PROGRESSIVE METAMORPHISM OF SPARAGMITE ROCKS OF SOUTHERN NORWAY

BY

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WITH 2 FIGURES IN THE TEXT

The Sparagmitian.

The Eocambrian Sparagmite Formation covers large areas in south-eastern Norway. Petrographically it is a coarse, quartzose sediment which in its unmetamorphic facies consists almost exclusively of fragments of quartz and feldspar, frequently conglomeratic. Due to the effect of the Caledonian folding the metamorphism of the Sparagmitian increases, generally speaking, from South-east to North-west. In the upper parts of Gudbrandsdalen and Østerdalen, in Rondane, and in the Atnasjø District, the sparagmite is typically schistose; unmetamorphic facies being quite unknown in these parts. Still closer to the central parts of the Caledonian folding the sparagmite rocks are overlain by pelitic sediments of the Trondheim syncline, but still farther to the West sparagmite beds crop out from underneath the syncline on its west side. The metamorphic grade is here somewhat higher, the rocks being flaggy and granulite-like. This series passes by gradation into an underlying series of epidote-bearing gneisses and gneiss-granites; this fact will be discussed in a later section, however. A few words should now be said about the mineral changes induced in the sparagmite by the progressive metamorphism.

Mineral Composition.

The mineral composition of the unmetamorphic sparagmite, as developed in the south-eastern parts of its area of distribution, is very simple: Clastic grains of quartz and feldspar are cemented together by an interstitial substance of chloritic appearance. It is worthy of notice that the feldspar is always and exclusively microcline; orthoclase is absolutely lacking and except for rare grains of albite in certain of the thin sections, no trace of plagioclase could be seen. The sparagmite was formed through weathering, transport and sedimentation of granitic rocks; by these processes the original granite plagioclase must have been destroyed (by sericitisation or saussuritisation) and removed as powder, whereas the mechanically and chemically more resistant minerals, viz: quartz and microcline, were left to form the coarse sediment. Thus the sparagmite contains no lime-bearing mineral and, other than microcline, no soda-bearing mineral is present.

In the schistose facies of the sparagmite, typically developed in the upper parts of Gudbrandsdalen and Østerdalen, clastic fragments of microcline and quartz are still plentiful, but the groundmass of the rock consists of streaks of recrystallized muscovite alined in the direction of the general schistosity, and of small grains of clastic pieces as well as of crystalloblasts of quartz and albite. (See Fig. 1 1.) The formation of muscovite is not necessarily due to an introduction of potash into the sparagmite; it is more reasonable to assume that the potash was derived from the original microcline fragments, which are manifestly in a state of incipient resolution, and was precipitated in the muscovite, which is manifestly in a state of growth. Thus the formation of muscovite is a process of metamorphic diffusion. The formation of albite, however, is essentially a process of metasomatism. But not all soda is of foreign origin, for the original microcline also contained some soda in its space lattice, and during the metamorphism, due to mechanical action paired with the action of low-temperature solutions, an almost complete exsolution of soda feldspar from potash feldspar resulted. This is evidenced in the thin-sections by the successively increasing amount of perthite lamellae in the microcline fragments as one passes from unmetamorphic into metamorphic facies of the sparagmite. However, to explain the albitic crystalloblasts in the groundmass of the metamorphic sparagmite, introduction of soda from outside sources has to be postulated.

In the granulitic facies of the sparagmite, typically developed in the Opdal District, west of the Trondheim syncline, relics of clastic microcline fragments can be observed as shapeless, patchy individuals that easily could be mistaken for porphyroblasts if it were not for the fact that microcline does not grow, but actually is being replaced in these rocks. This microcline, partly changed into chess-board albite, partly penetrated by growing crystals of quartz and albite, constitutes the last mineral of primary character. The remaining mineral constituents:

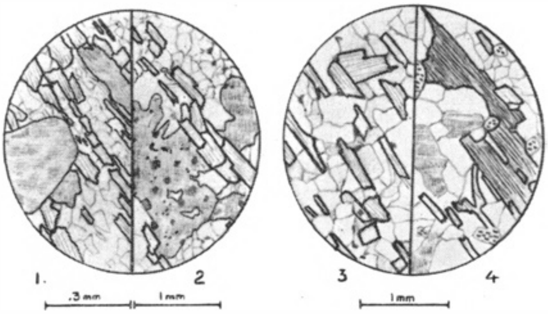

Fig. 1. 1 to 3. Successive stages of metamorphic sparagmite.
4. Basal gneiss.

