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CONTENTS

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Abstract

An area of about 2000 km² between the Skagerak coast (Tvedestrand—Risør) and the Southern part of the Telemark province (Tjønefoss—Neslandvatn) has been investigated and is considered to be a genetically homogeneous migmatitic complex. The evolution of the rocks is supposed to represent an orogenic development in which 3 fundamental phases have been recognized: 1) Deposition of geosynclinal supracrustals (mainly detrital or pelitic sediments and basic intrusions). 2) Widespread migmatization as a consequence of deformation and intermediate pressure regional metamorphism (Caledonian type). The grade of metamorphism is essentially controlled by the available amount of water as a free gazeous phase and decreases regularly from the Skagerak coast (hornblende granulite subfacies) towards the Telemark (low amphibolite facies). 3) Local retrograde metamorphism in elongated zones which have remained mobile well after the end of the regional migmatization. In connection with this late diapthoresis important movements brought in contact areas at different stages of migmatitic evolution, particularly the catazonal and deep catazonal Bamble and the mesozonal Telemark domains.

Introduction

The Precambrian basement of Southern Norway, a classical region for the study of regional metamorphism and granitization, is generally divided into 2 regional units: The Telemark—Rogaland, which constitutes the main part of the district and the Kongsberg—Bamble, a narrow fringe along the Skagerak coast and the Oslo graben (Barth, in Holtedahl, 1960). From about 1930 to 1940, total independance was the rule (Bugge, 1936), but it is to-day generally accepted that the whole basement is genetically homogeneous, even if in reason of intense deformations and widespread granitization the regional correlations have not yet been established (Holtedahl 1953, Dons and Barth, in Holtedahl, 1960).

The geological map described in this paper deals with a surface of about 2.000 km² around lake Vegår (Aust-Agder) and is precisely divided in its middle by the «Great Breccia» which separates classically the Telemark and

Bamble areas (Barth, in Holtedahl. 1960). This region thus offers a good opportunity to study the relationships between these 2 domains, a problem which in spite of recent great advances remains the key-problem of the regional geology. For 6 summers of field work (1959—1966), I have mapped in detail (scale 1/50.000) the area delimited by: the Nidelva river, the main road E 18) (Sørlandske hovedvei) and the road Sundebru—Gjerstad—Sandå (between Åmli and Tjønefoss). The geology of the remaining part of the map has been only cursorily investigated and derives mostly from the available literature. (See bibliography in the legend of the map).

In this notice only the most important results and general conclusions are given; details will appear in a more complete publication in the French periodical «Sciences de la Terre».

Regional features

Many studies have been devoted to Southern Norway and the most recent reviews (Barth and Dons, in Holtedahl, 1960, Barth, in Rankama, 1963) have established a coherent genetic scheme which will be taken here as a basis for the description of rocks. Primarily defined for the Bamble area (Bugge, 1943), but also valid for the whole investigated region, this scheme is based on a major distinction between:

a) an «old group» of ancient (and still unknown age) rocks of supracrustal origin, which in spite of the high level of regional metamorphism and a probably very complicated geological history have retained unmistakable traces of sedimentation, volcanic extrusion or superficial intrusion.

b) a «Younger group» of migmatites which resulted from the transformation of «old group» rocks under a regional migmatization initiated by an orogenic metamorphism. This metamorphism increases regularly from the amphibolite facies (mesozone and upper catazone) to the granulite facies, reached on a regional scale along the Skagerak coast (Barth, in Holtedahl, 1960). It must be clearly stated at once that the number of metamorphisms and possible migmatizations, which have eventually arisen since the unknown epoch of the deposition of the «old group», is by no means clear (Wegmann, in Holtedahl, 1960), but two fundamental principles will be admitted in this paper:

1) only one regional migmatization may be recognized on the field; it corresponds to an episode of metamorphism the date of which is given by many concordant geochronological measurements to about 1 billion years ago (Broch 1964). In spite of constant searches, no older granites and migmatites could be recognized on the field with any degree of certainty and, if any, they have

been obliterated or rejuvenated by the last 1 billion year old regional migmatization, a major orogenic episode which nevertheless is still waiting for a specific name.

2) migmatites and related granites on both sides of the «Great Breccia» belong to the same migmatitic cycle and must be regarded as cogenetic. The undeniable but sometimes subtle differences are thus only explained by the uneven development of migmatitic processes.

As now accepted by most geologist (Winkler 1965, Barth 1962), the development of migmatitic evolution is directly related to the level of regional metamorphism and in a general way the exposed rocks bear witness of the maximum metamorphism they underwent. However, the basement is dissected by elongated zones of deformed rocks and mylonites which show clear features of retrograde metamorphism. These diaphtorites have a particular importance in the investigated area, as they represent the key rocks to understand the true relationships between Telemark and Bamble within the limits of the map. Two types have been distinguished (Touret 1967b): the blastomylonitic R1 diapthorites (retromorphism in the epidote-amphibolite facies), which the interesting Vegårshei- and Gjerstad augen gneisses belong to, and the mylonitic R2 diaphtorites (retromorphism in the greenschist facies), mostly represented by the «Great Breccia mylonites» (Barth in Holtedahl 1960, Selmer Olsen 1950).

I. THE OLD GROUP

In the old group there occur many detrital or pelitic ancient sediments, now turned into quartzites, metagreywackes or paragneisses and a huge quantity of amphibolites; traces of ancient limestones also exist. These supracrustals are well known in the Bamble (Bugge 1943, Barth, in Holtedahl 1960), but it must be noted hat they have also been found without any exception within the Telemark area, where their relative scarcity is only due in my opinion to the much larger extent of the granitization north of the «Great Breccia».

Quartzites

The quartzites, very abundant along the Skagerak coast but occurring also on both sides of the Vegår lake, derive from ancient sandstones or arkosic sandstones. Sometimes very pure (Søndeledsfjorden), they generally hold biotite, feldspars (microcline or oligoclase) and accessories, among which zircons are very common. Sillimanite may be present, while apparently primary muscovite is to be found north of an Ubergsmoen—Sundebru line which corresponds to a «muscovite isograd» slightly oblique on the regional strike.

In the area of Søndeled and Haugland (road Ubergsmoen—Vegårshei), sillimanite occurs in considerable amount; the rock then may present a nodular texture and has formerly been described as «nodular granite» (Brøgger 1934). The nodules are rich in quartz and especially in sillimanite, while the matrix holds more feldspars and biotite. Several hypothesis have been put forward to explain the genesis of these rocks, but the most recent study (Elliott and Morton 1965) proposes a pure sedimentary origin by «multiple folding of a series of arkose and impure sandstone which contained ribs of hard, high-alumina quartzites».

If the sedimentary origin of quartzites, as indicated by the mode of exposure, the mineralogy and chemical composition, is no longer controversial (Barth, in Holtedahl 1960), the metamorphism has practically obliterated all traces of sedimentary structures; however, traces of a pebble have been found south of Midvatn, while possible cross stratifications occur along the lake Hauglandsvatn.

Selås banded gneisses (metagreywackes)

Rocks with a banded structure occur everywhere in Southern Norway and have generally been described as «banded gneisses» (Bugge 1943, Dietrich 1959). They are built up of alternating dark and light bands of varying thickness (some centimeters to several meters) and considerable petrographical complexity: amphibolites, quartzites, dioritic, granodioritic or granitic gneisses and gneissic granites etc. . . . It is highly probable that the first and foremost origin of the banding is the original supracrustal bedding (Dietrich 1963), but in most cases this original bedding may have been deformed and transposed by the synmetamorphic mobilization occuring during the migmatization (see p. 19 and Barth and Reitan in Rankama 1963). I will retain here the term «banded gneiss» for the only rocks whose layering is truly mimetic of the supracrustal stratification, keeping the name «banded migmatites» (p. 18) for the more common exposures where metamorphic recrystallization has been sufficient to suppress all traces of the original sedimentation.

This definition is of course very restrictive, but such banded gneisses have nevertheless been observed near the village of Selås (road Ubergsmoen—Åmli), where they occur as more or less continous layers several ten to hundred meters thick, interbedded in quartzites and amphibolites. They are made of alternating light and dark bands 5 to 10 cm thick, the light ones containing quartz, plagioclase (An 22 to 40), some poeciloblastic microcline, the dark ones being

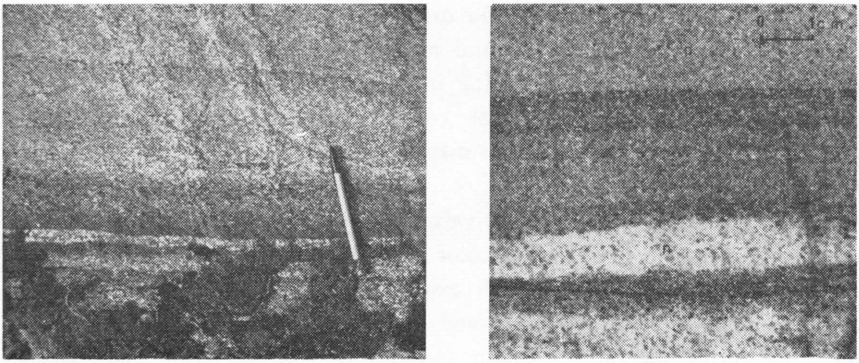

Fig. 1. *«Old group» rocks, 1: «Igneous layering» in hyperites (Teråsen, Songe). 2: Selås banded gneiss. The gradual darkening of the intermediate band is believed to be due to isochemical recrystallization of an ancient graded greywacke. n: granodioritic neosome.*
N.B.: In both cases, the top of the picture represents the top of the premigmatitic formation.

richer in biotite, graphite, pyrite, sometimes amphiboles. Small almandine garnets are scattered everywhere and often associated with biotite and graphite in very thin (1—2 mm) and continuous bands. The most interesting fact is a clear rythmicity of the bedding caused by a gradual transition light/dark band, while the opposite (dark/light) is very sharp (Fig. 1—2). I believe (Touret 1966) that this rythmicity may be explained by the isochemical recrystallization of a premigmatitic graded greywacke-like sediment; the similitudes between the chemical composition of greywackes and Selås banded gneisses are indeed striking.

The structure of the Selås banded gneisses is constantly interrupted by elongated dykes and patches of granodiorite (Fig. 3—1) which in my opinion is the «neosome» (p. 15) generated during the regional migmatization. Detailed investigations have shown that their chemical composition was very close from the average analysis of a composite sample of the banded gneisses.

The direction of the structural polarity of the gneisses (gradual darkening being the right way up?) may change many times on a single exposure as a result of the isoclinal folding which is the major structural event in the Bamble and unfortunately makes any attempt to reconstitute the original stratigraphy quite impossible.

Graphite paragneisses

I describe as «graphite paragneisses» a group of fine-grained gneisses which very probably comes from the metamorphism of clay - and organic matter-rich pelitic sediments. They contain quartz, plagioclase (An 28 to 35), some microcline, much biotite, garnets and sometimes sillimanite (along the Skagerak coast). Graphite, often occurring in close vicinity of iron sulfides, is extremely frequent in elongated or corroded flakes associated to biotite in orientated intergrowths. Cordierite may appear in the region of Tvedestrand (see p. 28).

Graphite paragneisses are relatively sensitive to weathering and present then a typical rusty to yellowish color easily recognizable on the field. They are very abundant in a broad belt extending from Sundebru (Southern end of the Gjerstadvatn) to Tvedestrand—Ubergsmoen, but have been highly modified during the migmatization and usually occur as small (some meters thick) patches scattered throughout the migmatites. Some occurrences have also been found within the domain of the granulite facies migmatites and it is my feeling that they were of primary importance in the supracrustal «old group».

The high-alumina content of the rocks in the above mentioned belt, known since the 19th century (Lacroix 1889) and indicated by the abundance of sillimanite, garnet and sometimes cordierite, may then be directly related to the clay-rich nature of the original sediments and is consequently another argument in favor of the constancy of rock chemical composition during the metamorphism.

Ancient calcareous rocks: cipolinos, skarns and Schuiling's residual cipolinos

Some cipolinos bearing calcite, diopside green hornblende and in the region of Nevestad, large (1—2 cm) graphite crystals occur along the Skagerak coast. But in a general way, calcite has disappeared during the metamorphic evolution and the ancient limestones have been transformed into a wide variety of calcsilicate-bearing rocks:

— Skarns are well-known South of the investigated area, particularly in the region of Arendal where they contain important iron ore deposits (Bugge 1940). A few exposures of small andradite hedenbergite skarns occur within the limits of the map, especially North of Vegårshei, and in close contact with or within the Vegårshei augen gneisses.

— many fine-grained quartzitic or leptynitic calcsilicate bearing rocks occur in the Bamble and Telemark areas as small reddish to greenish patches seldom exceeding 50 cm in their largest dimensions. Their mineralogical composition is often very unusual: much quarz, but also calcic garnets, diopside, basic plagioclases (compositions of An 75 and An 80 have been measured);

epidote may be very abundant, especially in the vicinity of the diaphtoritic areas (p. 35).

