9. Swedish Archaean Structures and their Meaning.

By

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Contents.

Introduction.

In the geological publications and discussions of recent years the Archaean of Sweden has mostly been regarded as consisting of three parts, or three groups of rocks: the *gneiss*-group, the *porphyry-leptite*-group, and the *granite* group. This division, which derives from A. E. TÖRNEBOHM (**11, 15, 33**) and has been followed by the Geological Survey of Sweden since 1901, succeeded the many attempts which were made in earlier years by FORSELLES, A. ERDMANN, TÖRNEBOHM and HUMMEL to ascertain a stratigraphical chronology for these old rocks. Although the division named formed, in a way, a regress from the more complicated stratigraphical systems which it had seemed possible to establish in the earlier days of Archaean geology, it was in reality an important step forward. For by this means the natural grouping of the Archaean rocks was more justified and the questions of stratigraphical subdivisions which have proved insoluble lost their predominance. In the well-known and excellent maps of TÖRNEBOHM (**4**), as in all later and more detailed maps, the natural difference between the gneiss-rocks, the leptite and granite group of rocks is well established. On the whole, the limits of the dominant rocks may also with certainty be determined by geological field-work, although in some cases the actual contacts may have become more or less indistinct owing to secondary processes.

As to the mode of formation, opinions at present agree very well concerning the granites and the porphyry-leptite rocks. The latter are generally considered to be *supercrustal* rocks, probably formed in a «shallow sea, where numerous volcanic islands existed» (**15**). Concerning the gneisses and the schistose granitic rocks connected with them (gneiss-granites or granite-gneisses), on the other hand, opinions diverge considerably. As the rocks of the group of gneisses and schistose granites exhibit the most complex phenomena of metamorphism, the determination of origin on petrographical grounds is in this case often impossible or attainable only through special researches. Even though the geology of this group has been much studied and discussed, yet various different opinions are still current concerning fundamental gneiss-problems. Some important advances, however, may also here be registered. TÖRNEBOHM, who regarded the gneiss-group on the whole as older than the porphyry-leptite and the granite group (**15**), has in the maps which he published in 1880 (**1**), 1883 (**2**), 1909 (**33**) reduced the areas of the older gneiss-group in favour of the granites. During the same period detailed studies had shown the great influence of metamorphic changes and especially those due to pressure-metamorphism on the texture of the Archaean rocks.

Especially important were the studies of A. G. HÖGBOM on the supposed old Archaean granites (in Swedish=*urgraniter, gneisgraniter, granitgneiser*) and gneisses of Upland (**8**), in consequence of which he con-

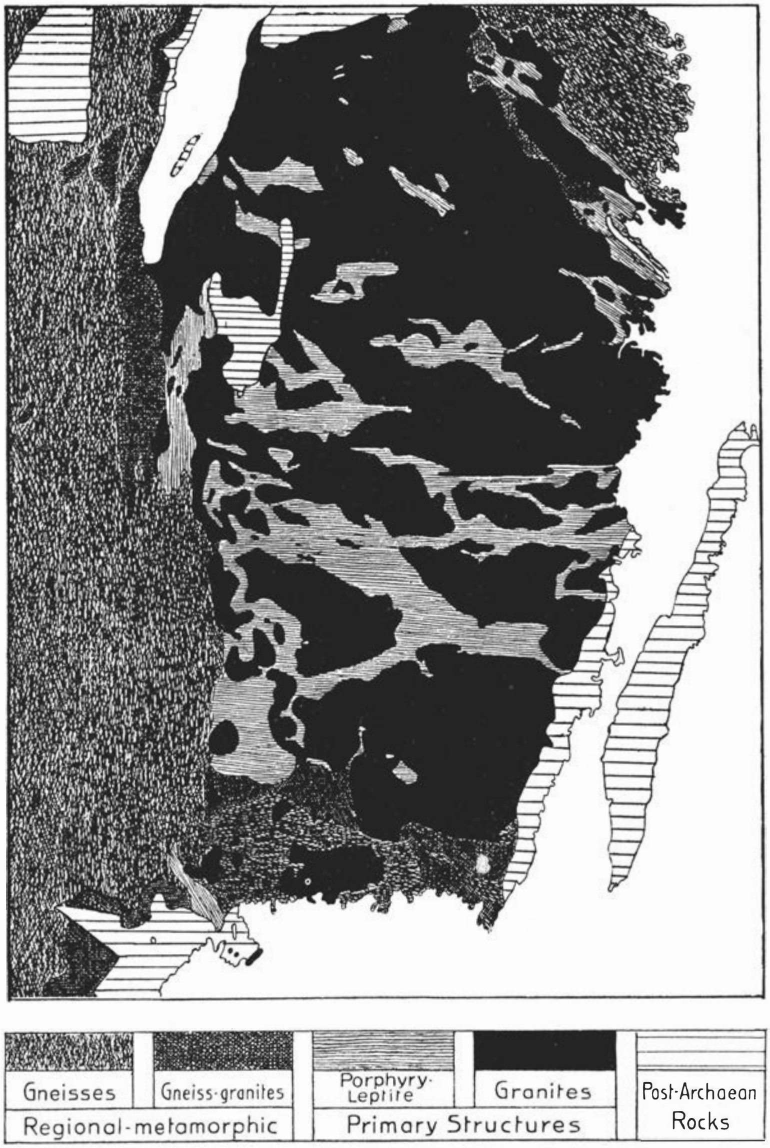

Fig. 1. Map of the Archaean of SE-Sweden. Copy, a little simplified, of the Geological Map of Sveriges Geol. Undersökning (**33**). Shows the porphyry-leptite rocks included in the great granite masses and the regions containing regional dynamo-metamorphic rocks (gneisses and gneiss-granites). Scale about 1 : 2,300,000.

cluded that these rocks, which by some geologists were regarded as formed under conditions and influences quite other than those of later geological periods, in fact show distinct analogies in both chemical and mineralogical respects and in geological appearance with certain postarchæan granites, and that their parallel-texture could be understood as produced through fluidal movements in the magma before and during its consolidation or through secondary pressure-metamorphism. HÖGBOM also says that secondary schistosity through pressure, on the whole, seems to be a more general cause of the parallel-texture of the rocks than fluidal movements in the not yet consolidated magma.

