Remarks on the Average Chemical Composition of Granulite Facies and Amphibolite-to-Epidote Amphibolite Facies Gneisses in West Greenland[1])

By

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In a general way there exists a positive relationship between grade of regional metamorphism and intensity of granitization. This fact has been recognized long ago by field geologists of the French and Scandinavian schools, but little statistical work has been done in an attempt to clarify the detailed character of the said relationship.

LAPADU-HARGUES (1949) appears to be the first to present such a statistical analysis based upon a large population of rock samples. By compiling analyses of sediments, schists, gneisses and massive rock bodies encountered in regionally metamorphosed complexes, LAPADU-HARGUES demonstrates that certain changes in bulk chemical composition accompany the change in metamorphic facies. The data essentially show that increasing metamorphic facies tends to create or stabilize a granodioritic composition of the affected rocks.

High facies of regional metamorphism means, in a general way, great depth in the earth's crust. Hence we realize that the result of LAPADU-HARGUES is in best harmony with the well-known fact that granodioritic composition prevails in deeper portions of folded mountain chains whereas the superincumbent rocks are less granitic in character, i. e., the latter are more or less altered greywackes, shales, carbonates and basic lavas. This shows us that the erosion which follows the rise of folded mountains is not commonly capable of digging through the outer gneiss-granitic shell of the earth.

Granitization, or rather quartzofeldspathization, is chiefly caused by upward motion of the major chemical constituents of granites. It follows that below some depth underneath areas of granitization the rocks (melts?) should be impoverished in the same elements which are relatively con-

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centrated within the superincumbent granitized complexes. In other words, *zones of wholesale degranitization, or basification*, should in all likelihood exist underneath areas of granitization.

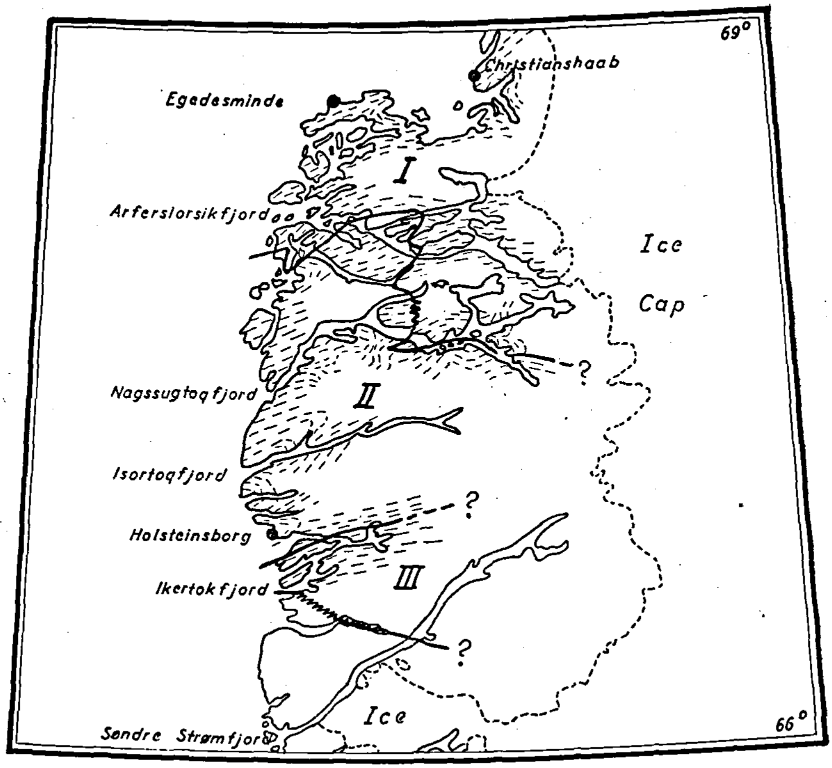

Figure 1.

Sketch map of the area between 66° North and 69° North in West Greenland. I = Egedesminde gneiss complex. II = Isortoq gneiss complex. III = Ikertoq gneiss complex. The chief structure pattern and the borderlines between the several gneiss complexes are shown.

Provided these zones be occasionally uncovered by deep-digging erosion, they should be traced within localities of maximum regional metamorphism; that is within zones of granulite facies.

The statistic compilation of LAPADU-HARGUES, op. cit., does unfortunately not contain rocks belonging to the true granulite facies. LAPADU-HARGUE's rocks appear to be ambassadors from the large P,T-field ranging from amphibolite facies down to green-schist facies and unaltered sediments. A search through available literature proved it practically impossible to construct representative figures of the mean composition of granulite facies rocks because no such area has been studied for that particular purpose. But in later years the activities of the young GRØNLANDS

GEOLOGISKE UNDERSØGELSE (GEOLOGICAL SURVEY OF GREENLAND) have resulted in valuable information on granulite facies gneisses. Of particular significance for our present problem is that we have found rather distinct differences between the mean chemical composition of a vast granulite facies complex on the one hand, and amphibolite-to-epidote amphibolite facies gneisses on the other hand.