Schuiling (1965) has suggested the name «residual cipolinos» for such «metamorphic rocks of quartzitic appearance, which consist of an equigranular mosaic of quartz and basic plagioclase with interspersed, large crystals of diopside and/or hornblende and/or garnet» and developed the stimulating hypothesis that these rocks, common in many metamorphic terranes, «derive from normal limestones and dolomites from which $CaCO_3$ and $MgCO_3$ were expelled in the course of metamorphism, leaving only sufficient Ca and Mg to combine with the impurities as Ca-Mg silicates».

Detailed studies have convinced the present writer of the value of Schuiling's hypothesis within the investigated area. The shape, size and distribution of the «residual cipolinos» are heterogeneous, but in some cases at least may correspond to old cherts or other types of «siliceous accidents» in limestones.

Consequently, if we accept the possibility of carbonate destabilization during the regional metamorphism-a fact commonly admitted by most petrologists (Barth 1962, Winkler 1965)-, it is important to note that this destabilization is not in direct relationship with the grade of metamorphism: primary calcite occurs near the coast, in the vicinity of the granulite facies area and in a region where the grade of metamorphism is obviously higher than in the interior of the country. No primary calcite has been found north of the muscovite isograd (p. 8), where granitization is more extensive than in the south: the disappearance of calcite thus seems more related to the extensity of the granitization than to the degree of metamorphism, a fact which in my opinion indicates that the role of water must have been a fundamental one (p. 31), and is more a dissolution, probably by hydrothermal acid solutions, than a true destabilization.

Volcanic acid effusives

No acid volcanic rocks are known in the Bamble, although some leucocratic layers of the banded migmatites may well represent ancient tuffs (see p. 15 and Barth, in Holtedahl 1960). Some fine-grained acid gneisses, rich in quartz, plagioclase and microcline (as small crystals and some large phenocrysts) occur near Haukedalen (north of the Gjerstad augen gneisses). They are rather similar to some Swedish leptites (Geijer, in Rankama 1963) and are probably recrystallized tuffs or ignimbrites.

The basic rocks: amphibolites and hyperites

Basic rocks are extremely abundant in Southern Norway and occur everywhere as concordant layers of variable thickness (1 cm to several 100 m). Several types have been recognized:

1) Olivine gabbros with a coronitic texture, locally known under the term «*hyperite*» (Brøgger 1934, Bugge 1943). Their age remains largely hypothetical (see p. 6 and 14), but they are in any case over 1 billion years old, as they are deformed by the synmigmatitic folding and grade locally into metamorphic amphibolites. Only known along the Skagerak coast, they occur as 100 to 500 m thick sills concordant with banded migmatites in the area of amphibolite facies as well as in that of granulite facies.

Under the microscope, the rock is composed of ophitic plagioclase (An 43-45), remains of olivine surrounded by a double coronite (inner rim of hyperstene, spinel, sometimes garnet, outer rim of clinopyroxene and green hornblende), diopside and dark green hornblende. In the granulite facies area the hyperstene is very abundant and the rock may then be called «norite» (Bugge 1943).

East of Songe, interesting examples of «igneous layering» (gradual decrease of plagioclase crystals in amount and size versus correlative increase of mafic minerals) have been observed (Fig 1-1). The chemical composition is basaltic (Bugge 1934 and Fig. 2).

2) By complete disappearance of olivine, replaced by clinopyroxene and green hornblende, the gabbros grade into *orthoamphibolites.* A new generation of more acid plagioclase (An 35), often as small and polyedric crystals, may appear, as well as poeciloblastic almandine garnet and some biotite. But some of the biggest plagioclase crystals at least are still oriented along an easily recognizable ophitic texture.

Such orthoamphibolites occur of course on the border of the hyperite bodies, but many others have been found much farther north, in the Bamble as well as in the Telemark, where they are very typical near Morkeheia (N. Gjerstad).

3) Far more abundant *common amphibolites,* medium grained dark rocks composed of plagioclase (An 30-35), green hornblende, uralite, biotite, possibly diopside, often almandine garnet, sphene and ilmenite. The texture is nematoblastic.

These amphibolites are probably the commonest rocks within the whole investigated area and, in boudinaged or brecciated (agmatite) horizons, constitute the most easily recognizable part of the migmatitic paleosome (see p. 15).

Their ortho- or para-origin has been a matter of discussion for many years and it is impossible to discuss this problem at length. Both origins probably

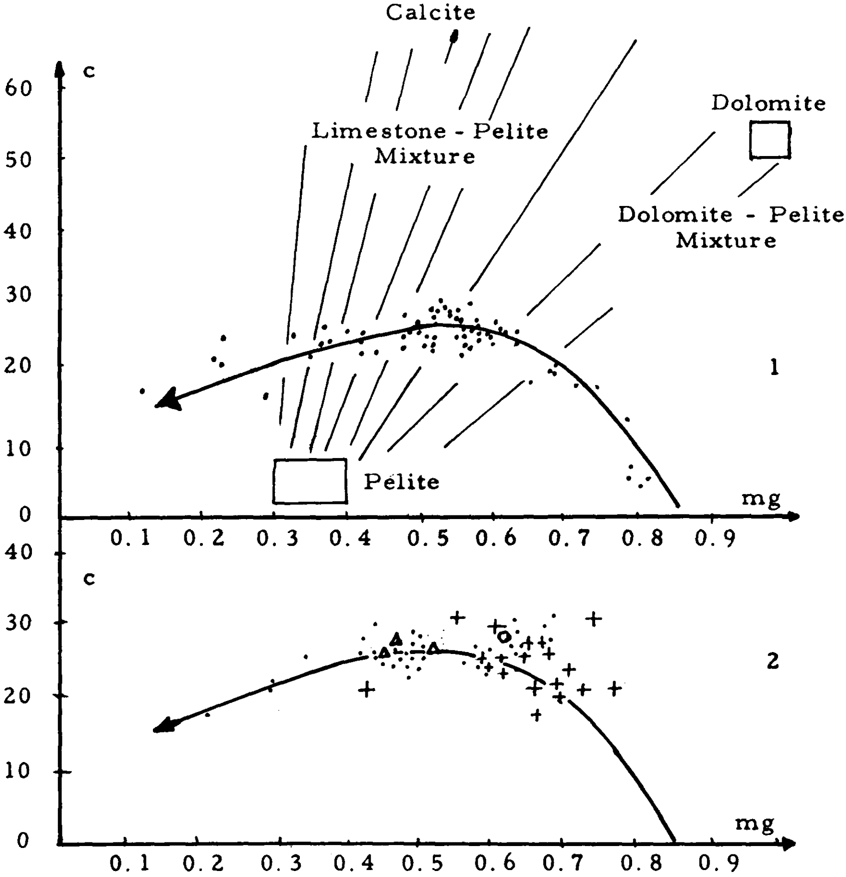

Fig. 2. *c/mg (Niggli parameters) of basic rocks (method of Leake, 1964).*
1: Karroo dolerites (dots) defining an «igneous trend» (curve with arrow) approximately at right angle of the lines pelite-calcite and pelite-dolomite.
2. Basic rocks in the investigated area. Dots: Bamble amphibolites, Crosses: Telemark amphibolites, Triangles: Hyperites, Circle: Postmetamorphic diabase.

exist (Barth and Reitan, in Rankama, 1963), but the constant orthoamphibolite — amphibolite transition indicates that an orthoorigin may be very common. This conclusion is supported by variation studies of the chemical composition of basic rocks, after the method recently proposed by Leake (1964), (Fig. 2). The similitudes between hyperites and amphibolites are obvious and the general trend approximates closely the evolution of Karro dolerites. Some rocks however depart from the general trend and may indicate, either para-amphibolites, or ancient igneous rocks chemically modified during the metamorphism. But their small number is a proof that they are the exception more than the rule.

I feel therefore that most amphibolites are orthoderivates and, at least for the most important ones, that they may represent recrystallized hyperites. There are unfortunately many incertitudes about the exact mode and time of emplacement of the hyperites. From transgressive contacts in the Arendal district, Bugge (1943) infers that, if they are older than the migmatites, they are also younger than the sediments of the «old group». On the other hand, many thin amphibolites are so finely interbedded within these sediments that a «mise en place» contemporaneous or subcontemporaneous of the sedimentation seems most probable. A possible solution for this apparent dilemna would be several phases of basic intrusions of nearly constant chemical composition, the first ones more or less contemporaneous of the sedimentation, the others, pre-or syntectonic ones, being more related to the development of the regional metamorphism.

Conclusion on the «old group»

The surprisingly well-preserved supracrustal features of the «old group» rocks allow a tentative reconstitution of the type of premigmatic formation. Abundances of detrital and pelitic sediments, presence of graded greywackes, probability of synsedimentary basic intrusions, all these facts indicate a flysch-like deposit in a geosynclinal area. Because of the widespread occurrence of «residual cipolinos», limestones were probably more abundant than formerly supposed, but they are common in many geosynclines, particularly in miogeosynclinal furrows (Aubouin, 1965). At the present state of our knowledge, it is however impossible to define accurately the type of geosynclinal deposits: limestones and well-sorted sands (now pure quartzites) are more typical of miogeosynclinal sediments, while graded greywackes, abundance of black shales (now graphite paragneisses) and particularly the possibility of synsedimentary basic intrusions would rather indicate eugeosynclinal ones.

A very important regional fact is the continuity of «old group» rocks on both sides of the «Great Breccia». It would be of fundamental importance to correlate these rocks with the «Telemark supracrustals» (Dons, 1962) occurring north of the wide Telemark granites. Recent geochronological determinations, carried out at the Lab. voor Isotopen-Geologie (Amsterdam), have indicated that the epimetamorphic Telemark supracrustals are over 1 billion years old and consequently belong to the same age range than the «old group» rocks. However, they are separated into different groups by major discontinuities which are blurred within the Telemark granites, and have not been yet rediscovered farther south. This problem remains still open and represents a major objective for the studies now going on.

II. THE ONE BILLION YEAR OLD REGIONAL MIGMATIZATION

As a result of the increase of regional metamorphism which occurred about 1 billion years ago, the «old group» supracrustals were «reworked» and transformed through the still mysterious process of mobilization, anatexis and granitization; they are consequently now exposed as migmatites (Barth, in Holtedahl, 1960). As it is impossible to discuss here at length the complicated and rather controversial migmatite petrology, I shall only indicate that the present study basically relies on the well-known notions of «paleosome» and «neosome» (Dietrich and Mehnert, 1960), which due to the exceptionally «dry» character of most migmatites (Den Tex, 1965, and p. 31), are particularly suitable for regional mapping in Southern Norway (Barth, 1962). As may be seen on Fig. 3, migmatites are composite rocks in which one is able to recognize on the field:

— an old part of «*paleosome*», which here is a rock belonging to the old group (Selås banded gneiss in the case of Fig. 3-1),

— a younger part of «*neosome*», generally of granitic or granodioritic composition, which represents the «mobile» part of the migmatites and consequently tends to transect the paleosome structures.

This definition is theoretically satisfactory, but its application may sometimes be difficult: some rocks of granitic composition may be recristallized effusives tuffs and ignimbrites and belong therefore to the «old group». However, detailed observations have convinced the present writer that all rocks of granitic or granodioritic can be taken as a neosome, as they were more mobile than «old group» rocks during the migmatization. I accept here Mehnert's definition of mobility: increase in migration capacity of a rock or part of a rock over and above the domain of a single grain, with no genetic implication concerning the state of aggregation of the rock or the mecanism of mobilization (Dietrich and Mehnert, 1960). The acceptation of «neosome» in this paper is then similar to the «mobilizate» of German geologists (Winkler, 1965).

