, but apparently accelerated them. Biotite growth was an early effect of the granitisation, but continued during and after the less extensive growth of neosome quartz and potassium feldspar. Laths were included in some of the latter minerals and in the more-sodic plagioclase.

Granitisation often formed a distinctive ‘marginal facies Pyribolite’ with a dark matrix and large, pink potassium feldspar and white plagioclase porphyroblasts and augen. This lithology may be from one to twenty metres in width and trace for several kilometres along the strike, nevertheless grading rather abruptly (within a few centimetres) to Pyribolite on one side and augen gneiss on the other. Its formation from Pyribolite can be traced outwards: plagioclase first recrystallised to porphyroblasts and augen (often antiperthitic) and the rock was enriched in small quartz crystals. Potassium feldspars then developed and nearer to the augen gneiss formed large porphyroblasts and augen (frequently perthitic). The mafics gradually broke down to biotite, remnant hornblende often becoming almost colourless (in thin section) and pyroxene disappearing.

The evidence presented shows that intrusive gabbroic or doleritic sheets underwent metamorphism reaching Granulite (or local ‘Hornblende-Granulite’) conditions. Subsequent Amphibolite facies metamorphism was not merely a retrograde phase during ‘cooling-off’ but a prolonged alteration producing static mosaics and local fabrics with a marked dynamic character. Granitisation induced extensive biotite growth and more localised development of potassium feldspar and quartz.

The Arendalite Series

The Arendalite Series is most extensively preserved along the Skagerrak coast and forms a distinctive group of rocks characterised by a dark green-brown coloration. Elsewhere remnants within granitised lithologies are usually overprinted by pink feldspars.

Compositions range from acid to intermediate and from Granulite facies rocks (of ‘charnockitic’ type – sensu lato) to retrogressed, hornblende-biotite bearing lithologies (of granitic, granodioritic and quartz-dioritic type). With-
in this framework complete gradation exists and all varieties exhibit similar relationships towards earlier metasediments and Pyribolites and towards later granitised lithologies.

The predominant Granulite facies rocks vary between charnockitic (s.s.) and enderbitic types, the latter grading to quartz-hypersthene diorites or ‘arendalites’ (s.s.) and hypersthene diorites. All intermediate compositions are represented with developments of charnockitic adammelites, quartz-monzonites, hypersthene-quartz syenites and mangerites (charkockitic syenodiorites). Table 1 shows the typical modal variations. Hornblende, biotite and garnet, have formed in many lithologies: Apatite and magnetite are constant accessories, the latter usually being associated with the ferromagnesian silicates and their transformations.

Layers, lenses and broken fold-hinges of Pyribolite occur within Arendalites (Plate 1; A): some of the latter are themselves large remnants in granitised rocks. Occasionally granoblastic, charnockitic-enderbitic rocks have cut gneissose Arendalites and Pyribolites, incorporating xenoliths of the latter and becoming contaminated with xenocryst aggregates of pyroxene (now rimmed by hornblende). Some of the Pyribolite inclusions within Arendalite have amphibolitic centres with abundant, large orthopyroxenes developed near their margins: others show aplitisation effects and gradational contacts. Evidence suggests Amphibolite facies assemblages prior to incorporation and Granulite grade metamorphism.

Arendalites with Pyribolite layers are sometimes cut by thin dikes which could also appear to be Pyribolitic. From thin section observations they are found to be partially amphibolitised coronites related to the later phase of intrusive ‘hyperites’.

On the islands south of Åkvaq, Arendalites grade into both metasediments and Pyribolites. The former gradation (map 5353) was discussed previously and corresponds to the ‘border migmatites’ of Bugge (1943) where banded gneisses and regional migmatites ‘gradually fade into the arendalite rocks without there being a distinct border between them’. On islands just to the southwest (map 4753) pyribolite (s.s.) and amphibolite remnants grade into enclosing charnockitic-enderbitic gneisses which are locally enriched in ortho- and clinopyroxene.

Arendalites have been extensively granitised and remnants usually grade into rocks of the Granitised Series. South of Åkvaq (map 5256) granitic augen gneisses have a sharp, slightly sheared contact of thin aplites (5–10 cm wide) against Arendalites. The latter have feldspar augen and a foliation accentuated by late biotite growths, but within 20 cm of the margin this fabric has been overprinted, partly mimetically, by pink, potassium feldspars (Plate 1; B).