The map (fig. 1) shows the main structure of the relevant area in West Greenland. The central granulite facies complex with the flanking amphibolite-to-epidote amphibolite facies complexes are visualized on the map.

All three areas consist of typical gneiss complexes which can be shown to have co-developed in the course of one pre-Cambrian cycle of orogeny. (H. RAMBERG, 1948 and 1949).

No detailed petrographic description is needed for our present purpose, but some of the crucial features shall be mentioned briefly.

The Granulite Facies complex.

The prevailing rock type in the Isortoq granulite facies complex is a rather dark hypersthene-antiperthite-quartz-carrying gneiss which usually has a prominent gneissose structure but occasionally grades into a more massive rock. This main gneiss is hence enderbitic in composition, according to the nomenclature introduced by TILLEY (1936). Remnants, "schlieren" and inclusions of usually hypersthene amphibolitic to dunitic composition are frequently encountered in the main enderbitic gneiss. Incorporated in this gneiss "body" are found some layers of sillimanite- and garnet- (graphite and cordierite) containing metasediment (granulites *sensu stricto*), some marble layers or reaction skarn lenses and bands, a few remnants after quartzites as well as rusty pyrite-graphite-carrying strata which once obviously were black shales.

These undoubted metasediments constitute rather thin but extensive folded layers incorporated in the main gneiss, the latter probably occupying more than 90 percent by volume of the whole Isortoq gneiss complex. The whole construction suggests strongly that the major portions of the enderbitic gneiss is formed on cost of the greywackes, mica schists, sandstones, etc. which necessarily were present, together with the still rather well-preserved metasediments, in the original geosyncline.

Scattered throughout the Isortoq gneiss complex occur pegmatites of cross-cutting and conformable character, but only a couple of major bodies of rather massive and homogeneous potassic granites have been found so far. These granites occupy the core of minor dome-shaped folds in the gneiss. The "core granites" contain the typical micro-perthitic potash feldspar which is so characteristic of granulite facies, and hypersthene and/or the hastingsitic titaniferous hornblende which also characterizes granulite facies. These properties place the granites themselves in the granulite facies of rocks.

Investigations of the main gneiss in powder and thin sections revealed that it maintains a rather amazingly constant composition throughout the whole granulite facies area which extends from Holsteinsborg in the South to Agto in the North (see map, fig. 1). The major minerals are antiperthitic andesine (An_{33+}) and quartz, the former usually possessing a typical greenish-brown color. The latter exhibits the bluish milky color which is so characteristic of granulite facies rocks. Hypersthene $\pm$ brownish hornblende $\pm$ garnet $\pm$ biotite constitute up to some 10 per cent by volume of the gneiss. Ilmenite and magnetite are invariably found whereas pyrite and pyrrhotite may or may not occur. Graphite flakes are occasionally encountered in the enderbitic gneiss (*sensu stricto*). It is remarkable that potash feldspar only very rarely occurs outside the inclusions and laminae in the antiperthitic plagioclase. Only in one thin section out of seventy of the main gneiss does potash feldspar constitute the major fraction of the feldspars; an analysis of this rock is given in Table I No. 130.

Table I.
Chemical composition of Isortoq gneiss.

Specimen Nos.	37651 [1]	37551 [1]	142 [1]	130 [2]	Average of 37651, 37551, 142
SiO_2	62.98	65.82	64.31	61.10	64.37
TiO_2	0.80	0.64	0.34	0.63	0.59
Al_2O_3	16.92	15.55	16.32	16.30	16.26
Fe_2O_3	2.23	1.11	2.45	1.67	1.93
FeO	3.67	4.72	4.82	3.49	4.40
MnO	0.08	0.07	0.13	0.09	0.09
MgO	2.45	2.41	1.77	3.36	2.21
CaO	5.31	4.82	6.96	5.18	5.69
Na_2O	4.16	3.66	2.69	3.45	3.50
K_2O	0.80	0.84	0.27	3.93	0.63
P_2O_5	0.39	0.40	0.17	0.38	0.32
H_2O+	0.18	0.11	0.17	0.30	0.15
H_2O-	0.18	0.14	0.06	0.15	0.12
Sum	100.15	100.29	100.46	100.03	

[1]) Analyst: B. Bruun; [2]) Analyst: Adams.