As pointed out by Mehnert (f.i. in Dietrich and Mehnert, 1960), the notion of «mobilization» is largely nongenetic, as no hypothesis is expressed on the mecanism of the migration or even the mode of formation of the granitoidic neosome. Its ubiquitous transgressive character, which is in complete contradistinction with the conformable character of most «old group» rocks, indicates however that most, if not all neosome has been truly created during the migmatitic evolution. Winkler's (1965) and Wyart's (Wyart and Sabatier, 1959) experiments have definitely shown that granitic or granodioritic rocks arise from pelitic rocks under P-T conditions corresponding to the metamorphic amphibolite facies, which has been reached or exceeded everywhere in the

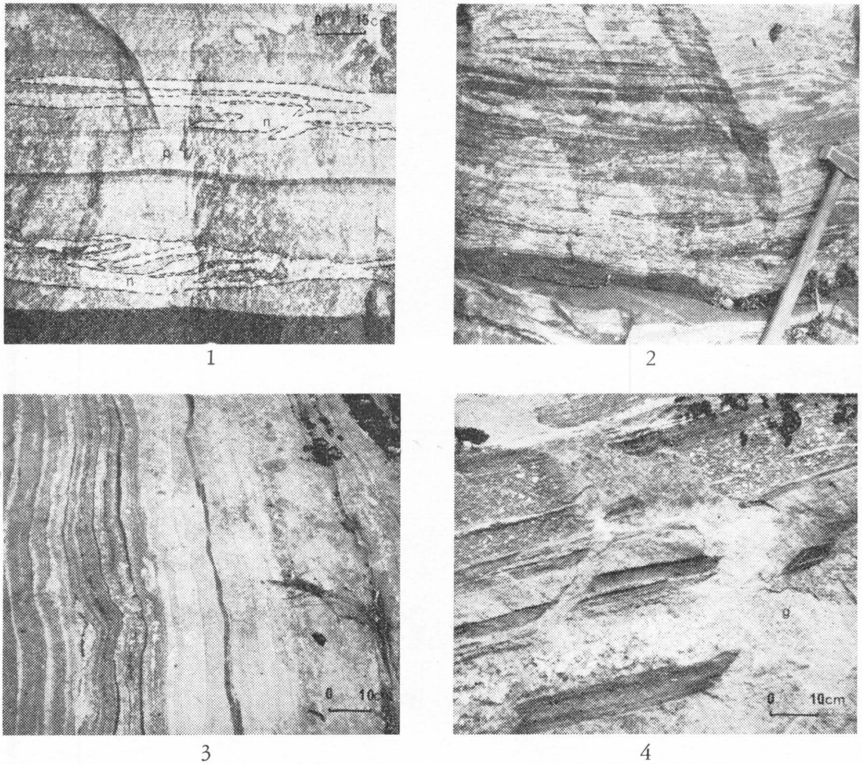

Fig. 3. *Four successive stages of migmatite evolution.*

1: Bamble banded migmatites. p: paleosome of supracrustal origin, in this case Selås banded gneiss. At the bottom of the picture, concordant amphibolite. n: granodioritic neosome, mostly concordant, but sometimes discordant on the supracrustal layering. (Lake Sandvatn, south of Selås).

2: Bamble banded migmatites. The dark part of the rock still represents the paleosome, but the supracrustal bedding has been transposed during the migmatization by isoclinal folds which may be seen above the hammer head. (Road Ubergsmoen—Espeland).

3: Telemark banded migmatites. The rock in the whole looks more granitic (higher «degree of evolution» of the migmatites, see p. 17). The ultimate origin of the bedding is probably supracrustal, but it has been completely transposel during the migmatization. (Tveit, south of Åmli).

4: Telemark banded migmatites. cut by dykes of leucocratic Telemark granite (g). The granite becomes progressively pegmatitic at the bottom of the picture. (Road Sandå—Fiskvatn).

investigated area (p. 32). These experiments have also pointed out the fundamental importance of water: when P-T conditions of the beginning of mobilization are reached, the evolution may only be complete if enough water (more than 4 % in weight - Winkler, 1965) is present. If not, the rocks will only be partially mobilized, the amount of mobilized material being strictly dependant upon the available quantity of water (Winkler, 1965). It will be seen that in Southern Norway, many arguments indicate that migmatitic evolution may have developed in a waterdeficient environment: the mobilization is then incomplete and rests of premigmatitic rocks (the paleosome) may still be preserved.

The scarcity of water also explains why some rocks may have attained higher metamorphic grade than the amphibolite facies (granulite facies) without complete mobilization: it is in my opinion the only way to understand the undeniable but highly paradoxical observation that rests of old group rocks are as much (or even more) abundant in the granulite facies - than in the amphibolite facies area (see p. 26).

Finally, even if no precise hypothesis is done on the exact mechanism of the mineralogical transformations (inter- or intracrystalline diffusion, hydrothermal permeation, «minimal melting», anatexis ?), it is admitted in this paper, that the migmatization may be considered as a progressive evolution during which the «old group» supracrustals are transformed into granitoids by a general or local mobilization directly related to the regional metamorphism. The amount of granitoids depends primarily on the available amount of water, while their nature is more dependant on the P-T metamorphic conditions. We may then describe successively:

— the migmatites in the amphibolite facies area, in which the ultimate products of the mobilization are granitoids and granites (granitic migmatites),

— the migmatites in the granulite facies area, in which the ultimate products of the mobilization are charnockites (charnockitic migmatites).

The granitic migmatites

Granitic migmatites are widespread in the biggest part of Bamble and in the whole Telemark. They constitute a continuous series from conspicuously banded rocks with much paleosome (banded migmatites, see p. 18) to almost pure neosome of granitic or granitoidic composition. The «degree of evolution» (Touret, 1962) of the migmatites may consequently be defined by the relative amount of neosome versus paleosome. Even if the structural complexity and the progressivity of the evolution avoids any quantitative measurement, it is a useful notion for field-work which allows to point out the real differences between the domains on both sides of the «Great Breccia»: this «degree of evolution» increases regularly from S.E. towards N.W. (i.e. in the opposite direction of the metamorphic gradient), with a marked jump at the «Great Breccia». The differences between Telemark and Bamble, which had so much impressed several authors (Bugge, 1936, Bugge, 1943), arise therefore essentially from the more granitic character of migmatites north of the Breccia. They support a distinction between Bamble and Telemark areas for the rocks description:

Bamble area (south of the «Great Breccia»)

Bamble banded migmatites

In a general way, the «degree of evolution» of Bamble migmatites is low, but increases somewhat towards S.W. (Barth, in Holtedahl, 1960). The most common migmatitic variety is a «banded migmatite» (see p. 8) which consists of a regular succession of paleosome and neosome layers. The thickness of individual bands varies greatly from some centimeters to several meters. Sometimes, the bedding is very regular and continuous and the rock may then be called a «stromatite» (Dietrich and Mehnert, 1960), but generally the neosome beds tend to transect the paleosome structure and the term «dyctionite» (Dietrich and Mehnert, 1960) is more appropriate (Fig. 3). It is however impossible to draw a sharp limit between these two types, as differences between concordant and discordant structures depends more on the scale of observation than on the rock itself.

The composition of the neosome is granodioritic to granitic, but its structure never absolutely isotropic: a kind of «ghost» foliation parallel to the migmatitic bedding is always to be found. Its mineralogy is rather simple and monotonous: fine-grained (1-2 mm) greyish rock containing as major constituents hypidiomorphic quartz, plagioclase (An 30), biotite and in many cases green hornblende. Microcline is very unevenly distributed and generally speaking, not very abundant: the neosome composition is more granodioritic and granomonzonitic than truly granitic (see Fig. 5). K-feldspar is often poikiloblastic and seems to corrode the plagioclases which are then bordered by conspicuous albitic rims or myrmekites. Large-size poikiloblastic almandine garnets — sometimes in bushy aggregates more than 20 cm in diameter — are abundant in neosomes occurring within basic rocks (orthoamphibolites and amphibolites) and alumina-rich paleosome layers (graphite paragneisses). Some epidote may be present, but is believed to be mostly of retromorphic origin (see p. 35). Among the accessories, apatite, allanite, zircons and especially iron ores (hematite and magnetite) have been recognized. Generally associated to biotite, the iron ores may sometimes be very abundant and constitute most of the dark minerals, as will be described later for some large scale granitoids (see p. 21).

Origin of the «banded migmatite» bedding as illustrated by the transition «banded gneisses» / «banded migmatites»

Although migmatitic layering is always concordant to supracrustal bedding, it can hardly be concluded that both structures are equivalent: the many traces of isoclinal folds which are observed within the banded migmatites indicate that «old group» rocks have suffered an intense isoclinal folding before or (more likely) during the migmatization. The evolution of migmatitic mobilization has been studied in detail in the case of the Selås banded gneisses, where the isoclinal folding may be recognized easily from changes in structural polarity (see p. 9). It is clear in this case that neosome is more likely to appear in the most folded areas and that increase of the migmatization leads to the obliteration of folds hinges. The migmatite bedding is then a true «transposition structure» (Turner and Weiss, 1963), which is as a matter of fact parallel to the axial plane of folds. This direction however is always parallel to the supracrustal layering, a fact which indicates that the synmetamorphic isoclinal folding has been concordant on the stratification, as usual in the low mesozone and catazone (Zwart, 1967).

Bamble granitoids

In some places, the neosome becomes more abundant and constitutes most of the exposed rocks. They have been described as «granites» (Bugge, 1943, Barth, in Holtedahl, 1960), but due to the wide mineralogical and geochemical variation range, the term «granitoids» seems more appropriate to the present writer. Representing the ultimate products of the migmatization south of the «Great Breccia», the Bamble granitoids occur in several lense-shaped (4-6 km × 1-2 km) bodies elongated along the regional strike. The contacts are very transitional and numerous traces of «old group» rocks are still to be found within the granitoids as xenoliths or skialiths, more or less parallel to the structure of the migmatites around the granitoidic body. The structure of the granitoid itself is also slightly oriented along the same directions. This mode of exposure is therefore typical of synorogenic granites (Raguin, 1957).

The petrography of the granitoids is somewhat variable, but the following minerals are generally present: quartz, perthitic microcline, often as 2-3 cm large phenocrysts, oligoclase (An 20-25), amphibole (green hornblende or hastingsitic hornblende) and accessories, among which iron ores, apatite, zircon, allanite are the most frequent. Myrmekite is very common, as are albitic rims around the plagioclase crystals.

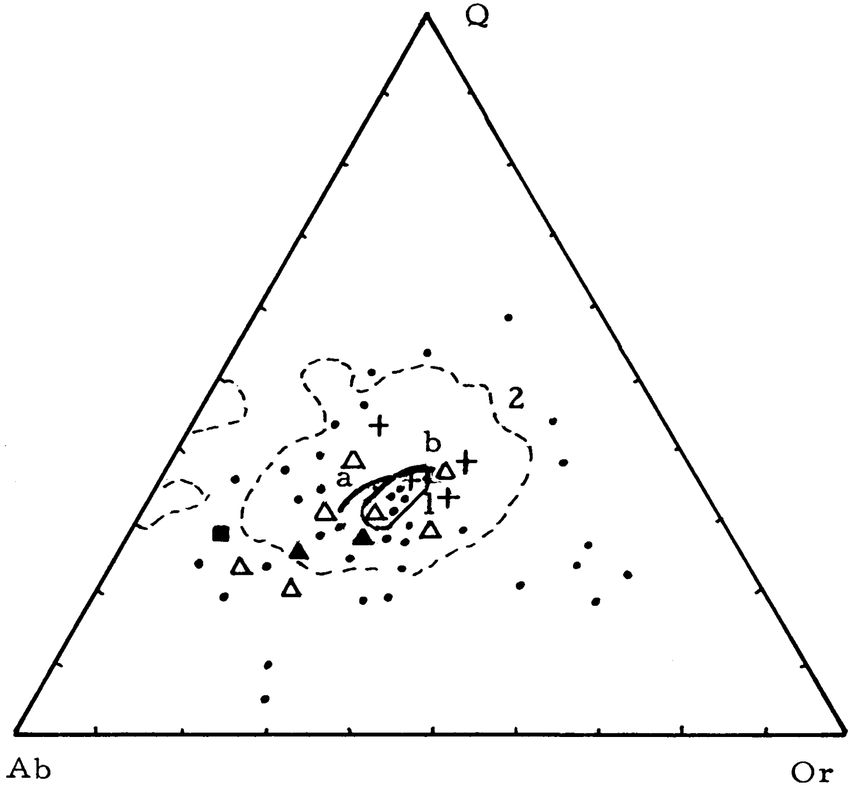

Fig. 4. *Q-Ab-Or diagram of granitoids and granites in the investigated area.*
Dots: Bamble granitoids (partially after Barth and Reitan, in Rankama, 1963). Crosses: Telemark granites. White triangle: Vegårshei and Gjerstad «normal» augen gneisses. Black triangles: «charnockitic» augen gneisses. Square: arendalite (after Barth and Reitan, in Rankama, 1963).
1 and 2: maximum concentration (1 = 14 %, 2 = 86 %) of granitic rocks (Winkler, 1965).
ab: minimum melting composition of the Q-Ab-Or system for P_{H_2O} from 4000 atm. (a) to 500 atm. (b) (after Barth and Reitan, in Rankama, 1963).

The relative proportion quartz/microcline/plagioclase is highly variable and most granitoids, especially if they contain amphibolitic skialiths, have a granodioritic more than granitic composition. They may consequently be compared to the well-known Levang «granite» (Hofseth, 1942, Barth in Holtedahl, 1960) occurring north of Risør. The variability of mineralogical composition in Bamble granitoids is very apparent on a Q-Ab-Or diagram (Barth and Reitan in Rankama, 1963), (Fig. 4). They evidently show no relationship with the eutectic of the system, a fact which indicates that pure magmatic processes are most unlikely for the granitoid genesis (Barth in Holtedahl, 1960). A slow migration of ions at submagmatic temperatures (Perrin and Roubault, 1937), probably facilitated or even made possible by intergranular fluids (Wegmann, 1935) or hydrothermal solutions (Marmo, 1967) is a more satisfactory model than a pure fusion.