Some coarse veins with crystals of 1–2 cm size are genetically related to the Arendalites, traversing them and sometimes transgressing into Pyribolites (Plate 1; J). They are normally less than a metre wide but continue for up to 300 metres with markedly discordant relations towards the enclosing rocks.
Plate 3. Photomicrographs of Granitised Series rocks (A–C) and Arendalites (D–H). A. 'Shadowy microcline' developing better cross-hatching against late microcline.× 22, crossed nicols. B. 'Shadowy microcline' resorbing sericitic, myrmekitic plagioclase.× 22, crossed nicols. C. Large porphyroblast (2 cm 1g.) of low-obliquity potassium feldspar ('orthoclase') with simple-twin and including resorbed, sericitised plagioclase.× 22, crossed nicols. D, E. Mafic layers in enderbitic Arendalite: Biotite (b) included in magnetite-packed diopside with garnet (g) and hornblende (h) in D. × 22. F. Charnockitic Arendalite. Slightly perthitic 'shadowy microcline' as two halves of a relict simple-twin. Cut by one of the larger chloritic veins with smaller satellite veinlets.× 22, crossed nicols. G. Charnockitic Arendalite. 'Shadowy microcline' with better cross-hatching adjacent to late, replaceive, type M crystals.× 22, crossed nicols. H. Charnockitic Arendalite. Granoblastic quartz-feldspar mosaic with elongate hypersthene aggregate. × 20.
and interlithological boundaries. The main components are green-brown quartz, green or yellow-brown feldspars and sporadic black pyroxenes. Biotite and pink, potassium feldspars are rarely developed against granitised rocks. Some veins are bent or folded and they are cut by granitic pegmatites with marked dilation effects (Plate 1; J).

The distinctive coloration of the Arendalites, particularly the grey-green or grey-brown of quartzes and the green-brown of feldspars, is thought to result from fine, hair-like veinlets and intergranular films observed in thin sections; similar effects are also seen in the less-amphibolitised Pyribolites. The veinlets contain a yellow or yellow-green material and cut several adjacent crystals, being particularly concentrated in feldspars. Larger veins (Plate 3; F) traverse entire thin-sections and are 1–2 mm wide, carrying serpentine, chlorite or both chlorite and calcite. The nature of material in the finer veinlets and films is unknown but Howie (1967) has shown that similar features in charnockites contain an iron-bearing mineral and suggested previously (Howie 1954) that it may be a chlorite. Touret (1968, p. 27) considered that the microcracks were filled with ‘yellowish hydro-micas and clay minerals (possibly iron rich nontronites)’.

The complex metamorphic history of the Arendalites is revealed by thin-section observations. The intensity of effects varies, but in general Granulite facies assemblages of orthopyroxene, plagioclase and antiperthite (with or without potassium feldspar, microperthite, quartz, diopside and garnet) were variously overprinted by Amphibolite grade, hornblende-quartz-plagioclase mosaics. Subsequent biotite and late, replaceive microcline and quartz were associated with the regional granitisation.

The granulite facies fabric is normally the earliest preserved, but rarely pyroxene is seen to have developed from earlier biotite. (Plate 3; D & E show magnetite-packed diopside which has grown around corroded biotite.) A similar phenomenon was described from Arendalites by Bugge (1943, p. 70) and more recently by Touret (1968, pp. 26–27) from ‘charnockitic migmatites’ of the Vegårshæ district.

In the present area, poikiloblastic orthopyroxenes rarely enclose quartz and sodic andesine: coupled with evidence of earlier biotite above, this suggests genesis from Amphibolite grade rocks. This hypothesis is substantiated by the orthopyroxene-rich rims on essentially amphibolitic enclaves within Arendalites.

Unaltered Arendalites (Plate 3; H) have a mosaic of sub-granoblastic or irregular, quartz and feldspar (maximum size 6–8 mm). They sometimes show curved triple junctions suggesting stressed, static growth. Pyroxenes and magnetites occur as granoblastic grains or as elongate crystals and aggregates. In the latter case they often form a discontinuous banding, possibly reflecting an inherited, segregated fabric. Such rocks, usually of enderbitic or intermediate type, are megascopically sub-gneissic with mineral banding and a crude foliation enhanced by later hornblende and biotite. They frequently have sub-granoblastic textures on foliation planes, but in
some rocks quartz and feldspar have a dimensional orientation and may
develop large porphyroblasts and multi-crystal augen (1–2 cm in length).

Where pyroxenes and magnetites formed discrete, granoblastic crystals,
these were usually randomly distributed through the mosaic and rocks were
massive with little or no retrogression. The transcurrent charnockitic-ender­
bitic rocks are of this type and are suggestive of once-mobile, ‘granitic’ rock
which underwent later, static metamorphism of Granulite grade.