muscovite, biotite (in some specimens only), quartz, albite, and hematite, are all secondary (see Fig. 1 2). In certain layers of the rock potash feldspar, entirely different from the above mentioned microcline, can be observed in cracks and interstices between the other mineral grains as a foggy, paste-like cement of obvious replacement origin. This potash feldspar is orthoclase, and as distinct from microcline it is stable and growths readily with increasing metamorphism. The expulsion of microcline from the sparagmite rocks is an interesting process which thus can be followed step by step. To begin with the microcline fragments are attacked by solutions and the extracted potash redeposited in muscovite; in a higher stage not only muscovite, but also orthoclase starts growing; thus microcline is devoured with increasing speed, and soon a stage is reached at which almost all microcline has disappeared, all potash feldspar being present as orthoclase (see Fig. 1 3). What later happens to the orthoclase shall be explained presently, first attention shall be focused on the chemical changes induced by the metamorphism.

Chemical Composition.

Specimens for chemical analyses have been collected at various localities as shown by the accompanying map (Fig. 2). The specimens from Engerdalen are representatives of the unmetamorphic, autochthonous sparagmite in its pristine condition. In harmony with the mineral determinations the chemical analyses show the rock to be essentially composed of quartz and potash feldspar.

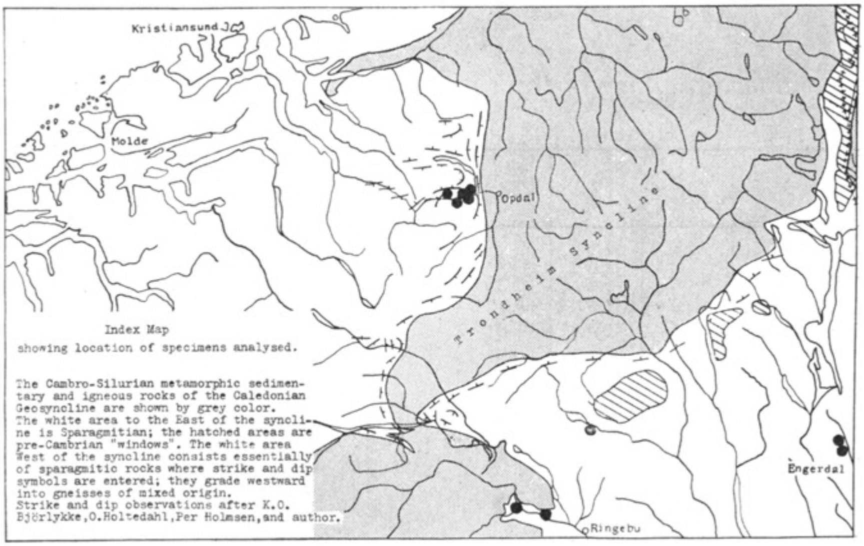

Fig. 2.

The specimens from Fron and Atnabru are representatives of the schistose facies. The analyses are in most respects similar to those from Engerdalen, but the soda-content is somewhat higher, this is in agreement with the newly formed albite as seen in the thin-sections. The lime content remains zero, or essentially so, showing that the newly formed albite has been unable to take any lime into solid solution, thus verifying the previous optical determinations. The potash-content seems to decrease — it certainly does not increase — thus proving that the potash content of the muscovite must have been drawn from the microcline, which, in agreement with the microscope observations, must be regarded as unstable.

The specimens from the west side of the Trondheim syncline are representatives of the granulite facies. The analyses show that the chemical changes initiated in the schistose facies continue regularly in the granulite facies: Soda, alumina, and magnesia increase, potash (probably) decreases, lime remains essentially zero.

Such regular chemical changes in the rock series may correspond to original variations that undoubtedly exist in many sediments. The arkose-like sparagmite is a proximal sediment which very likely will give way to more pelitic types as one approaches the more central

Table 1.

Chemical Analyses of Unmetamorphic and Metamorphic Sparagmites.