The structural position of granitoids is difficult to analyse precisely, but they seem to occur preferably at the hinge of migmatite folds (Smithson and Barth, 1967), most probably in the core of migmatite anticlines.

An interesting granitoid occurring west of Tvedestrand is known locally as the so-called Holt «granitell» (Barth, in Holtedahl, 1960). The rock is a reddish coarse - to medium-grained oriented granite containing quartz, perthitic microcline, oligoclase and iron ores (hematite and magnetite) as practically the only dark minerals. Biotite is present but very subordinate, while iron ores may constitute about 3 to 5 % of the whole rock. Apatite is rather abundant and the principal accessory mineral. Pegmatitic parts of the «granitell» contain important concentrations of hematite and magnetite which have been extensively worked out during the 19th century.

Telemark area (north of the «Great Breccia»)

Telemark banded migmatites

North of the «Great Breccia», banded migmatites are very abundant and at first glance rather similar to those of the Bamble. However, the local retro morphosis R 1 and R 2 which occurs along the Breccia and surrounding areas complicates the observations and, if we only compare the non-retromorphosed areas, some differences may be pointed out:

— the leucocratic neosome is generally speaking more abundant than in the Bamble or in other terms the «degree of evolution» of the migmatites (see p. 17) is increasing. The supracrustals rests are correlatively less abundant and more transformed by the migmatitic evolution (for instance, biotite is definitely more abundant in amphibolites). Only the rocks the chemical composition of which differs significantly from granites (quartzites, amphibolites, residual cipolinos) may be recognized as paleosome.

— the mineral paragenesis of the neosome is similar to that of Bamble granitoids, but K-feldspar (generally perthitic maximum microcline) is more abundant and occurs as poikiloblastic crystals growing apparently at the expenses of the surrounding quartz and plagioclase. Myrmekites and albitic rims around oligoclase are frequent.

— the transition neosome/paleosome is less sharp than in the Bamble and consequently the rock is more massive and looks more igneous. Besides, the bedding is less continuous and regular and the structure more dictyonitic than stromatitic (see p. 18). Finally, numerous crosscutting dykes of fine-grained Telemark granite, which are unknown south of the Breccia, occur everywhere (Fig. 3-4).

Nebulitic migmatites

In many places, especially in and around the numerous domes (Drivheia, Vedlausfjell, Harliheia, etc.) occurring between the «Great Breccia» and the domain of regional extension of the Telemark granite (extreme north of the map), the migmatites present a more granitic character and may be described as «nebulitic migmatites». The rock consists of successive layers of gneissic granite and granodiorite intersected by many granitic dykes. The limits of the layers are more or less blurred and the texture of the rock only slightly oriented. Numerous basic skialiths, amphibolitic boudins or agmatites occur everywhere. The general structure of the migmatites is highly deformed by numerous irregular and rapidly changing flow folds.

Augen migmatites (embrechites oeillées)

A peculiar type of «advanced» migmatites (i.e. highly granitized migmatites) is rather similar to the preceding nebulitic migmatites, but contain moreover many large (2-3 cm) K-feldspars phenocrysts regularly orientated along the migmatitic foliation (Feldspar Carlsbad twin-plane parallel to the foliation). As may be seen on the map, these augen migmatites, which correspond closely to the French term «embrechites oeillées» (Jung et Roques, 1952), are particularly abundant on the border of the above mentioned domes of nebulitic migmatites. It is important to note that they are completely free of any trace of deformation and cataclasis and are thus very different from the Vegårshei and Gjerstad augen gneisses (see p. 36).

Telemark granite

North of the «Great Breccia», the end product of the migmatization is a fine- to medium-grained nebulitic granite, well-known as the «Telemark granite» (Dons, in Holtedahl, 1960) which covers huge surfaces north of the investigated area and much farther north. Due to the gradual transition banded migmatites/nebulitic migmatites/granite, the southern limit of granite regional extension cannot be delimitated precisely, but it corresponds approximatively to a line Åmli - Vehus - Digerdal. But smaller occurrences of Telemark granite are also found south of this line, either as crosscutting dykes (see above) or as more important masses which seem to occur preferably in the core of the above-mentioned domes of nebulitic and augen migmatites. Some of these domes at least (Drivheia, north of Gjerstad) correspond to wide anticlines within the migmatites.

The petrology of the Telemark granite is currently investigated in detail (Ploquin - C.R.P.G. Nancy) and two varieties have already been recognized:

— *the Telemark granite s.s.*, a reddish and greyish fine - to medium-grained nebulitic granite which contains quartz, perthitic microcline, oligoclase (An 20—25), biotite, often amphibole (green hornblende), seldom small almandine garnets. Epidote is commonly present in minute quantities and unlike the epidote in Bamble Area, does not seem to be retromorphic. Some muscovite has also been observed. Among the accessories: apatite, zircons, sphene, iron ore (hematite) and especially allanite may be mentioned.

— *the Åmli granite,* well represented near Åmli and farther west, but occuring also north of Gjerstad (Digerdal). This leucocratic and fine-grained granite is more acid than the Telemark granite s.s. (SiO_2 content about 75 % versus 68—70 % for the Telemark granite s.s.) and, like the Holt «granitell» (see p. 21) is almost free of biotite and contains iron ore (hematite) as the only dark mineral. Like all granitic rocks in southern Norway, the Åmli granite contains many small pegmatites which in this case present some interesting features:

— The pegmatite feldspars often show red shades which call to mind the well-known Bamble «aventurine feldspars» (Divljan 1960).

— Biotite is often completely lacking in pegmatites, while still present in small amount in the surrounding granite.

More work is necessary to elucidate the petrogenesis of the Åmli granite which in some places (west of Åmli) seems to be closely related to old quartzites, but similitudes with the Holt «granitell» are obvious indeed and indicate that analogies between Bamble and Telemark areas are not only restricted to supracrustals rests and appear also among the products of migmatization.

The K content of Telemark granites is significantly higher than in Bamble granitoids (Fig. 5) and their composition more comparable to the «ideal granites» in a Q-Ab-Or diagram (Fig. 4).

In the Telemark granites occur numerous skialiths and xenoliths of banded migmatites, nebulitic migmatites or amphibolites. Inclusions of basic rocks (amphibolitic skialiths or amphibolite boudins or agmatites) are particularly abundant along a broad belt extending from Kjørull to north of Gjerstad and which possibly continues the Telemark supracrustals described by Foslie (in Dons 1960) along lake Nissevatn.

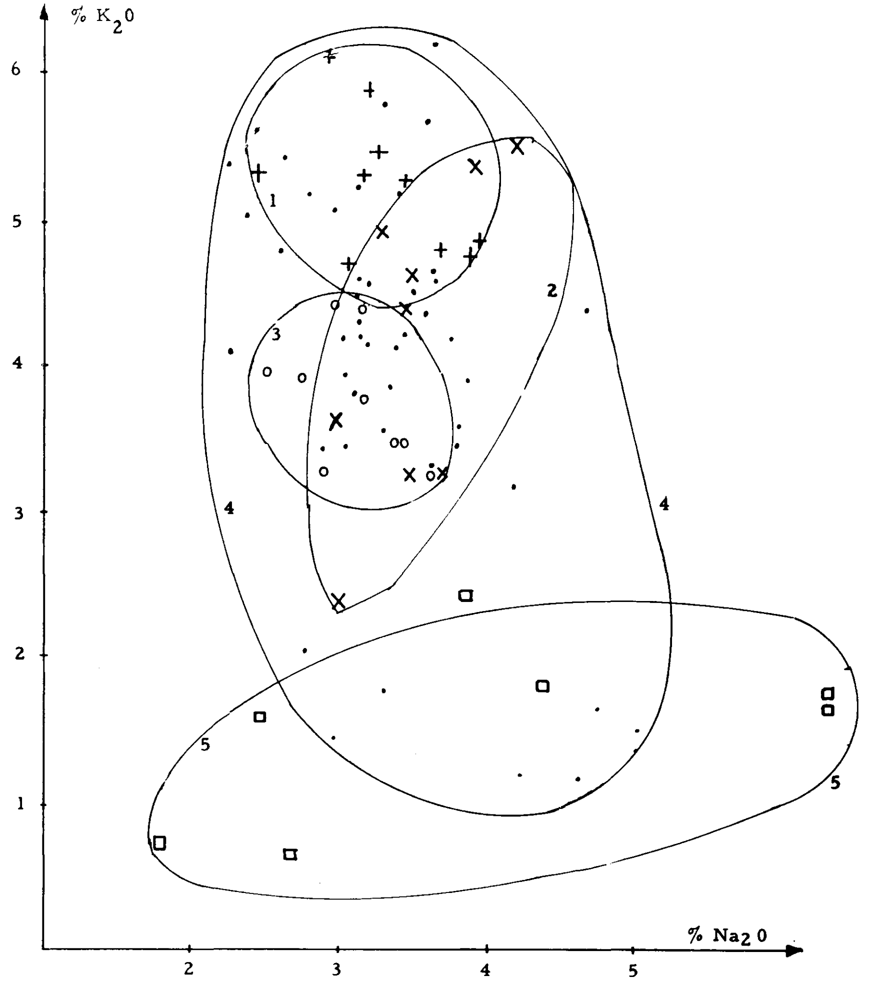

Fig. 5. *Alkaline content of granitoids and granites.*
1 (crosses): Telemark granites. 2 (St Andrew's crosses): Bamble granitoids. 3 (circles): Hovdefjell and Ubergsmoen «charnockitic» augen gneisses. 4 (dots): Vegårshei and Gjerstad «normal» augen gneisses. 5 (squares): arendalites.

Amphibolites may present rests of ophitic textures and are similar to those occurring south of the Great Breccia, but contain more quartz and biotite. They are also associated to a diorite composed of oligoclase, in slightly zoned idiomorphic crystals, green amphibole (tremolite-actinolite), some quartz and a variable but sometimes important quantity of biotite as large (1—2 cm) intersertal crystals. I have called «mobilised amphibolites» these mica-bearing diorites, which are similar to some lamprophyres but also to the so-called hercynian «vaugnerites» (Palm 1954).

The Nesknollen dome.

North of Vegår lake, the Nesknollen dome, whose elliptical shape appears very distinctly in the local topography, presents many unique features: the shape of the dome is well defined (see map), but the contact with the surrounding migmatites is always concordant and apparently very close to the actual topography. It consequently occurs in a kind of «window» within the migmatites. The dome itself is made of a fine-grained granitoidic gneiss whose composition varies progressively from dioritic (oligoclase, biotite, green hornblende, some quartz) in the outer zone to granodioritic and granitic (by increase of quartz and poeciloblastic microcline) in the core.

The outer dioritic gneiss, which contains many small pegmatite dykes, is conspicuously foliated and microfolded. The flatlying axes of the microfolds converge approximatively towards the center of the dome. The inner granodioritic and granitic gneiss is more homogeneous and less deformed, but its foliation always remains distinct and approximately parallel to the topographical surface of the dome.

The Nesknollen dome differs in many ways from the Telemark granites and migmatites and its origin remains problematic. As the similitudes with Eskola's «mantled domes» are obvious, it may be considered as palingenetic (Eskola 1949). This palingenesis howewer is difficult to understand. It could be of course a rejuvenation of an ancient basement during the regional migmatization, as originally proposed by Eskola (1949) in his famous paper. But this hypothesis cannot be valid here, as no other trace of any basement has ever been found in the investigated area, even in the deeper granulite facies area. It is in my opinion more probable that this palingenesis is only local and related to the second mobilization occurring in the domain of the R_1 diapthorites (p. 35).

The charnockitic migmatites

As a result of the progressive increase of regional metamorphism towards the Skagerak coast, the granulite facies is reached near Tvedestrand, as seen immediately on the field by the widespread occurence of orthorhombic pyroxene and the greenish-yellowish color of all rocks («couleur malgachitique», Lacroix 1923). The rocks of this area have been called «arendalites» or «Arendal charnockites» by J. A. W. Bugge (1943, 1960) and include a wide range from acid (more than 65 % SiO_2) to basic (about 50 % SiO_2) varieties. It is easy to become convinced on the field of the migmatitic nature of the arendalites: as for the granitic migmatites, the composite nature of the rock is indicated by the intimate association of isotropic or subisotropic charnockite (hyperstene granite and granodiorite) and banded granulites, in which rests of «old group» rocks may be observed. The bedding of the banded granulites is at least as well developed as in the banded migmatites, but not the rock foliation, what is however simply due to the scarcity of biotite in granulite facies rocks (see below).