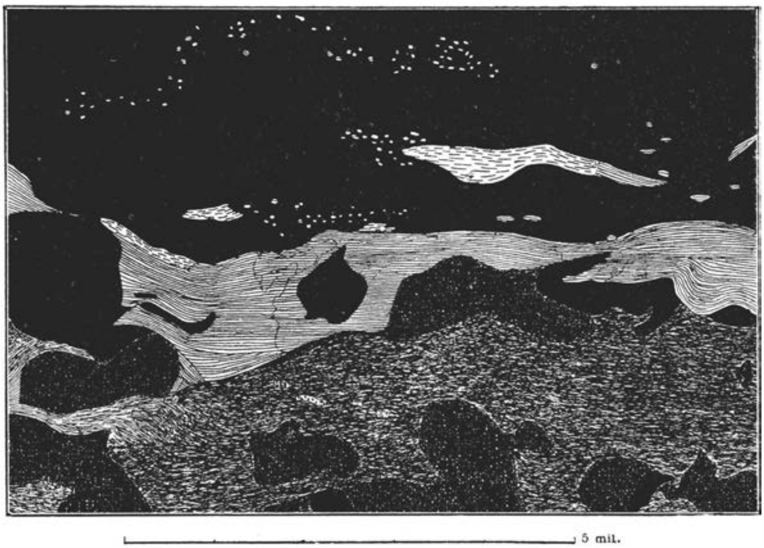

Fig. 2. Geological sketch-map of the Tammerfors-field and surrounding area in Finland according to the map published by SEDERHOLM (**13**). The designation is the same as in Fig. 1. Parallel linings and streaks mark Archaean supercrustal rocks. The scale: 5 mil = 50 kilomètres.

During the ensuing years the scientific development of this part of Archaean geology has gone in the same direction. It has become more and more evident that the gneiss-group cannot be the original bedrocks to the porphyry-leptite formation. Never have any conglomerates or discordances been discovered at the contacts between these groups, which have been subjected to close study, but it has been shown in several places that the gneiss-rocks consist of metamorphic granites, which in reality are younger than the Archaean schists, which now seem to rest on them as on a complex of older rocks (**26**). In my opinion, the geological position of the porphyry-leptite rocks of the Swedish Archaean is quite the same as that of the *Keewatin* series in North America. As this latter series of Archaean rocks has been found by A. C. LAWSON to rest on granites and gneisses (the *Laurentian*), by which they are intruded as by true younger eruptives, so are also the porphyry-leptite-rocks of Sweden embedded in younger granites.[1] In these parts (SE) of Sweden, where the Archaean rocks have been but little altered by regional metamorphism (pressure-metamorphism), this geological position is evident (Fig. 1). In the high-metamorphic regions (the gneiss districts) the primary geological position is more or less concealed by the mechanical deformation and the new crystallization which the rocks have undergone, but even in such cases the same position has been proved upon nearer examination.

The Swedish gneisses, however, have not been studied to such an extent as to give this conclusion universal validity. Hence the two great gneiss-formations of South-Sweden, the *magnetite-gneiss* (»järngneis») and the *garnet-gneiss* are still the subjects of rather different opinions. As to the magnetite-gneiss rocks, which occupy an area of about 60,000 km^2, they bear all evidences of having undergone very strong regional metamorphism, namely an abundance of deformation-structures connected with high and uniform («grobgranoblastisch») gneiss-texture. Geological observations by TÖRNEBOHM (**4,1**), E. ERDMANN (**7**), G. DE GEER (**14, 16**), H. BÄCKSTRÖM (**12**), H. HEDSTRÖM (**17**) and H. MUNTHE (**21**) have shown that there exist transition forms and zones of transition between the magnetite-gneisses and granites or leptites of common Archaean types. These observations have been made mainly in the eastern border-zones of the great magnetite-gneiss area, but I have come to the same conclusion by my own studies in the western parts of the district. On account of these facts there can hardly exist any doubt that, according to the opinion of many geologists, the magnetite gneiss-area represents a highly metamorphic region where rocks occur of the same origin as outside of this area, but in a condition of great alteration through regional metamorphism.

The *garnet-gneiss* and accompanying grey gneisses occupy also very great areas of the Archaean. In Central-Sweden the garnet-gneiss area has an extension of about 10,000 square kilometers and there shows a very uniform character. It is a veined gneiss containing segregation of a coarse quartz-felspar mass with vein-like forms in a denser violet-grey schistose ground-mass of felspar, quartz, garnet, biotite, cordierite and sometimes also sillimanite, pyrites and graphite. As moreover some of the few chemical analyses that have been made of this rock show a considerable amount of Al_2O_3, it has been thought to constitute a real *para-gneiss*. Its geological relations, however, are not in harmony with that opinion, since the rock never shows any sign of bed-structure, but contains numerous inclusions of other rocks in part evidently of leptitic origin. In the coast-region where the garnet-gneiss occurs, it may also be stated that the same is con-

[1] It must be observed that, as the dip in the porphyry-leptite and gneiss-rocks is usually very steep (60°—90°, and most commonly 80°—90°), it cannot always be stated which of two Archaean rocks is in reality the overlying one. In the gneiss-districts of SW-Sweden certainly the dip is less steep to flat, but the regional (dynamo-)metamorphism is there also most intense.

nected, through transition forms, with schistose granites. It is also to be observed that this gneiss has a very uniform composition throughout the whole of the great area in which it has been observed. Available geological data thus speak in favour of the opinion that originally this highly metamorphosed gneiss also had the character of a granite.[1]

To the same conclusion I have come by studying the geological and petrographical relations of the *Stockholm-gneiss*. Petrographically, this bears a close resemblance to the garnet-gneiss and, like this, has a veined structure, but it generally contains no garnet. Like the magnetite-gneisses and the garnet-gneiss, it is so greatly altered that most primary textures have been obliterated and the origin of the rock cannot be determined immediately. (Fig. 9.) Like the gneiss-granites, however, it has as a relic of its original nature, the homogeneity in composition which already TÖRNEBOHM pointed out as one of the most important field-characters of true granitic rocks (**1**).[2] Bed-structures are totally absent, but sometimes granitic textures which have escaped the metamorphism may be seen.

Moreover some other Swedish gneisses which have been reckoned as belonging to the older gneiss-formation upon which, according to the older opinion, the supercrustal rocks of the porphyry-leptite group were once deposited, I have found to be younger granites in a state of metamorphic alteration. It ought also to be observed that, in spite of the eagerness with which the gneiss-question has been discussed by our geologists in recent years, no positive proofs have been brought forward in favour of the common hypothesis that the gneiss group is older than the porphyry-leptite group.