	1	2	3	4	5	6	7	8
SiO_2	-	80.89	83.47	89.16	72.17	74.66	77.79	76.34
TiO_2	-	0.40	0.33	0.11	0.48	0.76	0.29	0.41
Al_2O_3	-	7.57	8.17	5.21	13.74	11.45	12.39	11.45
Fe_2O_3	-	2.90	1.61	1.25	2.76	4 32	1.90	3.00
FeO	-	1.30	0 81	0.43	0.38	0.44	0.52	0.30
MnO	-	-	tr.	tr.	tr.	0.03	tr.	-
MgO	-	0.04	0.03	tr.	1.04	1.04	0.02	1.07
CaO	-	0.04	0.10	0.04	0.31	0.09	0.06	0.16
Na_2O	0.55	0.63	1.12	1.02	1.33	2.11	3.86	2.17
K_2O	4.01	4.75	3.78	2.62	5.98	3.87	2.21	4.57
H_2O	-	1.11	0.70	0.26	1.47	0.99	0.89	0.95
P_2O_5	-	-	tr.	tr.	0.05	0.03	0.02	-
Sum	-	99.63	100.12	100.10	99.71	99.79	99.95	100.42
Q		59.6	62.2	73.4	39.3	45.7	44.7	44.5
Or		28.1	22.2	15.4	35.3	22.9	13.1	27.0
Ab		5.2	9.5	8.7	11.3	17.8	32.7	18.3
An		0.2	0.5	0.2	1.3	0.4	0.5	0.8
C		1.4	2.0	0.6	4.5	3.6	4.3	2.7
en		-	-	-	2.6	2.6	1.0	2.7
il		0.8	0.6	0.5	0.8	1.2	0.6	0.8
hm		0.8	0.5	0.5	2.8	3.2	1.0	3.0
mt		3.0	1.6	1.0	-	-	0.7	-
ap		-	-	-	0.1	0.1	0.1	-

1. "Red Sparagmite", Gråhøgda, Engerdalen.
2. "Grey Sparagmite", Borveggen, Engerdalen.

(Nos. 1 and 2 have been collected by Holtedahl during his mapping of this area. See O. Holtedahl: Engerdalen; Norges Geol. Undersøkelse No. 89, 1921.)

3. Dark schistose sparagmite, S. of Geitberg, N. Fron, (collected by W. Werenskiold).
4. Light schistose sparagmite, Øvre Fryvollseter, N. Fron, (collected by W. Werenskiold).
5. Light schistose sparagmite, W. of Knappen, Atnabru, (collected by Barth 1936).
6. Granulite, Svorunda Bru, Opdal, (collected by Barth 1936).
7. Granulite, W. of Svorunda Bru, Opdal, (collected by Holtedahl 1937. Fig. 5 in Holtedahl's paper.).
8. Granulite between Lønset and Sliper, Opdal, (collected by Barth 1936).

(Nos. 1 to 7 have been analysed by B. Bruun, No. 8 by Barth).

parts of the geosyncline. Passing along a cross-section from S.E. to N.W., normal to the axis of the geosyncline, it would seem possible therefore, that such variations affected the samples. However, the microscope investigations of the thin-sections, the occurrence of clastic microcline in the granulites, and the nature of the chemical changes, point to a rather homogeneous sediment along the whole section investigated. High silica content is common to all these rocks, and so is the very low content of CaO; these features are obviously inherited from an original sparagmitic sediment. With increasing metamorphism the soda content increases. It seems reasonable, therefore, to attribute this to a soda metasomatism that seems to have affected all recrystallized sparagmites, a process very common to regional metamorphic rocks.

Ferric oxide may have been introduced into some of these roks, but there has been no regular supply of this oxide; some sample show, however, an unusually large amount of hematite.

Magnesia increases slowly with increasing metamorphism, but this fact may just as well be due to an original higher content of MgO as to the result of a magnesia metasomatism.

Petrology.

A survey of the various mineral changes induced by the metamorphism in this rock series is provided by Table 2 giving the modal mineral content of the several rocks.

The regular increase of albite has been alluded to before. The presence of pure albite in contact with epidote proves the anorthite molecule to be unstable even as dilute solid solution in the albite feldspar, and is undoubtedly indicativ of a low temperature of formation. The table also shows the antipathetic variation of microcline and muscovite supporting the assumption that the latter was formed from the former.

The suggestion that the granulites of Opdal District are unrelated to the Sparagmite Formation, seems to be in direct conflict with the present petrographical and chemical data, which are best interpreted on the assumption that these rocks are sparagmite derivatives which have been subjected to a relatively low-grade metamorphism and a moderate soda metasomatism. This supposition is not new. It is supported by previous observations by Törnebohm, K. O. Bjørlykke,

Table 2.

Actual Mineral Composition of Unmetamorphic and Metamorphic Sparagmites.

	2	3	4	5	6	7	8
Quartz	60	73	62	39	44	45	45
Microcline*	34	22	27	32	18	-	(21)**
Albite	-	+	+	4	14	33	16
Chlorite	6	-	-	-	-	-	-
Muscovite	-	3	8	18	12	19	12
Biotite	-	-	-	-	5	-	-
Epidote	-	-	-	-	1	+	+
Ore, apatite, etc.	+	1	2	6	5	2	5

* With some soda feldspar in solid solution.
** Orthoclase.