In agreement with Den Tex's conclusions concerning the region of Cabo Ortegal (Spain) (Den Tex and Vogel, 1962) and the charnockite type area in India (Den Tex, 1965), I consequently consider the rocks occurring within the granulite facies area as charnockitic «dry migmatites» (Den Tex 1965), in which banded granulites are equivalent to banded migmatites in the amphibolite facies area, while charnockites correspond to former granitoids and granites. This hypothesis is in my opinion the only way to explain the occurrence of «old group» supracrustal rests within the banded granulite and the very gradual transition between the arendalite domain and the surrounding migmatites (Bugge 1943).

Mineralogy of the charnockitic migmatites

The transition granulite facies/amphibolite facies is recorded on the field by important and spectacular changes in rock-forming minerals which may be summarized as follow:

— K-feldspar is a monoclinic orthoclase (Heier 1957), often transformed into microcline along crystal cracks or limits (Touret 1963). Perthites are abundant as small discs or stringlets («hairperthites» Eskola 1952), their main composition closely approaches a mesoperthite (50 % orthoclase, 50 % plagioclase Michot 1961); K-feldspar is only abundant in the outer zone of the granulite facies area as 2—3 cm large phenocrysts often surrounded by complex (several generations of quartz droplets) myrmekites.

— Antiperthitic plagioclase (An 15—25) is common and occurs with bluish or milky quartz containing minute rutile inclusions.

—Orthopyroxene (hyperstene) is widespread. Diopsidic clinopyroxene and garnets (especially in some layers of the banded granulite) may also be observed. Amphiboles (dark hornblende and hastingsite) are almost always present as independant and idiomorphic crystals which are apparently non retromorphic: the degree of metamorphism consequently corresponds to the hornblende granulite subfacies.

— Biotite may be present as extremely corroded crystals closely associated to hyperstene or garnet. It is possibly secondary, but several observations indicate the probability of incomplete reactions of the following types:

Biotite $\rightleftarrows$ hyperstene + K-feldspar + water

or

Biotite + sillimanite $\rightleftarrows$ garnet + K-feldspar + water

The mineral paragenesis corresponding to the right side of the equations are stable in the conditions of the granulite facies, but the achievement of the reaction depends on the water pressure and may therefore be incomplete. During or after this evolution, yellowish hydromicas and clay minerals (possibly iron rich nontronites) are formed and fill the microcracks of all minerals, especially quartz and feldspars where they are very apparent under the microscope. I believe that they are essentially responsible for the dark shade of the granulite facies rocks: they are easily washed out by hot HCl solutions and the yellowish color then fades or even wholly disappears.

— Among the accessory minerals, sphene disappears, while iron ores are Ti-rich (Ti-hematite and ilmenite).

Fine-grained charnockites (arendalite s.sr.) and augen charnockites

Charnockites, which as stated above are equivalent to granites in the amphibolite facies domain, essentially occur in the core of the granulite facies area (islands of Tvedestrand). They are dark, massive, fine grained rocks containing quartz, antiperthitic plagioclase, hyperstene, hastingsitic amphibole and some biotite. Potash feldspar is rare and the composition of the rock is nearer to an hyperstene granodiorite (enderbite) than to an hyperstene granite (charnockite s.sr.). The available data concerning the alcaline content of the arendalites (Fig. 5) show a marked prevalence of Na over K and a remarkably low content of K, even compared to rocks with charnockitic affinities occurring elsewhere (De la Roche, in press). For this reason the term «arendalite», which seems to have been dropped by its own author (Bugge 1960) is worth, in my opinion, to be retained. Considerable confusion exists to-day about the exact acceptation of the term «charnockite», which should be restricted to true hyperstene granites (Subramanian 1959, Winkler 1965) and consequently cannot be applied to the arendalites. It might perhaps be useful to introduce a term like «charnockitoid» to preserve the parallelism with granite terminology (granitoid) and describe the whole charnockitic tribe.

In the outer zone of the granulite facies area, K-feldspar is more abundant in the mobilized part of the migmatites and occurs as large (2—3 cm) orthose phenocrysts, often surrounded by well developed myrmekites. Important occurrences of these «augen charnockites» have been observed near Gjeving, where they grade very progressively into Bamble granitoids. Their affinities whith the Hovdefjell and Ubergmoen «charnockitic augen gneisses» (see p. 37) are obvious.

A special type of deep catazonal rock: the fayalite mangerite of Morkeheia.

Deep catazonal rocks (i.e. corresponding to a regional metamorphism in the granulite facies - Michot 1960) are essentially occurring south of the «Great Breccia» and have consequently been determinant to support the old hypothesis of a total independance between Telemark and Bamble (Bugge, 1943). The recent discovery of a fayalite mangerite in the orthoamphibolites of Morkeheia (Touret, 1967a) is then important as it indicates that deep catazonal rocks are also liable to occur north of the «Great Breccia». (Other granulite facies rocks have also been discovered at Kallingsheia, W. of Åmli - Ploquin, unpublished). The rock is very similar to the Bjerkrem-Sogndal mangerite (Rogaland) (Michot, 1960) and consists of mesoperthite, An 32 plagioclase, fayalite (Fa95Fo5), clinopyroxene (diallage), some hyperstene, biotite, quartz and retromorphic amphibole. Near the mangerite some occurrences of antophyllite rich gneisses which are possibly retromorphosed ultrabasites have been observed.

The border zone of the granulite facies area: cordierite migmatites and cordierite-antophyllite gneisses

The transition amphibolite facies / granulite facies is gradual and takes place in a «border zone» indicated on the map by mixing charnockitic and granitic migmatite symbols and occurring around the whole granulite facies area (Bugge, 1940, 1943). In the border zone the typical granulite facies minerals progressively appear, but a supplementary fact of fundamental importance may be observed near Tvedestrand: the apparition of cordierite, occurring as blue and sometimes gem quality crystals (Lacroix, 1889). The presence of cordierite in various places of the Bamble is a well-known fact and most of them are along or near the Skagerak coast. Cordierite is very pure, often polysynthetically twinned along (110) and rich in Mg (2V about 70-80°). It contains numerous inclusions of quartz, biotite and iron ores (hematite with small ilmenite exsolution lamellae). It may crystallize as 15 or 20 cm large poikiloblasts often surrounded by myrmekite-like quartz plagioclase association.

Near Tvedestrand cordierite often occurs within graphite paragneisses. But it is by no means restricted to the paleosome and is also abundant in granodioritic neosome. Farther north (Akland, Søndeled) cordierite, if present, is systematically surrounded by ortorhombic amphiboles (antophyllite and gedrite), often in sufficient amount to give antophyllite-cordierite and gedrite-cordierite gneisses (Bugge, 1943) which occur in many instances at the contact between quartzites and ortho-amphibolites or hyperites (Bugge, 1943).

The genesis of the cordierite migmatites and cordierite-antophyllite gneisses is complicated and not fully understood. It is highly probable that an initial alumina rich composition and, in the case of the cordierite-antophyllite gneisses, a magnesium metasomatism have been important. However, cursory investigations have convinced the present writer that, for the Tvedestrand cordierite migmatite at least, the proximity of the granulite facies was the determinant factor: cordierite appears within paragneisses and old group rocks whose composition do not significantly differ from those occurring farther north (particularly between Nesverk and Ubergsmoen), which only contain sillimanite ,biotite and garnet.

It may therefore be concluded that, in the investigated area, cordierite is only stable as a regional metamorphism mineral near the granulite facies lower boundary. This important conclusion gives us one of the only liable arguments for a tentative determination of the P-T conditions of regional metamorphism (Fig. 6).

Cordierite seems to disappear within the granulite facies area itself, as it is not mentioned as a constituent of arendalites (Bugge, 1943)[1]). The regional stability field of cordierite in Southern Norway is therefore exceptionally narrow. It is likely that in the granulite facies area, pressure conditions are too high for the relatively low pressure cordierite which is probably replaced by garnet, quartz and iron ores.

The pegmatites

The description of the «younger group» would not be complete without mentioning the numerous pegmatite veins which occur everywhere within the investigated area (only some of the most important dykes could possibly be indicated on the map). Although all pegmatites are in my opinion related to the same type of hydrothermal processes, two types at least may be recognized on the field (Barth, in Holtedahl, 1960):

— Small, lense-shaped, concordant pegmatites particularly abundant in basic rocks and probably formed by lateral secretion (Reitan, 1956). Some at least

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[1]) The association hyperstene-cordierite has recently been found by the writer at Dypvåg; evidence of the predicted replacement of cordierite by garnet towards the core of the «arendalite» domain have also been observed (Note added in proof).

are closely related to the regional migmatization and may be considered as a neosome with a particularly heterogeneous grain size. Generally rich in plagioclase, they contain quartz, feldspars, biotite, often amphibole and garnets.

— Large discordant or sill-like bodies of nearly granitic composition (Barth, in Holtedahl, 1960), which hold much perthitic microcline and quartz, sometimes as graphic intergrowths. Many rare minerals have been found within these large pegmatites, which are extensively worked out for quartz and feldspars (see complete list in Barth, in Holtedahl, 1960). These pegmatites are always undeformed, even in the diapthoretic areas (see p. 33) and are obviously late-tectonic or post-tectonic. They bear witness of the hydrothermal activity which ended the migmatitic cycle and had such a great importance in zones affected by retrograde metamorphism.

Conclusion on the 1 billion year old regional migmatization

If the study of the «old group» had shown the unquestionable similitudes between Telemark and Bamble areas, the description of migmatites dwells on their no less obvious differences: granites are more extensive and migmatites more granitic in Telemark than in the Bamble. These differences (as well as the resemblances) appear at first glance on the geological map: black is reserved for supracrustals or slightly granitized rocks, while red (or violet) indicates the neosome rocks in the broadest sense. The proportion of red versus black is consequently more or less proportional to the amount of granitized (or «mobilized») rock during the migmatitic evolution. It becomes then clear that, south of the Great Breccia, black dominates and red is subordinate, while it is the opposite in the Telemark area. In other terms, granitization increases towards the north, but we have seen throughout the petrographical description that the evolution was very progressive, apart from the rather marked jump at the passage of the «Great Breccia». Moreover a good deal of arguments point to the definite similitude of granites and granitoids on both sides of the «Great Breccia», the most important being the ore rich character of the Åmli granite and Holt granitell (see p. 23). We may therefore speak of a «gradient» of granitization from the Skagerak coast towards the Telemark area, therefore inverse of the metamorphic gradient.

If we correlate the extension of granites with the degree of metamorphism, it consequently appears that in Southern Norway granites are widespread in the lower part of the amphibolite facies (indicated in the Telemark area by primary epidote, see p. 23), while they are less abundant in the upper part of this facies (sillimanite-muscovite-almandin and sillimanite-orthoclase-almandin subfacies) and in the hornblende granulite subfacies.

The relative scarcity of granites in the deepest zones of regional metamorphism has been pointed out by several geologists (Den Tex, 1965, Noe-Nygaard, 1955, Beloussov, 1966) and supports the notion of a «degranitization» zone under the widespread mesozonal granites (Noe-Nygaard, 1955, Beloussov, 1966). This scheme indeed fits the field observations within the investigated area, but the prevalance of supracrustals rests within the «degranitization» zone indicates that no huge granites of the mesozonal type have ever been formed during its metamorphic evolution and that the degranitized area do not arise from the transformation of earlier granites. The term «degranitization» may therefore be misleading and I would preferably use «agranitization» (a privative), which insists on the fact that no widespread granites have been formed when the rocks have been submitted to P-T conditions corresponding to the amphibolite facies.

How can we try to explain this remarkable situation, which seems by no means restricted to Southern Norway and appears to be the rule more than the exception in precambrian terranes where granulite facies rocks are exposed on a regional scale (Den Tex, 1965). It is impossible to discuss here this fundamental problem at length, but it is in my opinion very likely that, as suggested by many writers (Termier and Termier, 1956, Den Tex, 1965), the water balance during the migmatitic evolution has been of greatest importance. Extension granitization universally occurs under amphibolite facies metamorphic conditions (probably corresponding to temperature and pressure above the granite «minimum melting curve»), but only in a water saturated milieu (more than 4 % water in weight) (Winkler, 1965). If the milieu is water deficient, mobilization starts only at higher temperatures and, as shown experimentally (Winkler, 1965), the amount of mobilized material strictly depends upon the available quantity of water.

It may therefore be assumed that, in the Telemark area, enough water was present to allow an almost complete mobilization in the amphibolite facies — and the «dry» characteristics of the Åmli granite indicate that even in this region the quantity of water was near a minimum, — while south of the Breccia, a more water deficient environment made it possible to reach deeper metamorphic conditions (hornblende granulite subfacies) with only a local and partial mobilization (Den Tex's «dry anatexis») (Den Tex, 1965).

The fundamental reasons of this differential water behavior are still to be found. A simple way to reconstitute the metamorphic evolution, which has to be taken as a working hypothesis, may be summarized as follow:

1°) deposition of the supracrustal old group, followed by diagenesis and probably a first epimetamorphism during which most of the initial water has been expelled.