Orthopyroxenes vary non-systematically from En$_{45}$ to En$_{68}$ but are usually
within the hypersthene range, particularly in charnockitic rocks. Diopsides
occur in intermediate rocks and less commonly in charnockitic-enderbitic
types. The two pyroxenes exist either as separate, discrete crystals or in
stable association. Both normally show some retrogression to hornblende
(Plate 3; D) although this is minimal in granoblastic, charnockitic-enderbitic
rocks.

Plagioclases show a series of recrystallisations complementary to trans­
formations of the ferromagnesian minerals and particularly affected by
the growth of hornblende. Original compositions were in the calcic oligoclase-
sodic andesine range (An$_{84-38}$) with more-calcic andesine in some hyper-
sthene diorites. There is no systematic variation with rock-type, although
charnockitic lithologies normally contain oligoclase and enderbitic have an-
desine. The plagioclases are frequently antiperthitic (commonly with patch,
lamellar or hair textures). Myrmekite occurs in all rocks and can become
abundant. It is particularly well-developed against potassium feldspar and
especially around late, replaceive microclines.

The early potassium feldspars in the Arendalites are comparable with
those described from charnockites by Howie (1964) as ‘intermediate micro-
cline showing shadowy extinction and indistinct tartan twinning’. They are
frequently microperthitic (with patch, hair, film and flame textures) and
commonly have undulatory extinction. They replaced and enclosed plagio-
clase which became sericitised and myrmekitic. (Perthites and antiperthites
in the Arendalites were partly the result of replacement origins but were en-
hanced by subsequent metamorphism.) The ‘shadowy’ crystals formed be­
fore the main growth of hornblende and later biotite, but diopside and olive-
green hornblende were rarely included. This indicates that conditions were
probably of ‘Hornblende Granulite’ grade when these feldspars grew and
contrasts with similar ‘shadowy’ crystals in the Granitised Series where they
post-dated much of the biotite.

Diffractograms show that these feldspars have a large RD component
(e.g. Fig. 3, iv) and many give RD(M) traces. Where ORD and (O)RD
forms occur, they are always accompanied in the same rock by RD and
RDM types. A few of the larger porphyroblasts have Carlsbad twins with
two halves of differently orientated, shadowy RD(M) feldspar (Plate 3; F).
The composition plane is not [010] of the microclines and is almost certainly
inherited from a monoclinic form.

Cross-hatching has frequently developed on the margins of shadowy feld-
Fig. 3. Representative X-ray diffractograms of potassium-rich feldspars, showing perthite peaks in some.
(I) Late, cross-hatched, near-maximum microcline from porphyroblastic, granitic gneiss. Type M, $\Delta = 0.9$, RD nos. 6–7 (Christie 1962).
(II) Low-obliquity porphyroblast (with simple twins) from granitised, hornblende-rich rock (cf. Plate 2; G). Type ORD, $\Delta < 0.1$, RD nos. 2–3.
(III) Microcline augen from Granitised Series. Type M-RDM, with RD background, $\Delta = 0.9$, RD no. 6.
(IV) 'Shadowy microcline' from charnockitic Arendalite. Rare example of more-intermediate obliquity ($\Delta = 0.6$). Type RD(M) – strongly RD with dominance of high obliquity domains.

Garnets (most common in enderbitic and intermediate lithologies) are almandine-pyrope varieties ($Alm_{0.60-75}$, $Pyr_{12-21}$) containing minor amounts of the other end-members. Some are subidioblastic, clear crystals but most are intergrown poikiloblastically with quartz. They are always surrounded by
quartz-rich mosaics and tend to occur in layers with magnetite and pyroxene. The static garnets are Granulite facies minerals, in contrast with their development in the Pyribolites.

The post-Granulite facies metamorphism is shown in most rocks by the development of green and green-brown hornblende around pyroxene (Plate 3; D). More intense effects caused internal replacements and eventually formed a new mosaic of quartz, plagioclase and hornblende. This well-developed fabric was the result of a prolonged metamorphic phase and not of post-climactic cooling; in general it was static but locally was weakly dynamic.

Locally, retrogression of pyroxenes to chlorite and bastite has been preserved; in general, this preceded most of the hornblende growth although in one case, some hornblende was found to be marginally affected. Bugge (1943, pp. 70–72) noted similar chlorite growth in Arendalites and considered it frequently had ‘the character of a temporary product’.

In the initial stages of regional granitisation, biotite developed from pyroxene and hornblende, overprinting and growing into all pre-existing minerals, including the ‘shadowy’ microclines. Laths formed irregular growths (partly mimetic to previous crystal boundaries) or subpleidoblastic fabrics which enhanced or produced a foliation. Biotite growth started before that of neosome quartz and microcline and was more extensive, affecting many rocks in which the latter minerals never formed. It continued until late red-brown laths cut the new feldspars.