2. Grey, autochthonous sparagmite, Engerdalen.
3. Light sparagmite, N. Fron.
4. Dark sparagmite, N. Fron.
5. Dark sparagmite at Atnabru.
6. Granulite, Svorunda Bru, Opdal.
7. Granulite, west of Svorunda Bru, Opdal.
8. Granulite, between Lønset and Detli, Opdal.

and C. W. Carstens. Cogent reasons have also been set forth by Holtedahl in his paper dealing with the field relations of the present rocks; to be sure, the field evidences necessarily constituting the weightiest arguments in favor of this view, are so decisive, that further confirmation by chemical data would seem superfluous. Accordingly, the elucidation of the chemical side of this question is not supposed to be an end in itself.

The general petrographical survey of the sparagmites has been conducted in order to pursue the problem further, to attack in this way the more general problem of the origin and age of the various gneisses to the north-west of the Trondheim syncline in Møre and Romsdal. These gneisses are not well known, and numerous problems await investigation by modern methods. The area is large, and lack of sufficient field data make it impossible to suggest any definite conclusion. One object of the present paper is therefore to present some of the facts and preliminary conclusions, in the hope of arousing the interest of other geologists and of stimulating cooperative studies of these interesting parts of our country.

Basal Gneisses.

At present only the rock series named "basal gneisses" by Holtedahl will be described. These gneisses conformably underlie the granulites and grade into them by transitions. Some of the petrographical characters are shown by the thin-section, Fig. 14. Specimens from the transitional zone show no marked departure from the overlying granulites; they have the same characteristic matrix of quartz and feldspar and streaks of muscovite, biotite, and epidote. They have, however, a somewhat more gneissic appearance; biotite and epidote have become more important,.and the quartz grains are often elongated and welded together, thereby developing long, irregular surfaces. The plagioclase feldspar is no longer pure albite but an *albite-oligoclase* of about 12 An.

In the typical "basal gneisses" (see Fig. 9 by Holtedahl) epidote and biotite are essential minerals, the fissility is less conspicuous but streaks of epidote, biotite, and muscovite are much in evidence. Apatite and titanite are accessories. The groundmass consists of quartz, microcline, and *oligoclase* of uniform composition of 15 An.

It has been mentioned that orthoclase in the groundmass of the granulites regularly increased, whereas clastic fragments of microcline decreased with advancing metamorphism. In rocks transitional between granulite and gneiss the steady growth of orthoclase crystalloblasts can be closely followed. When a grain-size of ca. 1/3 mm is attained, microcline twins appear then the crystalloblasts are no longer orthoclases. It is worthy of mentioning that these crystalloblasts under certain circumstances seem to develop extraordinary powers of growth; porphyroblasts, the size of which are quite out of proportion to the other mineral grains, may develop. Thus are formed the augen-gneiss that is an integrant part of the basal gneiss complex.

At this point it should be emphasized that the occurrence of porphyroblasts of feldspars does not necessarily mean that the rocks have been feldspathized, but it does mean that the feldspar at that particular place was able to recrystallize in porphyroblastic habit essentially a phenomenon of metamorphic diffusion.

At the same time it should be remembered, however, that the pervasive solutions that helped the feldspars to recrystallize also carried into the rock a supply of material, whereby through metasomatic processes, the chemical composition of the original rock was slowly changed; the point at issue is that the new material went, not chiefly, or preferably, into the porphyroblasts, but into the groundmass as well. Undoubtedly rather concentrated solutions must have been introduced into the pre-existing rock material of the "basal gneisses", giving birth to injection gneisses and true augen-gneisses.

The temperature of the metasomatism of the "basal gneisses" must have been rather low, but definitely higher than that of the granulites. This is brought out particularly well by the fact that, contrary to the granulite plagioclase, the plagioclase of the gneiss is able to hold 15 % anorthite in solid solution. In consideration of certain experiments by Eskola and co-workers[1] the surmise may be ventured that the temperature of the metasomatism of the granulites and of the gneisses was about 300° and 400° respectively.

Chemical analyses of the "basal gneisses" are entered in Table 3. Worthy of notice are the figures for CaO and Na_2O. Contrary to these oxides silica decreases steadily.

Nature of Basal Gneisses.

What can be said now about the origin of the basal gneiss complex? The contact between granulite and gneiss is concordant and takes the form of a transitional zone. Structurally and petrographically the two rocks grade into each other. Such observations indicate a close connection between the two rock types. The mineralogical and chemical observations indicate much the same. Transitional types are typically present, the changes are gradual and progressive and correspond to a gradual rise in temperature.