2°) high grade metamorphism starting directly in the deepest zones (hornblende granulite subfacies), probably under the influence of a relatively sudden increase of temperature, and evolving towards the more superficial levels as a metamorphic «wave» progressively damped down.

The granulite facies metamorphism is characterized by dehydration reactions and liberates water which tends to migrate to regions of decreasing pressure, thus explaining the structural position of most mobilized rocks in the core of migmatitic anticlines (see p. 21). On the regional scale, the rock water content is therefore increasing when the intensity of metamorphism is decreasing and becomes sufficient for an almost complete mobilization in the upper part of the amphibolite facies. Water may also serve as a vector to carry the necessary alkaline, (Na and especially K (Marmo, 1967)) and explains the larger K content of Telemark granites (Fig. 5). Several mechanisms may be referred to to explain the mobilization itself (anatexis, diffusion by intergranular fluids, etc.), but the writer is inclined to believe that the «hydrothermal» model as recently presented by Marmo (1967) fits best the observed field evidences.

This tentative reconstitution of the metamorphic evolution is only possible of the climax of metamorphism is reached relatively rapidly in the granulite facies area. This could be explained by a sudden increase of heat flow at beginning the deep regional metamorphism, perhaps provided by syntectonic basic intrusions (Gates, 1967) and I for my part believe that some hyperites at least, far of being epizonal intrusions as generally accepted (see p. 14), could precisely have been intruded in the catazone and indicate (or even initiate?) the start of the regional migmatization.

P-T conditions of regional metamorphism in Southern Norway

From Telemark towards Bamble, the following metamorphic facies are successively encountered: Low amphibolite-facies (Telemark), high amphibolite facies (sillimanite-almandine-muscovite subfacies and sillimanite-almandine-orthoclase subfacies) and hornblende-granulite subfacies (Bamble).

Little can be said about the P-T conditions of the first of these subfacies, which does not contain any index mineral, but we may however expect that they were above the curve of «minimum melting granite» in a water saturated system, as all rocks are within the domain of regional migmatization (Winkler, 1965).

The other subfacies may be tentatively approached by the following considerations (Fig. 6):

— The only aluminium silicate occurring in the Bamble is sillimanite. The general P-T conditions must consequently lie within its stability field, which

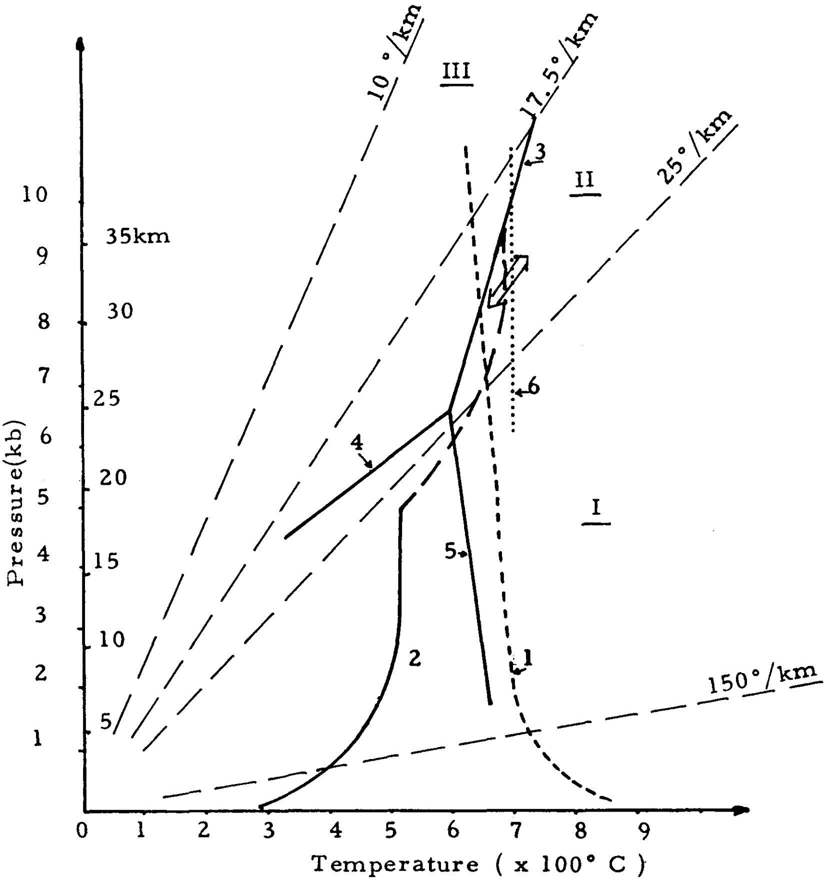

Fig. 6. *Tentative determination of the P-T conditions of the maximum regional metamorphism.*

1: Minimum melting curve of granite (Bowen and Tuttle, 1958). 2: lower limit of the stability field of Mg-cordierite (Schreyer and Yoder, 1964). 3: Kyanite-Sillimanite, 4: Kyanite-Andalusite, 5: Andalusite-Sillimanite (Althaus, 1967). 6: Temperature boundary (700° C) of the granulite facies/amphibolite facies transition (see text).

Double arrow: P-T conditions of the maximum regional metamorphism in the investigated area.

I: Low pressure (Hercynian) metamorphism, II: Intermediate pressure (Caledonian) metamorphism, III: High pressure (Alpine) metamorphism (Zwart, 1967).

in this paper is taken from the most recent determinations of Althaus (1967). — The transition amphibolite facies / granulite facies is marked among other facts by the widespread occurrence of mesoperthite of rough composition Or50 Ab50. This feldspar composition indicates a temperature above 660° C

(Michot, 1961), and being independant of water pressure, is certainly a good regional temperature indicator. Determinations by Barth's thermometer (Barth, 1955) have given 700° C to the writer, a result which closely corresponds to the maximum temperature of 680° C indicated by Barth (1955) for Bamble amphibolite facies rocks. I suggest therefore 700° C as a possible temperature for the granulite facies in the investigated area.

— The occurrence of cordierite at the close contact of the granulite facies area gives another important indication, as the stability field of Mg-cordierite is relatively well-known (Schreyer and Yoder, 1964). As may be seen on Fig. 6, the temperature of formation of cordierite increases rapidly in sympathy with pressure and effectively approaches 700° C for pressures of about 8-9 kb. These values (700° C, 8-9 kb) may consequently be taken as a reasonable order of magnitude for the granulite facies / amphibolite facies transition in Southern Norway.

All these data reported on the same P-T diagram (Fig. 6), bracket the possible field of maximum pressure and temperature reached during the regional metamorphism. It falls unquestionably within the range of intermediate metamorphism (Caledonian type) as defined by Zwart (1967).

III. THE RETROMORPHIC AND POSTMETAMORPHIC ROCKS

Evidences of a local retrograde dynamometamorphism: the R1 and R2 diaphtorites (Touret, 1967b)

Southern Norway as a whole shows but a few traces of retrograde metamorphism: the mineral paragenesis of all rocks already described corresponds to the climax of metamorphism, reached about 1000 million years ago, and has practically remained unchanged. This conclusion is particularly evident for the granulite facies rocks, in which as mentioned above amphibole is primary and biotite related to unachieved dehydration reaction.

But retromorphic minerals are to be found within definite zones which have remained mobile and petrographically active well after the end of the regional metamorphic paroxysm. This retrograde metamorphism is marked by specific deformations which indicate its dynamic character; on the basis of the deformations and neoformed minerals, two types of retromorphic rocks (diaphtorites) have been recognized:

— *The blastomylonitic R1 diaphtorites,* retromorphosed in the epidote-amphibolite facies, which occur in a relatively broad and continuous zone on both sides of the «Great Breccia» and are best represented by the spectacular Vegårshei, Ubergsmoen and Gjerstad augen gneisses.

— *The mylonitic R2 diaphtorites,* retromorphosed in the greenschist facies and most typical along the «Great Breccia», but also found as extensive mylonites which dissect the whole precambrian basement into great rhomboidal slices (Selmer-Olsen, 1950) and may have form at quite different periods: precambrian (end of the regional migmatization), silurian (caledonian orogenesis), permian (formation of the Oslo graben) or even tertiary, as indicated by recent paleomagnetic measurements (Storetvedt, 1966). These mylonites are often more easily weathered than the undeformed rocks and therefore appear in the topography as straight and narrow depressions. Many elongated fjord and lakes (for instance Vegår lake), most rivers and roads are following these depressions, so that a geological sampling restricted to road exposures would show the retromorphic rocks much more widespread than they really are.

The R1 diaphtorites (retromorphism in the epidote-amphibolite facies)

Polymetamorphic migmatites

In a several kilometers wide belt extending on both sides of the «Great Breccia», all rocks carry epidote (pistacite) in much greater amount than in the Telemark granite (see p. 23). Some basic rocks or residual cipolinos are mantled by a rim of pure epidote, which in this case at least is clearly secondary. At the same time, the plagioclases may conspicuously be altered (saussuritization), while hornblende presents bluish shades and muscovite, tremolite and actinolite are widespread.

This retromorphism is closely related to a particular type of deformation: migmatites are deformed by several folding phases, the axial plane of the isoclinal folding which is so widespread among Bamble migmatites (see p. 19) being refolded along new N-S axes (Fig. 7). Along these second axial planes, a new neosome appears as elongated epidote rich granodioritic dykes obviously discordant on the banded migmatites folds.

This granodioritic neosome indicates that a second mobilization did locally occur during the retromorphic evolution and the migmatites are therefore polymetamorphic. Important granitoidic bodies occur within these polymetamorphic migmatites near the villages of Vegårshei, Ubergsmoen and Gjerstad. They are made of very coarse grained rock which may only be called «augen gneiss», as unlike other Bamble granitoids it always presents a conspicuous foliation and/or lineation.

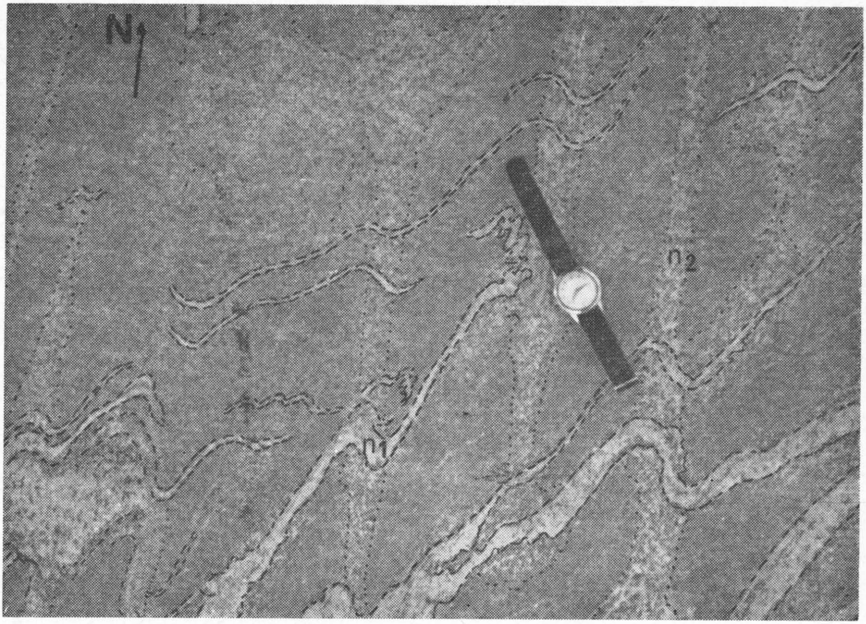

Fig. 7. *Polymetamorphic migmatites in the domain of the R1 diaphtorites. A new leucocratic neosome* n_2 *appears in the axial plane of late folds in the Bamble migmatites* (n_1 = *neosome contemporaneous of the regional migmatization). Kilane, south of Lake Vegår.*

The augen gneisses of Vegårshei - Ubergsmoen and Gjerstad (Touret, 1967b)

The augen gneisses of Vegårshei-Ubergsmoen and Gjerstad, which contain many feldspars phenocrysts of a remarkable size (up to 10 cm), have recently been described elsewhere in some detail (Touret, 1967b), and I shall only mention here the most important results.

Two principal types have been recognized:

— the «normal» augen gneisses, which contain quartz, microcline, plagioclase, biotite, green hornblende, sometimes garnet, secondary epidote and muscovite. The lense shaped «augen» are mostly feldspathic (microcline or plagioclase) and show obvious traces of deformation and recrystallization. They correspond in most cases to an old feldspar phenocryst which has been deformed (ondulous extinction, twisted twin planes), and is wholly or partially replaced by a mosaic of small size recrystallized feldspar crystals (granulation). The groundmass is almost completely recrystallized and the texture may therefore be described as «blastomylonitic» (Malaroda, 1946).

Detailed observations have shown that the most constant structural element in the augen gneisses was a more or less constant B-lineation (Touret, 1965b), often parallel to the late fold axes within the polymetamorphic migmatites; beside these linear augen gneisses more deformed foliated or microfolded types occur.