The natural conclusion of all this seems to be that *the last-named rocks are the oldest of our Archaean.*

As to the massive *Archaean granites* in Sweden, they seem at present to be unanimously regarded as younger than the porphyry-leptite group.

In settling the problems of the Archaean the discrimination between original and secondary textures or structures is a task of the greatest importance.

The following is an attempt to collect the more common cases, as regards the Swedish Archaean, in which original or secondary textures and structures may be said to occur and to discuss their meaning.

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[1] In my first studies on the garnet-gneiss I followed the opinion that this was a real para-gneiss, i.e. of sedimentary origin, although some of its characters even then seemed to harmonize ill with that opinion (**25**). Later on I found that the para-gneisses only occurred as smaller or greater inclusions in the garnet-gneiss, and that *the main mass* of this last was of granitic origin (**36**).

[2] Explanation to sheet 6 of the map, page 18.

Original Textures of the Archaean.

Petrographic Textures.

Igneous.

The abyssal Archaean eruptive rocks, as a rule, still show their original consolidation-structures. Some of the granites — viz. those of the but little metamorphosed regions, for instance in SE-Sweden (the granites of Småland and Östergötland), or in E-Vermland — are beautiful Perthite-Quartz-granites which closely agree, as to texture, composition and appearance, with the well-known postarchaean Rapakivi-granites upon which neither contact- nor regional-metamorphism has acted.

The fact that the Archaean granites—even when they macroscopically seem to be quite unmetamorphosed — always exhibit in the microscope the phenomena of the quartz which is called undulatory extinction and is supposed to be a result of pressure has been much observed by Scandinavian geologists. This feature makes a sharp distinction between Archaean and postarchaean granites, because the latter to the east of the Caledonian folding zone have not undergone any pressure-metamorphism. It is a curious circumstance that many of the Archaean granites, for instance the Stockholm type, show very strong deformation-structure of this kind in their quartzes, but no schistosity or any other macroscopical sign of deformation. Consequently the crystallographic deformation of the rock-quartz cannot, in this case, as usual be a consequence of regional dynamometamorphism (**20**, page 243; **31**).

Syenitic rocks are, on the whole, uncommon in the Swedish Archaean. Only in the iron-ore districts of northern Sweden do they seem to be comparatively often represented. They exhibit both primary and secondary (gneissoid) textures. The same is the case with the nepheline-syenites, of which especially the Lakarp syenite has a gneissoid appearance (**23**).

Very beautiful and undisturbed consolidation-structures are exhibited by the Archaean *gabbros* and *hyperites* when they occur in great masses. The hyperites of SW-Sweden are very remarkable in this respect. These rocks are perfectly well crystallized olivindiabases (sometimes containing a little hypersthene) with felspars blackened through pigmentation. In smaller masses, the Archaean gabbros and diabases are regularly converted through pressure-metamorphism into schistose dioritic rocks; and such rocks also usually form the borders of the greater masses.

The abyssal or infra-crustal Archaean eruptives accordingly very often have their primary textures well preserved. The same is also often the case with the effusive types.

Porphyritic rocks occur in the Swedish Archaean partly as dikes but mainly as stratigraphical components of the supercrustal porphyry-leptite group. In the first-mentioned rocks we find the porphyritic textures and often also the textures of the ground-mass very well preserved. The dike porphyries of Småland are in this respect especially to be mentioned (**9, 22, 19**). Porphyritic rocks seem to occur in all the areas of the porphyry-leptite-group, but they are present in varying amounts (**33**). In most cases these leptitic (granulitic or felsitic) porphyries have lost all their original ground-mass-textures, and only the more resistent porphyritic texture remains as a relic of the primary form of consolidation (Fig. 3). Moreover, its chemical

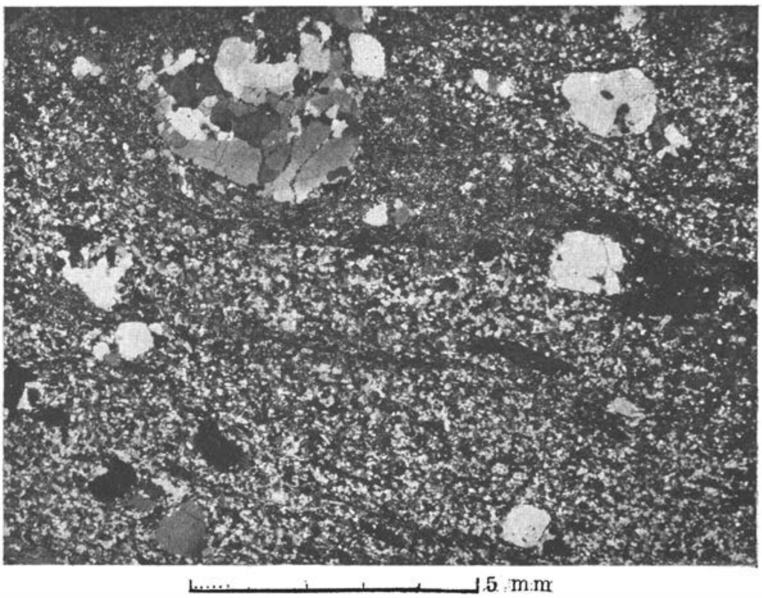


Fig. 3. Micro-structure of the quartz-porphyry-schist on Utö in the coast-region of Stockholm. Magnified 8 times. Nic. crossed.

composition in many cases still gives evidence of the original nature of the rock. In several cases it has been possible to show that the porphyritic rocks of the porphyry-leptite group enclose textures characteristic of acid porphyries and tuffs, i. e. spherulites, fluidal textures, perlitic cracks, pyroclastic and among them ash-textures. O. NORDENSKJÖLD found such textures in the »hälleflinta» of Småland (South Sweden) (**9**) and Dannemora (**10**). A. E. TÖRNEBOHM in a schistose porphyry from Dannemora (**15**) and K. WINGE in the porphyry-leptite rocks of Dalsland (**18**). A. G. HÖGBOM mentioned the occurrence of supercrustal igneous rocks and tuff in the Skellefteå-complex of North-Sweden (**31**), and N. SUNDIUS described a series of effusive igneous rocks and pyroclastic sediments in the hälleflintas of the Grythytte-complex (Central Sweden) (**48**).