At the present stage of our knowledge it is therefore reasonable to look upon the basal gneisses as *migmatic rocks,* representing a category of rocks the mode of origin of which we just recently have begun to understand. It has been made clear by Wegmann that in great depths there is no sharp distinction between magmatic and non-magmatic rocks. This distinction was introduced for rocks of the upper parts of the crust and for moderate depths, but it does not exist for rocks of great depths.

[1] P. Eskola, U. Vuoristo, K. Rankama: An Experimental Illustration of the Spilite Reaction: C. R. Soc. Geol. Finland, No. 9, 1935.

Table 3.

Chemical Analyses of Granulite and "Basal Gneiss".

	1	2	3
SiO_2	74.66	65.97	61.07
TiO_2	0.76	0.52	0.96
Al_2O_3	11.45	16.67	16.61
Fe_2O_3	4 32	3.58	3 21
FeO	0.44	0.82	2.65
MnO	0.03	-	0.03
MgO	1.04	1.20	1.67
CaO	0.09	3.35	4.95
Na_2O	2.11	3.17	3.79
K_2O	3.87	3.91	3.61
H_2O	0.99	0.79	0.97
P_2O_5	0 03	0.10	0.25
Sum	99.79	100.08	99.77
Q	45.7	23.4	13.6
Or	22.9	23.1	21.3
Ab	17.8	26.8	32.0
An	0.4	16 5	18.2
C	3.6	-	-
wo	-	-	1.4
en	2.6	3.0	4.1
il	1.2	1.0	1.8
hm	3.2	2.8	0 8
mt	-	1.2	3.5
ap	0.1	0.2	0.6

1. Granulite, Svorunda Bru, quoted from Table 1, anal. 6.

2. Basal Gneiss, relatively fine grained underlying the granulite, Bø, Opdal. (Collected by Holtedahl 1937, Fig. 8 in Holtedahl's paper.)

3. Basal Gneiss, more coarsely grained, Hol, Opdal. (Collected by Holtedahl 1937, Fig. 9 in Holtedahl's paper.)

(All analyses by B. Bruun.)

Migmatic rocks are formed, generally speaking, by stewing of pre-existing rock material in liquids of magmatic or anatectic origin; they are supposed to have a wide distribution in the lower parts of most areas of mountain folding and in regions of syn-tectonic intrusions. To this group of rocks the "basal gneisses" of Opdal can be referred.

The true nature of the chief genetic components of the "basal gneisses" viz.: the pre-existing solid material, and the pervading solutions, cannot easily be determined. If the injected solutions were granitic or pegmatitic in composition, the pre-existing solid material might have been of the nature of a calcareous argillite. However, this problem shall be the subject of an extended investigation.

Summary.

It has been shown that unmetamorphic sparagmite grades into schistose sparagmite and further into granulite-like rocks of the Opdal District. The geological continuity of the members of this rock series has been demonstrated by field observations of several geologists. One object of the present paper has been to trace the regional metasomatism that has accompanied the advancing metamorphism of the rocks and has been the chief agency in transforming the original sediments into recrystallized rock types.

A survey of the chemical changes is afforded by Table 4. The changes, small as they are, are mainly characterized by an increase of soda and alumina; essentially they correspond to an addition of

Table 4.

Average Chemical Composition of Successive Members of the Rock Series Sparagmite — Granulite.

	1	2	3
SiO_2	80.89	81.60	76.26
TiO_2	0.40	0.31	0.49
Al_2O_3	7.57	9.04	11.76
Fe_2O_3	2.90	1.87	3.07
FeO	1.30	0.54	0.42
MnO	-	tr.	tr.
MgO	0.04	0.36	0.71
CaO	0.04	0.15	0.10
Na_2O	0.63	1.16	2.71
K_2O	4.75	4.13	3.55
H_2O	1.11	0.81	0.94
P_2O_5	-	0.02	0.02
Sum	99.63	99.99	100.03

1. Unmetamorphic Sparagmite.
2. Schistose Sparagmite. (Average 3.)
3. Granulitic Sparagmite. (Average 3.)

albite to the original sediment (80 % of anal. 1 + 20 % albite make essentially anal. 3). It is reasonable to assume, therefore, that an almost ubiquitous solution from which albite was precipitated has permeated and soaked the sparagmite sediments in the region along the Caledonian folding zone. The temperature of these solutions might have been about 300°.

The "basal gneisses" in Opdal District conformably underlie the sparagmitian granulites, and are connected with them through transitional facies. The chemical relations are brought out by Table 3. The basal gneisses are interpreted as *migmatic* rocks formed by migmatisation of pre-existing rock material by invasive liqudis of magmatic and anatectic origin.

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