In slightly-granitised rocks, quartz and cross-hatched, type M microcline were granoblastic or elongated mimetically in the foliation (sometimes as discontinuous layers or multi-crystal fingers). These microclines do not have the pink coloration of later porphyroblasts developed during the main granitisation when most ferromagnesian minerals altered to biotite. They are grey-green and traversed by the veinlets observed in other minerals of the Arendalites. They replace plagioclase with the production of myrmekite, vein and film perthite and rare mesoperthite.

The lithologies of the Arendalite Series are similar to those in some other charnockitic terrains, but they developed by Granulite facies metamorphism of earlier Amphibolite grade rocks. Some transgressive bodies probably represent recrystallised granitic rocks which were once mobile. There is good evidence that the majority of the Arendalites were never magmatic although they all behaved plastically and ‘flowed’ around blocks of Pyribolite (Plate 1; A). Gradations with metasediments and Pyribolites suggest that the Arendalites formed by metamorphism of migmatites, and metasediments. It has already been noted that orthopyroxene-bearing metasediments show an affinity with biotitic enderbites.

The development of the early, ‘shadowy’ potassium feldspars occurred under ‘Hornblende Granulite’ conditions just prior to the metamorphic climax. True Pyroxene-Granulite grade was not attained everywhere and hornblende was still stable in some rocks at this climax.
Chemically, the Arendalites (Bugge 1943, de la Roche 1967) have low $K_2O/Na_2O$ ratios and high MgO contents compared to other charnockitic suites, particularly those suggested to be of igneous origins (e.g. from the Madras area – Howie 1954, Subramaniam 1960). De la Roche (1967) has shown that Bugge’s Arendalite Series, because of its very sodic characteristics forms a separate domain well above a three-dimensional ‘surface moyenne de la reference’ generated for the igneous rock suites.

*The Granitised Series*

A large proportion of the exposed rocks are of general granitic aspect with characteristic pink, potassium feldspars. Various types of granoblastic-, porphyroblastic- and augen gneisses have formed; different types grade into one another and all are related to a relatively late granitisation which obliterated major folds but involved no great disruption of the regional planar structure. Foliation is normally subparallel but steeper than that in adjacent rocks. Locally their overall conformity is destroyed where they transgress into Pyribolites and metasediments.

Some layers are rich in quartz, biotite, sillimanite or graphite and often grade into remnant metasediments. Relict Pyribolite layers, lenses and ghost nebulites are found throughout the Granitised Series and particularly within major bands of hornblende-rich augen gneiss, into which they grade. Distinct bands, full of such remnants, trace for considerable distances (e.g. on Risøya, map 3557). Locally disoriented xenoliths of Pyribolite suggest dislocation in a plastic medium. Arendalites are found as partially digested remnants with gradational margins, but at one locality (map 5256) discussed previously, augen gneisses have a sharp aplitic margin against Arendalites (Plate 1; B).

Specimens of augen gneisses and included Pyribolites from the present area have been radiometrically dated by O’Nions et al. (1969). Two specimens from Trollbergvika (map 7725) consist of an ‘amphibolite occurring in a sequence of augen gneisses’: the amphibolite (SN 73) yielded K-Ar ‘ages’ of 1010 ± 16 m.y. (biotite) and 1046 ± 32 m.y. (hornblende) and the ‘K-feldspar augen gneiss’ (SN 74) gave a biotite K-Ar ‘age’ of 1000 ± 16 m.y. Another ‘K-feldspar augen gneiss’ (SN 75) from Åkvåg (map 5542) gave a biotite K-Ar ‘age’ of 993 ± 15 m.y.

Thin section studies reveal the timing of the granitisation relative to transformations in the ferromagnesian silicates: they show a tendency of quartz and potassium feldspar to mimic a biotite fabric, although micas continued to grow until the end of the granitisation.

Various, slightly-altered lithologies have developed neosome quartz and RDM or RD(M) microperthites which replace plagioclase and become elongate in more foliate rocks. Later granoblastic microclines (type M) may also occur. Muscovite developed extensively in sillimanite-rich metasediments.

With more alteration, quartz, potassium feldspar and plagioclase devel-
oped a few impersistent schlieren and augen in the foliation and sporadic porphyroblasts across this fabric. Interlayer granitisation in the more-foliate rocks converted them to striped gneisses. In more advanced stages disorientated porphyroblasts obliterated intervening palaeosome layering. Independent schlieren and augen of potassium feldspar (often rimmed by quartz) then gave rocks transitional to augen gneisses. The distinct augen gneisses were formed by neosome minerals growing only as augen in the foliation, although in some, randomly orientated porphyroblasts developed later. Many rocks have only the latter type of crystal disrupting their palaeosome fabric and ultimately producing a rock resembling a coarse, igneous granite.