The mapping in the field and the microscopic investigations thus show that the main gneiss in the granulite facies complex is unusually homogeneous in mineralogical composition. It is therefore felt by the writer that even a small number of chemical analyses would give fairly representative values of the average chemical composition of the main granulite facies gneiss as shown in Table I. In order to avoid any misunderstanding it should be emphasized that our values do not represent the mean composition of the whole granulite facies complex, because the previously mentioned sedimentary layers, the amphibolitic remnants as well as the pegmatitic veins, etc., are not incorporated in the samples.

In addition to the chemical analyses and the microscopic data, some densities of the main enderbitic gneiss are given in table II.

Table II.
Densities of gneisses.

Specimen Nos.	Isortoq gneiss, density	Egedesminde gneiss, density
	g/c. c.	g/c. c.
37606	2.96	
37597	2.76	
37605	2.90	
27208	2.75	
177	2.73	
27590	2.78	
37339	2.72	
37113	2.78	
37985	2.89	
142	2.84	
37608	2.76	
37648	2.79	
130	2.76	
37453	2.75	
37651	2.76	
37987	2.65	
37651	2.77	
37771		2.68
37887		2.66
37889		2.66
37924		2.67
37888		2.66
37871		2.69
37927		2.66
37310		2.66
Average density	2.78	2.67

The Amphibolite-to-Epidote Amphibolite Facies complex.

With reference to construction and major structure, the Egedesminde gneiss complex and the Ikertoq gneiss complex are closely similar to the Isortoq complex (map, fig. 1). Lithologically, however, there are significant differences. Referring to the Egedesminde and the Ikertoq complexes one may speak of a main granodioritic gneiss in which metasediments and amphibolites are embedded, and in which cross-cutting as well as conformable pegmatites are rather numerous. Here and there, larger bodies of rather homogeneous potash-rich red granites are encountered. As described elsewhere (Ramberg, 1948), all the rocks correspond to amphibolite-and-epidote amphibolite facies, and are hence mineralogically distinctly different from the rocks of the granulite facies complex described above.

The field mapping and microscopic study revealed that the main Egedesminde gneiss is less homogeneous than the main gneiss in the Isortoq complex. For that reason a considerable number of chemical analyses were made in an attempt to determine the average chemical composition of the Egedesminde gneiss (see table III). We have good

Table III.

Chemical analyses of Egedesminde gneiss.

Specimen Nos.	1) 37326	1) 37871	1) 37039	1) 37041	2) 37771	2) 37764	2) 37768	2) 37888	2) 37424	2) 37927	3) K3	3) K4	Average
SiO_2	71.50	69.69	70.30	71.48	68.54	66.59	73.14	70.69	70.47	71.05	69.06	69.07	70.13
TiO_2	0.23	0.33	0.38	0.16	0.37	0.50	0.12	0.20	0.32	0.23	0.74	—	0.32
Al_2O_3	15.94	16.76	16.55	15.73	16.08	17.80	14.80	16.62	14.18	16.24	15.26	14.09	15.83
Fe_2O_3	0.42	0.62	1.20	0.66	1.00	1.36	0.16	0.68	1.49	0.21	0.68	1.49	—
FeO	1.22	1.78	1.64	0.89	1.98	2.52	1.12	1.44	1.76	1.58	2.53	2.37	1.78
MnO	0.04	0.00	0.03	0.03	0.02	0.03	0.01	0.03	0.04	0.02	—	—	0.03
MgO	(0.40)	1.00	0.68	0.55	1.10	1.12	0.41	0.58	0.61	0.61	0.34	0.98	0.69
CaO	2.27	4.81	3.11	2.22	3.34	3.75	1.59	2.71	3.45	3.02	2.83	3.14	3.02
Na_2O	4.84	3.69	4.22	3.47	4.42	4.31	3.20	4.77	3.58	4.29	4.88	5.18	4.23
K_2O	2.80	1.21	1.28	2.16	2.26	1.65	4.93	1.70	3.27	2.29	2.17	2.71	2.36
P_2O_5	0.14	0.17	0.15	0.11	0.14	0.20	0.06	0.07	0.16	0.09	—	—	0.13
H_2O+	0.36	0.46	0.65	0.36	0.44	0.49	0.19	0.40	0.37	0.68	—	—	0.44
H_2O-	0.04	0.04	0.03	0.08	0.02	0.03	0.01	0.02	0.03	0.02	—	—	0.03
F	—	—	—	—	—	—	—	—	0.03	—	—	—	—
Sum	100.19	100.56	100.22	97.90	99.71	100.35	99.74	99.91	99.76	100.33			

1) Analyst: Adams; 2) Analyst: H. B. Wiik; 3) From Krueger, 1928, p. 108.

reasons to believe that the mean composition of the Ikertoq gneiss is also closely similar to that of the Egedesminde gneiss. Some densities of the Egedesminde gneiss are compiled in table II.