The mineralogical composition of the augen gneisses widely varies from acid microcline rich types to basic ones, in which the eyes are almost exclusively plagioclasic. In an interesting variety occurring south of the Morkeheia amphibolites, the eyes are made of recrystallized green hornblende. It is highly probable that these «reverse augen gneisses» (Touret, 1967b) derive from deformation and recrystallization of amphibolites or basic migmatites.

— the «charnockitic» augen gneisses occur at the southern end of the Vegårshei (Hovdefjell)- and Ubergsmoen (Slettåsheia)- bodies. Their mineralogical composition is in many ways comparable to that of charnockitic migmatites: bluish quartz, mesoperthitic orthoclase, antiperthititic plagioclase, orthopyroxene and clinopyroxene, dark green and brownish hornblende, poeciloblastic garnet and highly corrodated and indented crystals of dark brown to reddish biotite. Retromorphism is indicated by the partial microclinization of orthoclase (Touret, 1967b) and by the sporadic occurrence of epidote. The texture is also blastomylonitic, but most augen are cataclastic and only partially recrystallized. Two types have been recognized: one is garnet rich (Ubergsmoen type), while in the other (Hovdefjell type) orthopyroxene predominates.

The similitudes between the charnockitic augen gneisses and the charnockitic migmatites are obvious, but so is also the gradual transition between normal augen gneisses and charnockitic augen gneisses. In the region of Vegårshei and Ubergsmoen, numerous observations have established the following evolution, which corresponds to an increase of the metamorphic gradient along the regional strike NE-SW:

«normal» augen gneisses → «normal» garnet rich augen gneisses → «charnockitic» garnet augen gneisses (Ubergsmoen type) → «charnockitic» orthopyroxene augen gneisses (Hovdefjell type).

As may be observed in great detail within the Vegårshei body, this evolution is absolutely gradational; as metamorphic facies is increasing, the rocks look more homogeneous and igneous, but always contain many inclusions of surrounding rocks (older as well as younger group). The tendency towards an igneous appearance culminates for the charnockitic augen gneisses, which occur at Hovdefjell and Slettåsheia as intrusive like circular bodies which resemble some granitic plutons but always however remain concordant with the surrounding migmatites.

Origin of the Ubergsmoen-Vegårshei and Gjerstad augen gneisses

The Ubergsmoen-Vegårshei and Gjerstad augen gneisses are similar in many ways to some granitoids which have been described within the Bamble: the «normal» augen gneisses to coarse-grained Bamble granitoids (p. 19) and the «charnockitic» augen gneisses to charnockitic augen migmatites occurring at the periphery of the arendalite area (p. 27). It would however be a great oversimplification to consider that the augen gneisses are but granitoids which have been subsequently deformed and dynamically retromorphosed. The geochemistry of the augen gneisses is different indeed from that of granites and granitoids, particularly for Na and K, which vary much more widely in the augen gneisses that in any other granitic group within the investigated area (Fig. 5). The main size of feldspars phenocrysts is significantly higher than in any Bamble granitoid; many K-feldspar appear to have replaced former plagioclase phenocrysts. (Touret, 1967b).

Several observations indicate that the first deformative movements did occur very early, when the grade of regional metamorphism was still at its maximum. During this early deformation, a feldspar metablastesis took place, most probably under the influence of an alkaline metasomatism carrying the necessary Na and K. The cataclastic movements did continue after the period of metablastesis and during the retrogressive evolution and gave the augen gneises their peculiar blastomylonitic textures.

It is admitted by the author that the alkaline metasomatism results from a slow percolation of hydrothermal solutions carrying $Na+$, $K+$ and much silica (Korjinskii's percolative metasomatism, 1965). In this respect the genesis of augen gneisses is not fundamentally different from that of Bamble granitoids, if we accept Marmo's «hydrothermal model» (see p. 32). It is however certain that the alkaline metasomatism has greatly been facilitated by the specific deformations which occurred in the domain of the augen gneisses. The R1 diaphtorite belt may therefore be considered as a wide zone of specific mobility where hydrothermal solutions could percolate easily and have remained petrographically active well after the extinction of the metamorphic «wave» (see p. 32) in the rest of the basement.

Metamorphic facies of the R1 diaphtorites:

Polymetamorphism is very apparent among R1 diaphtorites, which have always retained some traces of the maximum metamorphic facies they have reached (Touret, 1967b). Two metamorphic facies may therefore be defined for these diaphtorites: a maximum one, which was probably attained at the end of the K-feldspar metablastesis, and a minimum one which indicates the end of the retrograde metamorphism.

The maximum corresponds to amphibolite facies (normal augen gneisses) or hornblende granulite subfacies (charnockitic augen gneisses). It is interesting to note that they are definitely higher than the metamorphic facies of the surrounding rocks. This fact consequently confirms Barth's observations (Barth and Reitan, in Rankama, 1963) that augen gneisses are formed at higher temperatures than any other granitoidic rocks. (Barth's determinations indicate 680° C as maximum temperature for augen gneisses in the amphibolite facies, very close indeed to the 700° C which have been taken here as the temperature of the amphibole facies/granulite facies boundary).

Little can be said about the minimum metamorphic facies of the R1 diaphtorites: the abundance of epidote, the alteration of oligoclase correspond to the amphibolite-epidote facies (Barth, 1962, Ramberg, 1952), but the absence of any aluminium silicate polymorph, due to the alkaline metasomatism, makes it impossible to determine precisely the P-T conditions of the retrograde metamorphism.

The end of the cataclastic movements: the R2 diaphtorites (greenschist facies retrograde metamorphism) and postmetamorphic rocks

The R2 diaphtorites

The R2 diaphtorites occur as a fracture net which dissect the whole basement into great rhomboidal slices (Selmer-Olsen, 1950), but are best exposed along the «Great Breccia» as important (10 to 100 m. thick) layers dipping roughly 40-50° SE. The very fine grained rock is reddish (hematite) or greenish (epidote), highly jointed and sometimes banded. Near the mylonites, the migmatites are intensely deformed by complicated small-scale folds which are due to several phases of folding and are truncated by the mylonite bands. Under the microscope, rests of cataclased minerals (mostly feldspars) appear in a very fine grained and hardly recognizable quartz rich matrix where typical greenschist facies minerals occur: chlorite, muscovite, actinolite. Epidote and hematite may be very abundant, tourmaline is common and fluorine has been found in one exposure along the southern coast of Vestfjorden. In or near the mylonites numerous hydrothermal quartz dykes occur. They contain sometimes very big crystals of actinolite, dolomite and calcite (Selåsvatn). These dykes may be so imbricated that they produce true quartz breccia, as for example between Mo and Gjerstad.

In southern Norway, a much debated problem refers to the relative movements on both sides of the «Great Breccia» (Barth, in Holtedahl, 1960, Elders 1963). Numerous traces of movements (slickensides, lineations) have been observed, but they are superficial and very difficult to interpret in the very complex general structure. Most measurements indicate however a relative downwarping of the Eastern Block (Bamble), which is in agreement with the conclusions of earlier workers (Elders, 1963, Selmer-Olsen, 1950). But the study of Vegårshei and Gjerstad augen gneisses has shown that the region of the «Great Breccia» corresponds to a very early zone of tectonic mobility which has remained active throughout the geological history of southern Norway and has suffered many phases of deformation. The R2 movements are very late and did occur at a relatively shallow level of the Earth crust. They may consequently have no relationship with the earlier and deeper movements contemporaneous of the R1 retrograde metamorphism, which are more in my opinion in the opposite direction, in order to bring in contact the deep catazonal Bamble -and the mesozonal Telemark migmatites.

The postmetamorphic rocks: dolerite dykes and albite-carbonate breccia

Within the investigated area, two types of intrusive or extrusive rocks did occur after the end of metamorphic evolution and are obviously related to some of the R2 mylonites (Barth, in Holtedahl, 1960, Barth and Ramberg, 1966): dykes of dolerite and an explosive albite-apatite-carbonate rich breccia.

Dolerite dykes

Most dolerite dykes occur along the Skagerak coast, but some have also been found in the whole Bamble and even in the southern part of Telemark. Their mineralogical composition is rather variable: most rocks occurring along the coast contain about 50 % plagioclase (zoned labradorite An 50-70) and 50 % dark minerals: brown hornblende and augite (Barth, in Holtedahl, 1960), while new occurrences found north of the «Great Breccia» (south of Vallekilen, east of Nesknollen) are very basic rocks indeed with augite and brown hornblende as only phenocrysts in a subaphanitic matrix. Iron ores are very abundant. The groundmass is more or less altered into chlorite, serpentine and hydromicas. Vesicles filled with calcite, zeolithes, sometimes quartz are common. Some dykes (east of Nesknollen) show a distinct increase in grain-size towards the middle of the dyke while others (Vallekilen, east of Nesknollen) present a conspicuous orbicular texture.

The age of these dykes remains still an open problem. Basic intrusions of permian age certainly occur towards the border of the Oslo district, but it would be highly speculative to extrapolate this age to the whole southern Norway. Recent paleomagnetic determinations in the region of Egersund have given tertiary ages and show that basic intrusions may occur within a wide time range (Storetvedt, 1966). It is therefore interesting to note that the chemical composition of basic dykes exposed near Vegårshei is tholeitic and close to the one of other premetamorphic basic rocks (Fig. 2), thus indicating a remarkable constancy in the composition of basic rocks during the whole history of the region.

The albite-apatite-carbonate breccia

An albite-apatite-carbonate-bearing explosive breccia has been recently discovered along the road Ubergsmoen—Vegårshei, 1 km about north of Haugland bridge, and is in my opinion related to the fault which bords the lake Hauglandsvatn. The breccia is exposed on about 200 m, in orthoamphibolites, as an intricate net of 2-3 cm thick veinlets made of clouded albite, calcite and apatite. The veinlets grade into larger green and pink patches which contain great amount of apatite, sometimes in beautiful idiomorphic crystals and some calcite. Idiomorphic ilmenorutile, rutile or amphibole may also be present. Amphibolitic fragments in and around the breccia are conspicuously altered: replacement of plagioclase by small muscovite, chlorite, epidote and calcite, neoformation of actinolite, albite, chlorite and calcite.

The Haugland breccia is likely to be due to an episode of explosive volcanism and may therefore be compared to the numerous explosion sites described in southern Norway, the most famous being at Fen (Telemark) (Barth and Ramberg, 1966). The similitudes with the Fjone «calcite syenite» (Dons, 1962) are also obvious. Another breccia which was probably of a comparable type has been mentioned by A. Bugge (1934) on the southern shore of the lake Vegår (Rennesund), but due to the bad quality of exposures could not be found again by the present writer.[1])

The age of this explosive volcanism remains rather uncertain. The Fen carbonatites are between 565 and 603 millions years old. It has been supposed (Barth and Ramberg, 1966) that all carbonate rich explosive breccias were more or less contemporaneous and consequently related to the development of the caledonian orogeny.

Acknowledgements

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[1]) This exposure has been rediscovered during the summer 1968 at Degernes and appears to be an intrusive plug of ultrabasic hornblende peridotite. (Note added in proof).

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N.G.T. = Norsk Geologisk Tidsskrift.