Interlayer granitisation and augen growth appear to have been broadly contemporaneous and to have occurred in a weak stress field. The random crystals developed slightly later, cutting across the foliation and showing no strain or deformation. The granitisation was therefore an extended process.

The resulting lithologies can be divided into ‘acidic’ and ‘basic’ gneisses. The former have a groundmass of plagioclase, potassium feldspar and quartz, normally with biotite as the only mafic. Rarely a little resorbed hornblende is present. Augen and porphyroblasts are of quartz and both feldspars. Bulk compositions vary from granitic to granodioritic, adamellite and quartz-monzonitic.

The ‘basic’ gneisses often form distinct bands but laterally grade abruptly into more granitic types. They have a groundmass of quartz, plagioclase and abundant biotite, normally accompanied by remnant hornblende in the process of alteration to mica. Augen and porphyroblasts are of plagioclase, potassium feldspar and quartz. The more basic lithologies have a dark, hornblende-rich matrix with layers and porphyroblasts of plagioclase and subordinate quartz and potassium feldspar.

Muscovite and almandine garnet are minor components of some rocks and sillimanite and graphite occur in those derived from metasediments. Magnetite and apatite are constant accessories. A few modal analyses are presented in Table 1.

Some granoblastic, granitic rocks occur as patches and bands within the Granitised Series. They have both sharp and gradational contacts with occasional transgressive relationships and are thought to have been partially fused material which was mobilised plastically or magmatically and solidified under static conditions. West of Trollbergvika (map 7529) a small dome of these rocks seems to have been diapiric: it has sharp margins against disturbed augen gneisses.

Some patches in both foliated and granoblastic rocks have an igneous appearance and were probably local anatectic material which consolidated relatively late. Bands of aplitic granite were associated with this phase and small, cross-cutting aplite veins accompanied later pegmatite activity.

Thin ‘granitic’ pegmatites (10 cm–1 m wide) have sharp or gradational contacts with surrounding granitised rocks and both types can be discordant to the foliation of the latter. They transgressed into neighbouring Pyribolites
and metasediments where they caused marked dilation effects and developed chilled margins (Plate 1; J). Most are simple pegmatites but some contain pyrite, magnetite, tourmaline and orthite.

Large, discrete bodies of pegmatite are much less common than in the Amphibolite facies area to the north (Starmer 1969a). They are concentrated (and cause local amphibolitisation) around the Laget ‘hyperite’ body which is thought to have provided a low-pressure zone to which fluids could migrate.

Plagioclase-rich pegmatites (containing quartz, biotite, hornblende magnetite and pyrite) are sporadically cut by granitic types and formed somewhat earlier by segregation effects in mafic lithologies.

Several features, already mentioned, indicate mobility and diapirism after the main metasomatism. Throughout the area, mobilised rocks have encircled broken Pyribolite layers and formed larger injections into major bands. Small scale injections of augen gneiss into Pyribolite are also common (e.g. map 3043).

Diapiric movement is evident on the margins of augen gneiss bodies on the Sandnesfjorden coast, where ridges have thin lateral veneers of Pyribolite and metasediment (e.g. map 3515). Surrounding lithologies have a disturbed foliation and often little feldspathisation. Augen were pushed together and strained with peripheral cataclasis; around them groundmass feldspar, biotite and quartz were granulated, strained and deformed. The lack of retrogression implies that these movements occurred under Amphibolite facies conditions.

Thin sections of the Granitised Series show the replacement origins of these rocks.

Augen (reaching 3–5 cm in size) developed as single crystals or as a number of interlocking grains. Palaeosome material was often pushed aside around augen and porphyroblasts and sometimes included in their margins. Plagioclase and biotite are often bent and the latter often forms muscovite reaction-rims against potassium feldspar. Palaeosome and neosome quartz (crystallised or recrystallised during granitisation) fills eroded features in biotite, hornblende and plagioclase and forms pressure- shadows on the ends of augen.

Plagioclases have sutured margins and became sericitised and myrmekitic before replacement by potassium feldspar (Plate 3; B, C). They are normally oligoclase or sodic andesine (An16–32) but may be as calcic as An40 in the more basic rocks. Compositions vary in one specimen and recrystallisation has occurred to more sodic forms with occasional marginal zoning. This process was accelerated near potassium feldspar but the latter replaces all stages. Lamellar and patch antiperthites are sporadically developed especially in the larger porphyroblasts.