The major minerals occurring in the Egedesminde and Ikertoq gneisses are: quartz, acidic plagioclase—often as myrmecite—, microcline, and some biotite. Epidote, hornblende, and muscovite may or may not occur. Sphene is very common. Ore minerals like magnetite and pyrite are found in minor amounts.

On account of the data presented above the writer thinks that we have arrived at fairly reliable mean chemical compositions of the main gneiss components in the Isortoq granulite facies complex, and in the Egedesminde amphibolite facies complex, respectively.

Discussion.

We shall then focus our attention upon the differences in mean composition of the two said gneiss complexes. The crucial question is whether the chemical differences between the two complexes are pre-metamorphic or syn-metamorphic. To the present writer it seems unlikely that the compositional difference should be pre-metamorphic mainly because the change in mean composition, to our best field knowledge, corresponds rather closely to the change in metamorphic facies. This is also true when the boundary between the granulite facies and amphibolite facies crosses the major strike as it does in the fiords Arfersiorfik and Nagssugtoq (Nordre Strömfjord) (See map, fig. 1). It does not seem likely that the degree of metamorphism should coincide with compositional differences within the original geosynclinal column and its basement. A more natural explanation would be that the bulk composition has changed in the course of the dynamothermal metamorphism: An accompanying regional metasomatism has changed the granulite facies and the lower-facies gneisses in a somewhat different trend.

From tables I and III it is seen that the main gneiss of the granulite facies area is distinctly more basic than the main gneiss of the amphibolite facies area. The former is relatively rich in Mg, $Fe^{\cdot\cdot}$, $Fe^{\cdot\cdot\cdot}$, Ca, Ti, and Mn; the latter in Si, Na, K, O and H_2O. This is in direct contradiction to the statistical work by LAPADU-HARGUES (op. cit.), and to the common experience that rocks tend to approach an acidic granodioritic composition when affected by an increasing grade of metamorphism. Our data show that the high-grade gneiss tends to be more basic than the low-facies gneiss.

An explanation lies close at hand: The general tendency of metasomatic approach to a granodioritic bulk composition does only hold as long as the grade of metamorphism is lower than granulite facies. Within granulite facies wholesale basification starts to operate.

As indicated in the introduction, it is most natural to believe that the relatively basic composition of granulite facies rocks is due to the relatively great depth at which such rocks have developed. It actually appears that we are glancing at the floor of the "granitic" shell in these deeply eroded areas. Granitization is a differentiation process on a global scale (K. RANKAMA, 1946) which tends to materialize the stable situation of the "granitic" minerals being concentrated within the outermost global shell. This migration process is intensified and catalyzed by dynamothermal metamorphism so that the higher the grade of metamorphism, the more powerful the migration of rock-making matter. Therefore one finds that on the average, amphibolite facies gneisses are more granitic or "granodioritic" than low-grade schists. In other words, the findings of LAPADU-HARGUES demonstrate a relationship between grade of metamorphism and *rate* of the metasomatosis which creates quartzo-feldspathic gneisses. Our findings, however, that granulite-facies gneisses (in Greenland!) are more basic than gneisses belonging to lower facies demonstrates some crucial facts about the thermodynamic stability of the outermost portions of the earth. In the deep-seated granulite facies the stable rock is not granitic or granodioritic; hence, even though the power of metasomatic alteration is at a maximum in these deep zones, the ultimate result of the alterations is not an ideal granite or granodiorite, but actually a quartzdioritic gneiss of moderately basic composition. The tendency to create granitic composition does not exist at these depths.

In short one may say that when rocks are "pushed" down to the zones of granulite facies during orogenetic evolutions, then some elements and their molecular compounds are chemically "squeezed" out of the rocks and minerals. This process is partly caused by the gravitational field, partly by the geothermal gradient as explained in several papers by this writer. Thermodynamics requires that H_2O, Si, K, Na, and O, shall preferably be "squeezed" out of the deep-seated rocks, these constituents moving upward and undertaking granitization, silicification and hydrolyzation on their route toward shallower depths. To balance this upward migration of matter, swelling of the "granitized" upper zones and shrinkage of the deeper "basified" layers take place. Calcoferromagnesian elements are also liberated within the zones of granitization so that these constituents may move down and help to basify the underlying rocks.

However, it is not the aim of this paper to discuss the mechanism of *granitization* and allied processes. The writer only hopes to have shown that there are some significant differences between the bulk chemical composition of granulite-facies gneisses and lower-facies gneisses, respectively (in West Greenland). It would be very interesting if this is a general rule because it is in the best harmony with what one should expect on grounds of the modern view on large-scale metasomatism.

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