In the effusive rocks which accompany the great iron-ore mass of Kiruna N. SUNDIUS found *pillow-lava* structures, viz. in a sort of rocks called soda-greenstones, to which he had devoted special study (**46, 47**).

My own researches also in the Utö area had shown that the leptite-complex could only be understood as composed of igneous effusive rocks, alternating with stratified deposits of tuffitic origin (**36**).

In the Archaean the effusive greenstones have generally only preserved their original porphyritic texture. This seems to be the usual case when the rock lies conformably with the leptites. In some cases, however, and especially in dikes the ground-mass-textures (ophitic or intersertal-texture) may also be seen.

Sedimentary structures.

Sedimentary textures are hardly less common in the Archaean than are primary igneous (eruptive) textures (**27**).

A regular *bed-structure* is noted in the Archaean *quartzites* in Skåne (Vestanå), Småland, Dalsland, Vermland and Lappland. In some cases current bedding has also been observed (**31**).

The Archaean *clay-slates* have well developed bed-structures, as, for instance, at Grythyttan, Långban and Loos.

The »*hälleflintas*» very often show an excellent bed-structure, for instance on Utö and at Dannemora.

Of all Archaean rocks the *leptites* exhibit the most beautiful bed-structure. Especially remarkable are the grey leptites through their often very evident bedding.

The Archaean *limestones* are probably always bedded rocks and also very often exhibit marked bed-structures; but as these rocks, on account of their plasticity, easily undergo deformation, the primary structure is often obliterated and mechanical flow-structure or brecciation appears.

Of special interest is the bed-structure which characterizes the Archaean *quartz-haematite iron ores*. These consist of alternating layers of quartz and haematite and seem to be metamorphosed forms of iron-ores corresponding to the well-known American *jaspilites*. Jaspilitic features are sometimes still visible in such ores (**40, 41**).

Archaean *gneisses* of the types which have been called *banded gneiss* usually show a very regular bed-structure. Such gneisses are often closely connected with the bedded leptites and are obviously only to be regarded as leptites changed through metamorphism into more coarse-grained types. At Utö, Ornö, Bråviken and in Bohuslän, Västergötland, Vermland, Södermanland and Blekinge there occur banded gneisses which seem to be of the same nature.

Clastic textures. It is obvious that clastic material only very seldom appears in the Archaean beds. Although many such rocks have undoubtedly been formed as mechanical sediments and occupy extensive areas, the clastic texture is generally absent or replaced by a holocrystalline, dense or sometimes coarse-crystalline development. Among the clastic rocks, the coarse types, conglomerates, agglomerates etc., undoubtedly possess the greatest resistance to metamorphic powers and thus seem more able to escape complete destruction than the originally fine grained sediments.

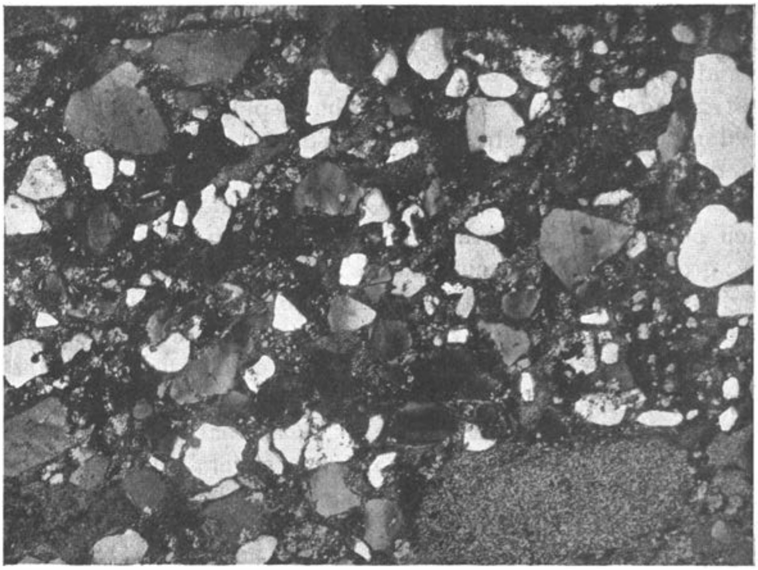
Several conglomerates have also been discovered in the Archaean rocks of Sweden (**39**). As they seem to belong to the porphyry-leptite group and have never been found at contacts between rocks of this group and the gneisses, and as they do not in any case contain pebbles of such gneisses or gneiss-granites, they must be considered as interformational. Mostly they appear as more local assemblages without any great coherent horizontal extension. Their pebbles usually consist of rocks of the same kind as the common types of the porphyry-leptite group. But in some cases pebbles of granitic rocks occur, which seems to indicate that the erosion-channels at least in some cases, during this old Archaean time were cut out to such a depth that even abyssal rocks were reached. These granites, however, generally are of other types than those now existing in these regions. In the Skellefteå-complex, however, HÖGBOM found Archaean conglomerates that contained pebbles of granitic type, showing nearly the same characters as a granite which now forms the rock-ground in the vicinity (**31**). This granite should therefor be older than some supercrustal rocks belonging to the Archaean schists, a fact which undoubtedly deserves the greatest attention.

Archaean conglomerates have been detected in Skåne (Vestanå), Småland (Malmbäck), Dalsland (Åmål), Västmanland (Älfvestorp), Ångermanland (Skellefteå-complex), Lappland (Kurravara and the Hauki-complex) and several other localities which have been but slightly studied (**39**).

A very good starting-point and foundation for more intimate studies of the Archaean sedimentary rocks which are represented in our hälleflintas and leptites seem to be provided by the researches of N. SUNDIUS in the Grythytte-district (**48**). This area, which to the west borders the great iron-ore-bearing leptite-district of Central Sweden. contains Archaean clay-slates, hälleflintas, limestone, porphyries, greenstone-rocks and granites. The sedimentary hälleflintas show excellent clastic structures and often also beautiful bed structure. Clastic beds of different coarseness are found. Their grains consist of angular mineral fragments — felspar, quartz etc. — more or less mixed with ash-particles. The rocks have thus the character of primary clastic (pyro-clastic) sediments. In some cases they are of tuffitic nature. Coarse agglomerates are also discovered in this interesting district.

In the eastern iron-ore-bearing districts of Central Sweden the interesting researches of LINDROTH proved the bedded ore-bearing leptites at Ramhäll and Norberg to be composed of clastic (pyro-clastic) material, LINDROTH was able to show that the coarseness of the bedded material varies in a very regular manner with the bed-structure and that the formation of the bedded iron-ores is closely connected with these clastic rocks (**45**).