Remnant hornblendes occasionally include a quartz-plagioclase mosaic with rare pyroxene; they altered to biotite and disappeared as more potassium feldspar formed.
Diffractograms and thin sections show extreme variability in the potassium feldspars. Granoblastic granitic gneisses contain small crystals of near-maximum microcline. Some have a few ‘shadowy’ porphyroblasts of RDM, RD(M) or more rarely (O)RD feldspar.

The potassium feldspars of the augen and porphyroblastic gneisses show great variability sometimes even within single, large crystals. They vary from grid-twinned forms to ‘shadowy’ types similar to those in the Arendalites, but showing later growth relative to ferromagnesian silicate transformations. Many crystals have irregularly spaced domains with sporadically developed grid-twining. Perthites are intermittently developed with film, vein, flame, patch and lamellar textures.

Larger crystals, often with fringes of myrmekitic plagioclase (An$_{16-22}$) or quartz, have varying degrees of obliquity and disorder, but most have a strong RD component. The commonest types are RD(M) and RDM feldspars ($\Delta > 0.75$). Completely RD feldspars are rare, as are well-ordered M types. A few rocks contain isolated ORD crystals, but east of Ákvåg (map 5757) in a zone of intense minor faulting, granitised, hornblende-rich rocks contain almost entirely ORD types (Fig. 3,ii). These crystals (2–3 cm in size) include and replace plagioclase and have simple, Carlsbad twins (Plate 3; C).

Some large augen and porphyroblasts have obliquity increases towards their margins, giving rims of cross-hatched near-maximum microcline. Their centres are commonly of RD type or less often of low-obliquity ORD feldspar ($\Delta < 0.2$). The same process has been stimulated where ‘shadowy’ feldspars are adjacent to late microclines (Plate 3; A) and its exact parallel is seen in the Arendalites.

The late microclines are found in all the granitised rocks as granoblastic or mimetically elongated crystals. They are always cross-hatched RDM or M types.

The Granitised Series obviously developed by alteration of extensive tracts of metasediments and some conversion of Pyribolites and Arendalites. There is no evidence of the augen gneisses having formed by shearing of pre-existing granitic rock and cataclasis observed is the result of late movements.

The conditions prevailing during and immediately after granitisation were representative of sillimanite/andalusite/orthoclase and sillimanite/andalusite/muscovite subfacies. (Where sillimanite was absorbed from the metasediments it remained partially stable but some alteration to muscovite was common in this potash-rich environment.) Very local retrogressions to Epidote Amphibolite and true Greenschist facies conditions are shown by the growth of zoisite and clinozoisite and the late development of chlorite and muscovite from biotite.

One thin band of granoblastic ‘granitic’ rock in the Sandnes metasediments (map 6111) may represent an isochemically reconstituted arkose (i.e. an ectinite) since it shows none of the features of feldspar porphyroblasts.
The evolution of the complex

The tectonic and metamorphic history of the complex is summarised in Fig. 4 and correlated with events in the Amphibolite facies terrain to the north. The area is a complex F2 anticlinorium complicated by second order F2 folds. The dominant planar elements are S2 foliations and S1 planes re-orientated by F2. Late regional granitisation, concentrated in this anticlinorium, partially obliterated major fold hinges. Analysis is therefore largely reliant on the interrelationships of minor structures.

The oldest rocks represented were metasediments into which were intruded gabbroic-doleritic sheets (the proto-Pyribolites). Original bedding (SS) is sporadically preserved in the form of graphitic, sillimanitic and quartzitic layers. Intrusions were semi-concordant to a bedding-plane foliation and segregation banding. Immediately to the north, the equivalent phase of intrusives (now amphibolite) contain disorientated blocks of foliate metasediments.

Metamorphism of Amphibolite grade converted most of the intrusives to amphibolite. Felsic and mafic gneissose banding (Sa) was developed but no details of any accompanying deformation have been recorded.

As conditions rose to Upper Amphibolite and local 'Hornblende Granulite' grade, intense deformation (D1) produced major and minor F1 isoclinals and a penetrative axial planar foliation (S1). The latter was enhanced by shearing and by much later mimetic biotite growths. Minor folds are often

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Fig. 4. The metamorphic and tectonic evolution of the complex.
difficult to recognise but careful examination of foliated surfaces reveals tight, angular hinges, often with small, angular microfolds (Plate 1; C, Fig. 5; I–III). Some are picked out by deformed, quartzo-feldspathic layers although new segregation banding also developed. Axial mineral alignment (L1) is often the cause of oblique lineations on S2 and re-orientated S1

Fig. 5. Deformation styles. (Quartzo-feldspathic layers are stippled and alignment of mafics is shown in some.) IX-shows D3 tightening of an F1/F2 refold of Pyribolite in more plastic Arendalite. XV—the interference pattern is developed on sub-horizontal surfaces. XIX—shows F6 monoclinal micro-flexures.
planes. The axes of all folds are now steep or subvertical. Major structures have been partially obliterated by F2 folding and granitisation but these F1 isoclinals had axial planes sub-parallel to the lithological banding giving essentially bedding-plane foliation.