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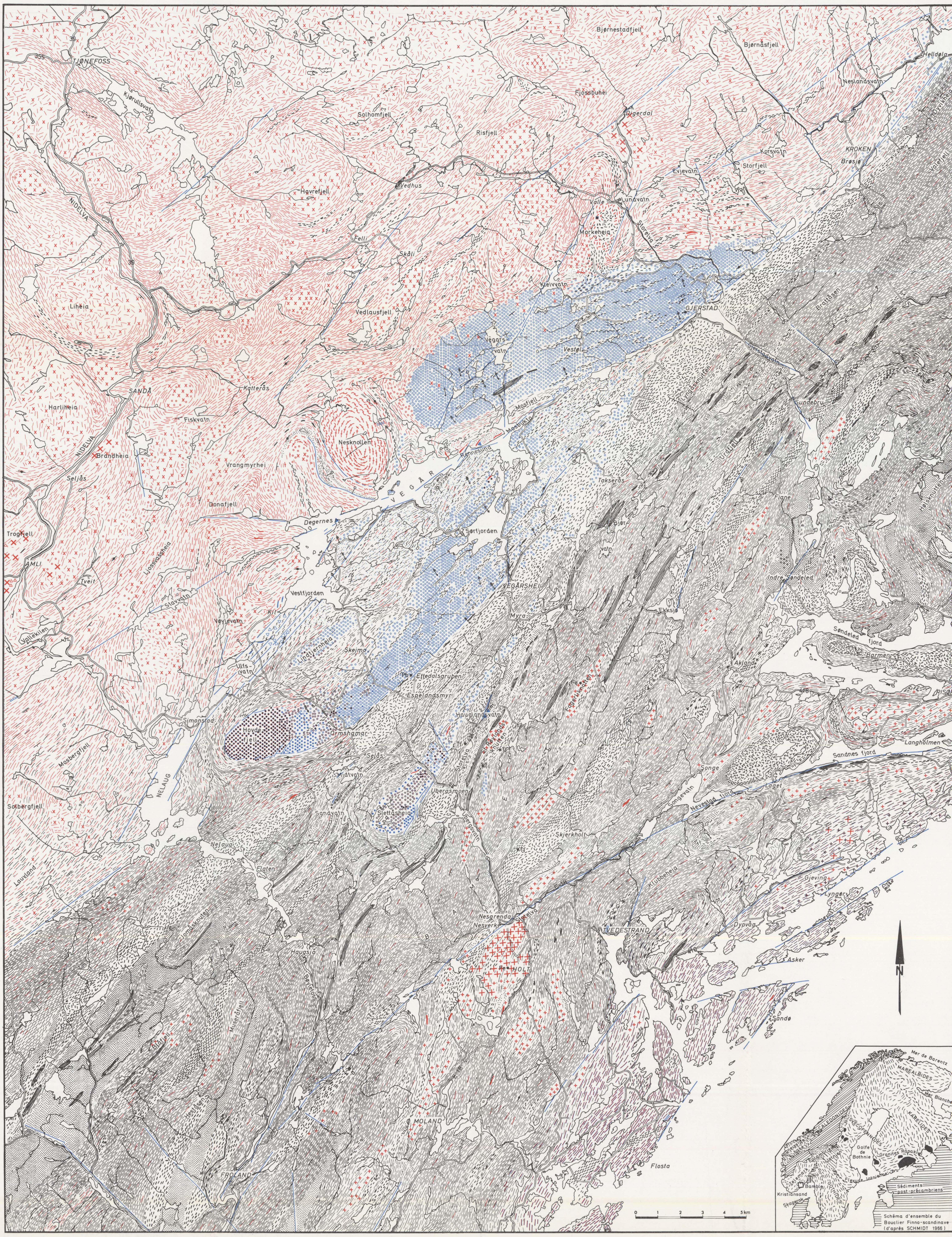
CARTE GÉOLOGIQUE DU SOCLE PRÉCAMBRIEN AUTOUR DU LAC VEGÅR

(DÉPARTEMENT D'AUST-AGDER, NORVÈGE DU SUD)

PAR J. TOURET (1967)



LÉGENDE

DIAPHTORITES R2 (RÉTROMORPHOSE DANS LE FACIÈS SCHISTE VERT) ET ROCHES IGNÉES NON MÉTAMORPHIQUES.

R2 DIAPHTHORITES (GREEN SCHIST FACIES RETROGRADE METAMORPHISM) AND POST-METAMORPHIC IGNEOUS ROCKS.

42: Brèche d'explosion à albite, apatite et calcite, et ultrabasite intrusive.
Albite, apatite and calcite explosion breccia, and intrusive ultrabasite.

41: Filons de dolérite et diabase postmétamorphiques.
Post-metamorphic dolerite and diabase dykes.

40: Filons hydrothermaux à actinolite, dolomite et quartz.
Hydrothermal dykes containing actinolite, dolomite and quartz.

39: Brèches d'origine tectonique à ciment de quartz.
Tectonic quartz breccia.

38: Mylonites de la «Grande brèche».
«Great Breccia» mylonites.

DIAPHTORITES R1 (RÉTROMORPHOSE ATTEIGNANT LE FACIÈS AMPHIBOLITE-ÉPIDOTE).

R1 DIAPHTHORITES (EPIDOTE-AMPHIBOLITE FACIES RETROGRADE METAMORPHISM).

37: Gneiss oeillés «normaux» à texture blastomylonitique des massifs de Vegårshei, Ubergsmoen et Gjerstad.
Blastomylonitic «normal» augen gneisses of Vegårshei, Ubergsmoen and Gjerstad.

36: Gneiss oeillés «normaux», variété à grenats.
«Normal» augen gneisses with garnets.

35: Gneiss oeillés «normaux» microplissotés.
Microfolded «normal» augen gneisses.

34: «Antigneiss oeillés »: gneiss oeillés blastomylonitiques dans lesquels la plupart des yeux» sont constitués par des phénoblastes de hornblende verte.
«Reverse augen gneisses»: blastomylonitic augen gneisses where most eyes are made of green hornblende.

33: Gneiss oeillé charnockitique de Ubergsmoen (variété à grenat et hornblende verte).
Ubergsmoen charnockitic augen gneiss (garnet, green hornblende).

32: Gneiss oeillé charnockitique de Hovdefjell (variété à pyroxènes orthorhombique et monoclinique et hornblende verte).
Hovdefjell charnockitic augen gneiss (with ortho- and clinopyroxene and green hornblende).

31: Migmatites polymétamorphiques liées à la rétromorphose R1.
Polymetamorphic migmatites related to the R1 retrograde metamorphism.

MIGMATITES ET GRANITES LIÉS À LA MIGMATISATION RÉGIONALE À 1 MILLIARD D'ANNÉES. (GROUPE RÉCENT).

MIGMATITES AND GRANITES RELATED TO THE 1 BILLION YEAR OLD REGIONAL MIGMATISATION (YOUNGER GROUP).

a) Niveau de métamorphisme régional correspondant au faciès amphibolite (mésozone à catazone supérieure).
Amphibolite facies regional metamorphism (mesozone to upper catazone).

30: Pegmatites, en général à microcline, parfois à texture graphique. (Seuls certains filons parmi les plus importants ont été représentés).
Microcline-rich pegmatites, sometimes graphic (Only some of the more important dykes have been indicated).

29: Diorite et granodiorite orientés du dôme de Nesknollen.
Orientated diorite and granodiorite of the Nesknollen dôme.

28: Diorite et granodiorite microplissotés du dôme de Nesknollen. (Plis d'échelle centimétrique).
Microfolded diorite and granodiorite of the Nesknollen dôme. (Folds of centimetre scale).

27: Migmatites basiques à cordiérite de Tvedestrand, situées en bordure du domaine des charnockites.
Tvedestrand cordierite basic migmatites, on the border of the charnockite area.

26: Gneiss à cordiérite-antophyllite.
Cordierite-anthophyllite gneiss.

25: Migmatites oeillées du Telemark (embréchites oeillées).
Telemark augen migmatites.

24: Granites nébulitiques du Telemark, en général à grain fin.
Telemark nebulitic granites, generally fine-grained.

23: Granite nébulitiques du Telemark, variété d'Åmli (granite leucocrate à magnétite).
Telemark nebulitic granite of the Åmli type (fine-grained magnetite-bearing leucocratic granite).

22: Granitoïdes de Bamble (granites, granites monzonitiques et granodiorites, porphyroïdes, à texture plus ou moins orientée).
Bamble granitoids (coarse-grained granites, monzonitic granites and granodiorites, more or less orientated).

21: «Granitel» de Holt: granite porphyroïde à magnétite.
Holt «Granitel»: coarse-grained magnetitic granite.

20: Amphibolites mobilisées et parfois surmicacées du Telemark (vaugnérites).
Telemark amphibolites, mobilised and biotite-rich (vaugnerites).

19: Migmatites nébulitiques du Telemark, recoupées par de nombreux filons granitiques.
Telemark nebulitic migmatites with numerous cross-cutting granitic dykes.

18: Agmatites.
Agmatites.

17: Migmatites rubanées du Telemark, non différenciées (stromatites à dictyonites à néosome abondant de composition essentiellement granitique; nombreux filons sécants de granite du Telemark.
Undifferentiated Telemark banded migmatites (stromatites to dictyonites with an abundant and mostly granitic neosome; numerous cross-cutting Telemark granitic dykes).

16: Migmatites rubanées du Telemark, plissotées (plis d'échelle décimétrique à métrique).
Folded Telemark banded migmatites (folds of decimetre to metre scale).

15: Migmatites rubanées du Bamble, non différenciées (endomigmatites à stromatites à néosome peu abondant et de composition essentiellement granodioritique; pas de filons granitiques sécants).
Undifferentiated Bamble banded migmatites (endomigmatites to stromatites with a scarce and mostly granodioritic neosome; no cross-cutting granitic dykes).

14: Migmatites rubanées du Bamble, plissotées.
Folded Bamble banded migmatites.

13: Migmatites «évoluées» du Bamble (stromatites à dictyonites). Bien que très subjectif, le «degré d'évolution» des migmatites mesure l'importance relative du néosome par rapport au paléosome. Il est ici proportionnel à l'abondance des traits rouges dans le figuré des migmatites rubanées de Bamble.
Bamble «evolved» migmatites (stromatites to dictyonites). The «degree of evolution», which is very subjective, is roughly proportional to the relative amount of neosome versus paleosome. It is shown here by the density of red strokes in the Bamble banded migmatites symbol.

b) Niveau de métamorphisme régional correspondant au faciès granulite (subfaciès hornblende granulite) — Catazone profonde.
Regional metamorphism in the granulite facies (subfacies hornblende-granulite) — Deep catazone.

12: Mangérite à fayalite en enclave dans les amphibolites de Morkeheia.
Fayalite-bearing mangerite occurring as xenoliths in the Morkeheia amphibolites.

11: Charnockites porphyroïdes associées aux granitoïdes de Bamble dans la zone de transition des arendalites.
Coarse-grained charnockites mixed with Bamble granitoids in the border zone of the arendalites.

10: Migmatites charnockitiques non différenciées (arendalites).
Undifferentiated charnockitic migmatites (arendalites).

ROCHES SUPRACRUSTALES ANTÉRIEURES À LA MIGMATISATION RÉGIONALE À 1 MILLIARD D'ANNÉES (GROUPE ANCIEN).

SUPRACRUSTALS OLDER THAN THE 1 BILLION YEAR REGIONAL MIGMATIZATION (OLDER GROUP).

9: Amphibolites, souvent à grenats, d'origine indéterminée.
Amphibolites of undetermined origin, garnets very common.

8: Orthoamphibolites (traces de texture ophitique visibles au microscope).
Orthoamphibolites (traces of ophitic texture under the microscope).

7: Gabbros à olivine et coronites (hypérites).
Olivine gabbros with coronites (hypérites).

6: Gneiss acides à grain fin, probablement anciennes roches volcaniques acides. Ne sont connus que dans le domaine du Telemark, au Nord de la «Grande Brèche» (S-W de Morkeheia).
Fine-grained acid gneisses, probably older acid volcanics. They occur only in the Telemark area, north of the «Great Breccia» (S-W of Morkeheia).

5: «Cipolins résiduels»: roches finement grenues, riches en quartz, contenant des silicates calciques: diopside, grenat calcique, anorthite, épidote très abondante dans le domaine des diaphtorites R1 et R2. c: cipolins à calcite primaire, diopside et parfois graphite (n'affleurent qu'en bordure du Skagerak). s: skarns à andradite-hédenbergite.
«Residual cipolinos»: fine-grained quartz-rich rocks, containing calc-silicates: diopside, calcic garnet, anorthite, much epidote in the domain of the diaphthorites R1 and R2. c: cipolinos containing primary calcite, diopside, sometimes graphite (these occur only along the Skagerak coast). s: andradite-hedenbergite skarns.

4: Gneiss rubanés de Selås: métagrauwackes ayant conservé les traces d'une ancienne sédimentation rythmique.
Selås banded gneisses: metagraywackes with traces of a primary rhythmic layering.

3: Paragneiss à graphite: gneiss finement grenus, souvent altérés et de couleur jaunâtre, à graphite et biotite en associations orientées, sillimanite et grenats.
Graphite paragneisses: fine-grained yellowish gneisses, often weathered, containing graphite and biotite in orientated intergrowths, sillimanite and garnets.

2: Quartzites riches en sillimanite, à texture nodulaire («nodular granites» de la région de Søndeled).
Sillimanite-rich nodular quartzites (Søndeled «nodular granites»).

1: Quartzites plus ou moins feldspathiques, souvent à biotite ou biotite-sillimanite. Muscovite primaire au Nord de la ligne Ubergsmoen-Sundebru (isograde de la muscovite).
Quartzites, more or less feldspathic, often containing biotite or biotite-sillimanite. Primary muscovite north of a line Ubergsmoen-Sundebru (muscovite isograde).

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DONNÉES STRUCTURALES:
STRUCTURAL DATA:

Pendages
Dip and strike

Couches horizontales
Horizontal

Verticales
Vertical

Axes de plis
Fold axes

Linéations (linéations en B, pénétratives)
Lineations (Penetrative B-lineations)

: Inclinées de 0 à 20°, : 20—60°, : >60°
: *Dipping from 0 to 20°, : 20—60°, : >60°*

Indices minéralisés ou anciennes exploitations minières:
Old mines

Pb : galène Fe : magnétite Ti : rutile

Fond topographique d'après la carte topographique de Norvège à l'échelle 1/50.000. Feuilles 1612 I, II, III et IV.
Topography after the topographical map of Norway (scale 1/50.000) Sheet 1612 I, II, III and IV.

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