Sometimes the clastic and porphyritic hälleflintas may resemble each other macroscopically. In the clastic forms, however, the grains are irregularly scattered and sometimes gathered so that they make up nearly the whole of the rock mass. (Fig. 4.)



5 m.m.

Fig. 4. Micro-structure of an hälleflinta rock from Dannemora with evidently clastic texture. The quartz grains exhibit partly corroded forms. Magnified about 10 times. Nic. crossed.

Original Geological Structures.

Igneous.

As such may be considered the geognostic relations between the eruptive rocks to each other and to older rocks in general, the differentiation and assimilation processes, the endogenous contact-metamorphism and fluidal structure. Only some of these structures, namely those of special interest to Archaean geology, shall here be discussed at some length.

Of the geological relations between the different eruptive rocks which are parts of the supercrustal porphyry-leptite group, very little is known. It is observed, however, that these rocks occasionally contain detached fragments of other rocks in the same group. Such relations are seen, for instance, in the Utö-series (**36**).

Of greater interest are *the relation of the porphyry-leptite rocks to the Archaean granites.* Its general character has already been sketched in the introductory remarks to this paper (Page 128). It seems certain that everywhere when clear contacts between an Archaean granite and rocks of the porphyry-leptite group are met with, the granite always proves to be the younger.[1] In the *great* granite massives the contacts mainly follow the parallel-structure of the supercrustal rocks. This fact, to which TÖRNEBOHM and others have attached great importance when settling the difference between older and younger (serarchaean) granites, seems to be the other side of the general fact, that the porphyry-leptite group was subsided in the granite magma and *appears on the whole* as detached fragments embedded therein. (See fig. 1, 2, page 127, 128.) The granites have split up the supercrustal rocks mainly along their own stratigraphical structure-lines and torn away or assimilated unknown masses of layers both on the foot-wall- and hanging-wall-side of the remaining complex. Only the younger (serarchaean) granites which penetrated the earth-crust in so late a period of the Archaean that the great abyssal granite masses were wholly consolidated, and in some regions also had been strongly metamorphosed, appear independent of the structures of the porphyry-leptite complex. In other words, there are only fragments now visible of that old earth-crust which the great granite masses penetrated, while the crust in which the serarchaean granites were intruded is the same, in the main, as that now existing. It also seems probable that the old granitic magmas never »erupted» in the usual meaning of the word, but received and enclosed the broken and folded crust-masses as they sank down from the cooling surface.

The relation of the granites to each other. The general rule in the Archaean of Sweden seems to be that the complex or femic granites are older than the simple or salic ones (**20**). In a region where many types of granites occur, the Ca-rich amphibole-granites, according to my experience, are always penetrated by the intermediary types, and these again by more acid granites. As the latest rocks in such a series aplitic granites and pegmatites generally occur. This rule constitutes large areas of the Archaean of Sweden, certainly at least the whole of South- and Central-Sweden, one petrographical province.

The greenstones, which belong to the Archaean infracrustal rocks, are mainly gabbros (and diorites) and hyperites. In comparision with the granites they are very subordinate, but large massives occur both in the south and especially in the northernmost part of Sweden. The greenstones are younger than the porphyry-leptite group, but generally older than all the granites. In some of the high-metamorphic districts young-archaean

[1] The above-mentioned Jörn-granite is the only exception. It ought to be observed that this granite is a miarolitic and micropegmatitic rock. It has thus not at all an »old appearance», but resembles young supercrustal granitic rocks and is unmetamorphosed or but little altered, like the complex of rocks which it accompanies and to which it presumably belongs.

greenstones are also represented, viz. the *hyperites* of S- and Central-Sweden and the *norite* or *hypersthene-gabbro* at Loftahammar in the SE (**35**).

As primary structures may also be designed those heterogeneities in igneous rocks which are due to processes of *differentiation* or *assimilation*. On account of the fact that *inclusions* of older rocks have been observed in so many of the Archaean eruptives, especially in the granites, several Swedish geologists are disposed to interpret as veritable inclusions, however greatly altered, also such fragments as cannot be identified with any known rock. The discussions on the origin of the inclusions in the Upsala-granite is conspicuous in this respect (**6, 38**). The same evidences are observed also in strongly schistose granites, gneiss-granites, for instance, in the gneiss-granite mass which borders the iron-ore field of Grängesberg to the east. This last contains along the borders numerous fragments of denser rocks, and at the Långblå mines it encloses also fragments of iron-ores, which undoubtedly have been detached from the ore-bearing leptite rocks in the vicinity.

Good evidences exist that extensive *assimilation* processes have also taken place, when the granite magmas invaded the old supercrustal rocks. In several cases it can be shown that the granites, when they enclose or border greenstone rocks, are enriched with femic components, but tend to a more salic composition if the inclusions or adjacent older rocks are siliceous. These facts agree well with the observations which SEDERHOLM reported from the Archaean of Finland (**13**). SEDERHOLM found also that the inclusions through the enclosing granite were often strongly altered and called this *digestion-metamorphism*.

Endogenous contact-metamorphism has taken place at the borders of the granite areas near to the older rocks. HÖGBOM in his memoir on «The Precambrian Geology of Sweden» sets forth the evidences which demonstrate this fact. In some cases porphyritic textures and micro-pegmatite appear in the granites along their contacts, but mostly the granite only becomes denser in texture near the contacts. In several cases also this influence seems to be wanting, though the granite evidently breaks through the other rock.

Not seldom *fluidal structures* are seen in the infracrustal Archaean rocks both in the greenstones and in the granites. It seems to be a still undecided question whether *protoclastic* structures also occur.

Sedimentary.