Granitisation then formed migmatites with many retaining a mimetic S1 foliation and banding. The ‘shadowy’ feldspars of the proto-Arendalites developed at this time. Gradations produced between granitised rocks and metasediments were later to form the ‘border migmatites’.

The centres of a few larger doleritic bodies were not amphibolitised; a feature commonly observed in the later ‘hyperites’.

A second intense deformation (D2) produced tight to sub-isoclinal F2 folds with rounded or angular hinges and dihedral angles often greater than 15° (Plate 1; D, Fig. 5). The overall stress pattern seems to have been a shear couple which caused both drag-buckling and shear folding, giving pseudo-similar style folds, somewhat variable from layer to layer. There was an alternation, on both a major and minor scale, of folded belts and planar zones. F1 and S1 were refolded but a semi-penetrative to penetrative foliation and new segregation banding developed together with axial lineations and microfolds (L2). F2 axial planes were aligned in a general NE–SW or ENE–WSW direction but had variable dips. As with the F1 structures, many of these features were enhanced by much later, mimetic biotite growths.

Granitic material in the migmatites was plastic during F2 and minerals often aligned themselves parallel to S2. Basic rocks behaved more passively to the folding but in the later stages underwent boudinage.

Conditions were rising towards Granulite grade and, where water was still available, partial fusion occurred in some rocks forming transgressive mobilisates which occasionally cut F2 structures.

At the climax under static Granulite or ‘Hornblende Granulite’ conditions, the complete replacement of hornblende by pyroxene was local and dependent on the ability of rocks to completely lose their water. Amphibolites were upgraded to pyroxene-granulites and pyribolites (s.s.) and metamorphic pyroxenes grew in previously unaltered doleritic rocks. Metasediments developed diopside and rarer orthopyroxene. The Arendalites formed from migmatites and metasediments from which most of the water had been driven off: pyroxenes and garnets grew in them but a few retained remnant biotite, sodic andesine and quartz. Earlier folds were recrystallised and sometimes destroyed but frequently preserved their deformed mineral banding. The cross-cutting granitic rocks recrystallised to granoblastic charnockitic-enderbitic lithologies.

The metamorphic grade then decreased to static Upper Amphibolite or local ‘Hornblende Granulite’ conditions, depending on the activity of water. Local translation gliding (D3) occurred parallel to the S1–S2 foliation direction (the main plane of weakness) with a differential, simple-shear in a general ENE–WSW direction. Only locally were effects intense with boudinage of Pyribolite bands and encirclement by plastic Arendalite hosts; F2
folds were tightened, hinges isolated and L2 lineations bent (Plate 1: A, Fig. 5). Some hornblende probably grew at this time.

Retrogressions of ferromagnesian minerals to chlorite and bastite are still preserved in a number of rocks and may record a period of anorogeny prior to the intrusion of gabbroic 'hyperites'. These bodies in Amphibolite facies rocks to the north either cut F2 structures or partially follow them (Starmer 1967, 1969b). The intrusives developed corona growths but the degree of amphibolitisation was very variable. Noritic masses southwest of Laget were heavily amphibolitised (Rodwell 1968) as were similar dikes east of the main Laget body.

The prolonged metamorphism, which amphibolitised the 'hyperites', developed hornblende-plagioclase-quartz mosaics in Pyribolites and actinolite-quartz (-plagioclase) fabrics in the metasediments. The granoblastic, massive Arendalites were little affected by this, or later retrogressions, but in more foliate types much of the pyroxene was replaced by hornblende. In all rocks, Amphibolite grade fabrics contain both static and dynamic elements and may have grown partly during the D3 stage and partly at this time. It is difficult to separate the two growths although phlogopitic biotite related to S4 fabrics was often oblique or even perpendicular to actinolite (Plate 2; D) and may indicate two growths under different stress fields.

The S4 fabrics developed under intermittent compressions which foliated the amphibolitised 'hyperite' margins and bent the metasediments around these bodies. These compressions acted on a strongly planar rock complex and tended to flatten or tighten ENE-WSW structures. They waned during the subsequent granitisation but were sporadically revived, foliating the granitic gneisses. The S4 fabrics were therefore essentially parallel to pre-existing planar structures and often partially mimetic.