The most important of all primary geological structures in the Archaean is undoubtedly the *stratigraphical arrangement* of the rocks belonging to the porphyry-leptite group. It is the most striking general feature of this group, and the best mark that can be used in distinguishing them from the granites and gneisses. In all the areas which have been mapped as belonging to the supercrustal group of rocks, the structure is that of stratigraphical complexes. (Fig. 5.) The rocks have their extension in the directions of strike and dip. On crossing the strike in such an area, one cannot fail to observe the alternation of rocks of different composition and texture. It is also evident that this stratigraphical arrangement is a true primary geological feature and accordingly has nothing whatever to do with secondary changes or metamorphic processes. Together with the original petrographical characters of the porphyry-leptite rocks, which

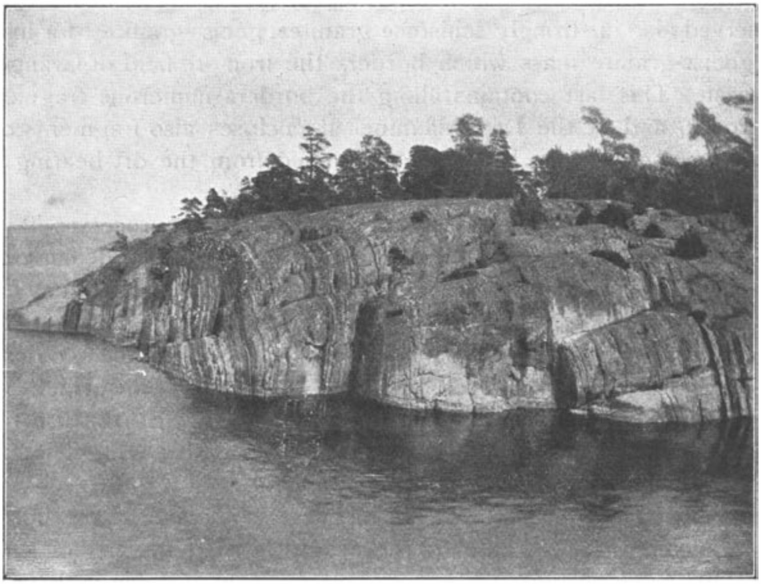


Fig. 5. Leptite, showing beds of very different thickness. The figure illustrates the usual, nearly vertical position of the bedded, supercrustal rocks in the Archaean. View on the east side of the little island Ängsholmen near Utö.

have already been discussed here, the stratigraphical structure forms strong evidences for the conclusion, now almost unanimously accepted by Swedish geologists, that this group is of supercrustal origin.

It is to be noted that the bedded porphyry-leptite rocks in some regions have undergone intense regional metamorphism and thereby lost their dense texture and become gneissic rocks. Such *Para-gneisses* occur among the *Ortogneisses* in the gneiss-group districts and seem especially to be abundant in some parts of the great magnetite-gneiss area of SW-Sweden.

Secondary Features of the Archaean.

It seems to the present writer that the metamorphic changes which the Archaean rocks underwent after their formation are as likely to be overlooked as overrated. As has been demonstrated in the foregoing pages, primary textures and structures have to a great extent been left undestroyed. On the other side there are rock-masses in the Archaean which have been so completely altered, both petrographically and geologically, that their origin still seems undeterminable. This is the case with some of the gneisses. The metamorphic forms of the granites are only partially known, namely so far as some primary features may still be observed in them. It can hardly be doubted also that some Archaean rocks have taken part in more than one metamorphic process.

Petrographic Textures.

Contact-metamorphic.

The conclusion to which H. BÄCKSTRÖM arrived through his petrographical studies of the Vestanå region of Archaean schists and granites, namely that the former possessed a contact-metamorphic texture which was older than their dynamo-metamorphic changes, seems to me to have general validity for the Swedish Archaean. BÄCKSTRÖM writes (**12**): »The effects of contact-metamorphism ... have a general distribution among the rocks of sedimentary origin, and even in most of the highly dynamo-metamorphosed rocks a primary structure, due to contact-metamorphism, may be recognized ... As the granites are as much dynamo-metamorphosed as the older sedimentary rocks, it is evident that the granites and the contact-metamorphism are older than the whole, or at least the later part, of the tectonic movements that raised and folded the schists of the region.»

Nearer acquaintance with the different areas of porphyry-leptite rocks gradually showed me that they only in part, and in some cases to a very slight degree, owed their charateristics to the dynamo-metamorphism, and that they had a texture which was primary to this and appeared to be of contact-metamorphic origin (Fig. 6). At the same time the examination of the gneiss-question had led me to the conclusion that far the greatest part of the Archaean in Sweden consisted of massive or gneissoid granites, which were all younger than the supercrustal rocks that are subsided in them (**26**). Consequently the possibility or rather necessity of an extensive contact-metamorphic influence of the granites on the supercrustal rocks seemed evident. The petrographical study of the rocks and the examination of their geological relations thus pointed in the same direction, and were also in accordance with the results which BÄCKSTRÖM had obtained in the Vestanå-district.

Especially the Utö-area, which I have studied in detail, has given very good information on the existence of contact-metamorphic textures in the leptites (**36**) and proved that the dynamo-metamorphism has acted as a far later process on these rocks (**26**). In fact the »hälleflintas» and leptites agree very well with common hornfels-rocks in appearance and texture. (Fig. 6.) But in the same degree as they have been subjected to mechanical deformation, that is to say taken part in the regional- (or dynamo-) metamorphism of the Archaean, they had lost these characters

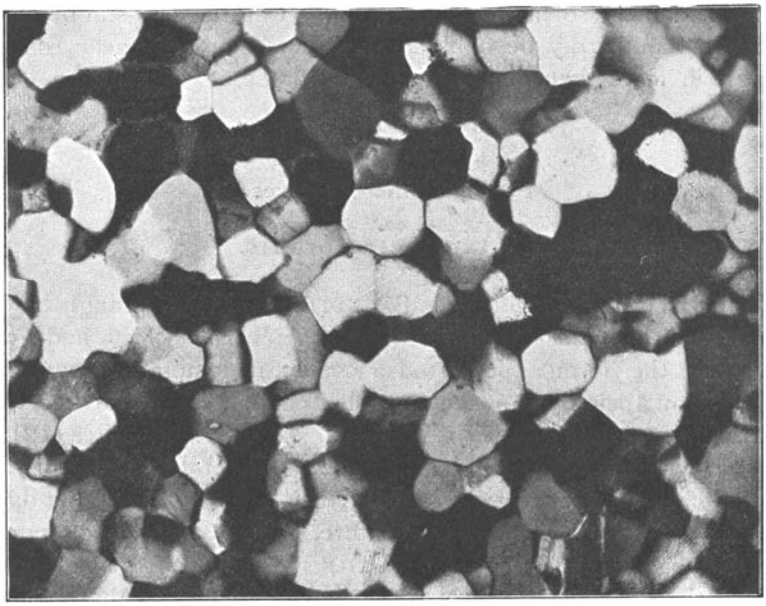


Fig. 6. The micro-structure of bedded leptite from the east shore of Utö. Magnified 180 times. Nic. crossed.

and become more and more schistose rocks. HÖGBOM also says that it seems to be more probable that the leptite rocks have acquired their actual characteristics through contact-metamorphism at the boundaries of the great younger granite-masses than through a dynamo-metamorphism (**29**).

It is well known that the iron- and pyrite-ores which occur in the porphyry-leptite areas of Sweden, are accompanied by rocks which show a contact-metamorphic character, namely the »*skarn*»-rocks. In close connexion with them also the Archaean limestones often exhibit a mineralization, and even metallization, which seem to be of contact-metamorphic (contact-pneumatolytic) origin. But these occurrences are far more local than the contact-metamorphic texture of the leptites and seem to stand in no connexion with the Archaean granites. The iron-ores of the Archaean, and also at least the greater part of the pyrite-ores, are so closely related to the porphyry-leptite rocks that it seems more probable that they are products of processes that took place during the time when these rocks themselves were being formed. Consequently the mineralization of some of the Archaean limstones must be older than the general contact-metamorphism of the leptites.

The generally accepted view, that metamorphism does not considerably alter the chemical composition of rocks, does not deserve to be considered as in all cases wholly trustworthy. Is has been shown that mylonitic (cataclastic) and schistose rocks have suffered considerable changes in chemical composition through the pressure-metamorphism which they have undergone (**37, 42, 43**).

Radical alteration is exhibited by such rocks as have been exposed to contact-pneumatolytic action. The greissen, the cordierite-anthophyllite- and cordierite-quartz-rocks form examples of this. ESKOLA hos shown that normal leptites gradually alters to cordierite-anthophyllite-rocks (**44**). Thereby both their structures and their composition in a high degree become altered.

Though pneumatolytic action of this kind so far as hitherto known, are confined to smaller areas, the possibility that similar processes may have been *to some degree* active also in greater areas undoubtedly deserves to be taken into consideration in researches on the regional metamorphism of the Archaean rocks.

Dynamo-metamorphic textures.

The dynamo-metamorphism appears in the Archaean as a regional metamorphism consisting of mechanical deformation and new crystallization of the rocks. It has, in other words, the same character as in the folding zones or mountain ranges of later geological periods. The rocks show the same regional-metamorphic features, namely cataclastic texture, schistosity, gneissoid texture etc. The last-named of these textures, which is considered to be formed during dynamo-metamorphism at great depth, exhibits in the Archaean a manifold of various types and occurs in extensive areas. In some of the granites and gneisses of Finland SEDERHOLM has thought to have found evidences of a regional re-fusing and forming (through *palingenesis*) of younger granite magmas (**24**). In the Swedish Archaean no such re-fusing can be proved, but *ultrametamorphic* processes appear in many of the areas where acidic gneisses occur. These processes consist in a partial or complete recrystallization of schistose and folded gneisses, through which they are converted into pegmatitic gneisses and granites. Secondary pegmatitic and aplitic magma rocks are also closely connected with these areas, where the regional metamorphic processes obviously reached their maximum of intensity. The most striking feature of the ultrametamorphism are the vanishing of the schistose structures and the abundant appearance of pegmatitic material in the metamorphic regions. The pegmatization becomes in this case a regional process. The gneiss-district in Södermanland (the garnet-gness region) and the very extensive magnetite-gneiss-area in SW-Sweden are good examples of this. There seems to be no possibility of bringing this pegmatization into connection with any granite. I am convinced that a general segregation of the quartz-felspar-material from the rocks took place at this high degree of the regional metamorphism, and that it marks the first steps of remelting of the

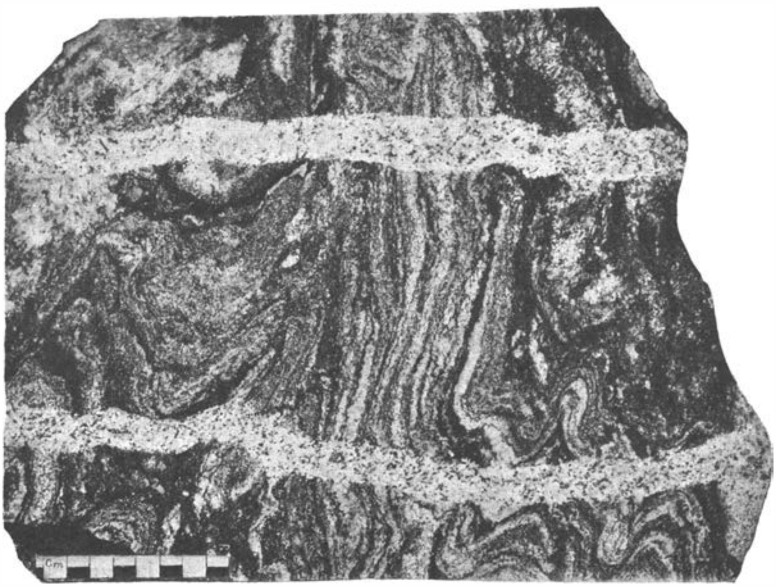


Fig. 7. Grey veined Stockholm-gneiss penetrated by small dikes of Stockholm-granite.

crust. I cannot find, however, thct the process in the Swedish regions has gone farther than the forming of pegmatitic and perhaps also some acid granitic magmas.

Regional (dynamo-) metamorphism struck the Archaean in a very different manner. In some regions the primary textures of the rocks are still well preserved, and but little deformation can be seen. This is the case in many of the granite areas. But the porphyry-leptite rocks in several regions also almost entirely escaped the pressure-metamorphism. In other regions they were transformed into schistose and folded rocks or acquired the uniform flowage-texture (*Kristallisationsschieferung*. BECKE), In the gneiss-districts we find them with coarse gneissoid habit.

Even though the regional metamorphism had a very different influence on the granites and the supercrustal rocks, yet the gneisses on the other hand never fail to show the results of intense metamorphism. In other words they are always high-metamorphosed rocks. This distinction is naturally no evidence of their great age or original formation, as has often been supposed, but simply a consequence of the method of investigation, hitherto used in the Archaean, according to which all high metamorphosed rocks, when not clearly connected with granites or with the porphyry-leptite rocks, were gathered in the gneiss-group.