The formation of S4 biotite fabrics marked the onset of regional granitisation under Upper Amphibolite facies conditions. The biotite growth started before that of neosome quartz and microcline and affected many rocks in which the latter minerals never formed. Foliate lithologies, particularly the metasediments, were extensively altered by the granitisation, but Pyribolites and Arendalites were less affected.

Some granitised rocks were partially fused and mobilised masses occasionally developed cross-cutting relationships. The augen gneisses show evidence of plastic mobility, lubricated by pore-fluids, with later diapirism and internal deformation under Amphibolite facies conditions.

Late, aplitic granites developed (e.g. around the Laget gabbro where they and adjacent augen gneisses were later adinolised by the intrusion of olivine-free gabbro).

Subsequent folding (F5 and F6) occurred under Middle and Lower Amphibolite conditions, bending the foliation without developing any significant axial planar structure. Biotite grew on deformed foliae, often giving a strong axial lineation accompanied by microfolding and crenulation (L5 and L6).

The aplitic granites were occasionally deformed by F5 folds but later
pegmatites, aplitic veins and segregations spanned the F5 and F6 phases, generally cutting most F5 structures, but being deformed, broken and crushed by F6 folds.

F5 minor folds were of 'open' to 'close' style (Fleuty 1964) with dihedral angles usually between 40 and 80° (Plate 1; E,F, Fig. 5). Larger minor folds, with amplitudes of one metre or more, normally developed cylindrical, concentric forms with sub-vertical axial planes and E-W trending axes. Differential flattening in smaller structures produced forms approaching a pseudo-similar style. The smaller folds were more variable and were influenced in style and orientation by earlier structures and S-planes. No major structures were produced comparable with those bending elongate 'hyper-ites' in Amphibolite facies rocks to the north of Risør. F5 structures deformed the granitised rocks and refolded F1 and F2.

F6 minor folds and associated axial microfolds were 'open' or 'gentle' in style (Fleuty 1964) with dihedral angles of 60–120° (Fig. 5). Larger minor structures were concentric with subvertical axial planes and three distinct axial directions: N–S (F6'), NW–SE (F6''), and NE–SW (F6'''). Flattened smaller folds again approached a pseudo-similar style. Small foliation flexures were normally monoclinal with dihedral angles of 90–120° (Fig. 5).

In contrast with the area immediately to the north, NW–SE (F6'') axial directions predominate over N–S (F6') and neither form major structures. Their relative ages vary, but the less common NE–SW (F6''') folds were clearly later. On the islands in Sandnesfjorden, F6' structures refold F5 folds and F6'' refold F2.

The D6 structures reflect a series of tectonic pulses in a somewhat variable stress field with an overall E–W compressional component. Late shearing and fracturing in F6 folds occurred as the grade decreased to Greenschist conditions which accompanied the major faulting. Chlorite and epidote grew adjacent to shear zones but elsewhere retrogression was minimal. Immediately to the north, dextral NE–SW and sinistral NW–SE wrenches preceded normal faults (Starmer 1967). Only the latter phase has been found in the present area, but some fractures show oblique or small, wrench components.

Although detectable movements on the Sandnesfjorden fault were relatively late, involving Greenschist retrogressions and shearing, this feature may have been a syn-metamorphic movement zone which brought up the Granulite facies rocks. Selmer-Olsen's work (1950) indicated that 12 km south west of Laget the breccia structure on this fault line had a northerly dip of 70°. This suggests an overall normal movement with upthrown Granulite facies rocks on the south. On some islands in Sandnesfjorden, vertical axis drag-folds indicate a small wrench component. Sheared and deformed rocks in all cases, show retrogression to Greenschist assemblages of chlorite, epidote and quartz. Later movements on some fractures have caused further alteration to clay-minerals.

Radiometric work has only recorded some of the later events. The intru-
sion of gabbroic 'hyperites' is thought to represent the beginnings of the Sveconorwegian regeneration which overprinted most earlier dates. 'Ages' recorded by O'Nions et al. (1969) from rocks of the present area relate to this regeneration. It is significant that Broch's biotite K-Ar dates from the Arendal-Hisøy banded gneisses and arendalites (1345 to 1010 m.y.) are somewhat older than 'ages' from lower facies rocks in this region (Broch 1964). The dates are thought to relate to the retrogressive (S4) biotite fabrics but do suggest that Granulite facies metamorphism may have occurred before $\sim 1350$ m.y. Broch commented 'The Langsev age of 1345 m.y. may be the first of the much missed 1400 m.y. ages'.

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