In most cases when mechanical deformation-textures and traces of other textures occur together, it can be shown that the first-named is the latest. As the granites, gabbros etc. possess a schistosity which is younger than their igneous textures, so do we also find generally in the Archaean porphyries, hälleflintas and leptites a secondary schistosity by which they were converted into porphyritic schists, schistose hälleflintas, schistose leptites, and micaschist or gneisses. I also have always found the same relation between the hornfels-(contact-metamorphic) and the schistose textures of the Archaean leptites. Consequently, in my opinion, it can hardly be doubted that the main period of regional dynamo-metamorphism belongs to a later epoch of the Archaean than the contact-metamorphism. As the granites were deformed together with the supercrustal rocks — which, for the Vestanå-area, is also pointed out by BÄCKSTRÖM — the conclusion must be that *the dynamo-metamorphism set in so late in the Archaean time, that at least the main masses of the Archaean granites had been consolidated.*

Secondary Geological Structures.

The upraised Position of the Archaean Supercrustal Rocks.

One of the most striking features of the Archaean is the upraised position of the supercrustal bedded rock-complexes. These complexes form the rather small remnants of the first surface rocks of which we have any positive knowledge. BRÖGGER pointed out that the position of the Vestanå-schists — which he thought to be younger Archaean sediments pressed down into older rocks — has protected them from being destroyed by erosion (**5**). Even if the granites and gneisses which surround the other occurrences of porphyry-leptite rocks, as I have tried to show, are younger than these, the geological position in respect to the effect of the erosion is the same. Obviously only such parts of the old crustal and supercrustal rocks as had been deeply subsided into the underlying granitic magmas, have been preserved. But of these certainly large masses were destroyed through assimilation-processes in the granite magmas.

The commonly accepted opinion as to the cause of the raised position which the porphyry-leptite rocks exhibit, is that they have taken part in an Archaean folding process. This idea also formed the theoretical foundation for the attempts which have been made to settle the stratigraphical sequence of tbe Archaean rocks and especially for the constructions of synclines and anticlines in the leptitic and gneissic areas.

The regional Dynamo-metamorphism of the Archaean.

The upraising of the Archaean schists and their pressure-metamorphism have generally been regarded as contemporary processes caused by the forming of mountain ranges through folding-processes. This opinion, however, seems not to be in harmony with our present knowledge of the Archaean, which indicates that *the pressure-metamorphism belongs to a much later epoch of that period than the consolidation of most of the granites* and that *the occurrence of upraised Archaean schists is independent of the zones of regional metamorphism.* The porphyry-hälleflinta-complexes and the surrounding granites in Småland, where the regional metamorphism on the whole caused very little deformation and alteration, show the same geological position as is usual in the regions of Central Sweden that have been most powerfully affected by this process. Steep dipping is regularly seen also in smaller areas of leptitic rocks which are completely enclosed in granites and penetrated by them (Fig. 2). The relation between the great granite-masses and the supercrustal rocks seems to be that of the underlying granite-magma to an old crust of the earth, while the regional (dynamic) metamorphism has acted upon a much younger earth-crust, in which consolidated granite-masses made up nearly as much of the total as they do at the present time.

It may be objected, however, that the present position of the porphyry-leptite rocks — that they seem to have been subsided in a granitic bottom-magma — could also have come about through a folding process, which was followed by a re-fusion of the original bottom (gneisses and granites) of the porphyry-leptite rocks. SEDERHOLM, as is well known, has tried this, in order to explain some questions of the Archaean of Finland (**24**).

According to this hypotheses the porphyry-leptite rocks were subjected, *first* to a regional folding-metamorphism and *afterwards* to a regional re-fusion. In some regions later on contact-metamorphism and a second dynamo-metamorphism followed.

The actual well-preserved condition of the rocks named in all districts where the dynamic structures are but little visible, but yet the supercrustal rocks appear subsided in the great granite masses (Småland, Upland, East-Vermland), is, however, quite inconsistent with the idea of such a polymetamorphism[1] of the porphyry-leptite rocks. The many original textures and structures which these rocks still exhibit (See page 131—138) would certainly have been quite destroyed if a regional pressure-meta-

[1] J. KOENIGSBERGER. Compte Rendue du XI Congrès Geologique International (1910): 670.

morphism and a regional refusion had acted upon them. It is also to be noted that no dynamo-metamorphosed rocks have hitherto been observed among the boulders which occur in the Archaean conglomerates. Nor has any proof been given of a regional re-fusion in the Swedish Archaean.

Several other geological facts telling against the hypothesis of an infolding and re-fusion of the original bed-rocks of the porphyry-leptite rocks could be adduced.[1]

Concluding Remarks.

The regional (dynamic) metamorphism behaves to the original tectonic relations between the great granite-masses and the supercrustal rocks in a quite analogous manner as to the primary petrographical textures and structures. As these have been more or less obliterated, so also have to a large degree the eruptive contacts, which originally seem to have marked the boundaries between the old Archaean supercrustal and infracrusral rocks. In the same degree as the granites show alteration through schistosity their contacts are difficult to interpret, and often only through careful examinations can relics of the eruptive features be detected. It deserves once more to be pointed out that in no such case has the examination hitherto brought forth any sign of a stratigraphical relation between the porphyry-leptite rocks and supposed older gneiss-granites (schistose granites),

According to the evidences stated in the foregoing pages, the following *sequence of events* for the Swedish Archaean seems probable.

The porphyry-leptite-rocks are the oldest known Archaean formations. Probably they represent fragments of very old and to a great extent ashy volcanic formations.

The porphyry-leptite rocks were subsided in the underlying granite-magma masses and by them contact-metamorphosed and partly assimilated.

The cooling of the masses at the earth's surface proceeded towards the interior and thus also the granites consolidated, after which dynamo-metamorphic processes, comprising both these granites and the old supercrustal rocks included in them, came into action.

The last events to which the textures and structures of the Archaean rocks witness are the regional dynamo-metamorphic alterations of original petrographical and geological features into secondary. These processes followed certain regions in the consolidated crust and left others more or less untouched.

Some granites were at this epoch intruded in the crust and these appear now in their occurrence to be independent of the porphyry-leptite

[1] Törnebohm has pointed out (G. F. F. **30** (1908): 411) that the leptitic complexes enclosed in the granites are often bordered on both sides by granites of different composition, a interesting and undoubtedly very important piece of evidence.

zones. In the regions where the dynamo-metamorphic processes reached their greatest intensity ordinary gneiss-rocks and ultrametamorphic types of gneisses were formed.

With the ultrametamorphic processes are closely connected the pegmatitization; and the last eruptive masses of the Archaean consist of acid granites, aplites and pegmatites.

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