4. On the intrusion mechanism of the Archean granites of Central Sweden.

By

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The characteristic different relations shown by the older and younger Archean granites of southern and central[1] Sweden to the surrounding older rocks have long been known, but comparatively little has been done to carry the investigations of these relations so far as to give a more definite idea of the mechanism of the granite intrusions, and the cause of the remarkably different behaviour of the older and the younger granites. This is largely due to the generally low relief of the country, and the rather extensive drift covering, two factors that necessarily limit the possibilities of such a study.

Work for the Geological Survey of Sweden in a district, where the features in question were highly pronounced, caused the author to undertake a survey of available literature on granite intrusions in younger mountain chains, where deeper sections and a more easily interpreted structure ought to facilitate the study and make the results more reliable. The author is aware that the conclucions that have been attained in this way concerning the Swedish Archean granites, largely consist only in a corroboration of views that are commonly held, but he believes that the great importance of the questions involved will make even a very moderate progress welcome.

Before turning to the characteristics of the two granite groups in question, we must make clear what scope we are going to give to the terms older and younger granites. For many reasons, all attempts to

[1] »Central Sweden» is here used in the common although matematically wrong sense, meaning the country between latitudes 58°40′ and 60°40′ approximately.

establish a chronological grouping of the numerous granite massifs in central Sweden have encountered great difficulties. However, certain points are proved. The youngest Archean granites, the Serarchean granites of HÖGBOM[1], form a fairly well defined group, characterized, inter alia, by a rather slight metamorphism, by cross-cutting relations to the older rocks, and by the abundance of granite dikes in the country rock and of country rock fragments in the granite. Thus, in their relations to the invaded formations, the Serarchean granites furnish excellent examples of the features that are quoted by DALY[2] in favor of the hypothesis of batholithic intrusion by »overhead stoping». These granites are often accompanied by great masses of pegmatite. A typical representative of the group is the Stockholm granite.

The older Archean granites naturally are more strongly metamorphosed. In the form of the massifs, they always show a very marked dependence on the structure of the surrounding rocks, never breaking across their strike so plainly as do the Serarchean granites; also, the brecciation of the country rock by the granite, so conspicuous a feature in the latter, is almost absent here. These characters are more or less pronounced, and it is clear, even when taking into account the uncertainty of the degree of metamorphism as a function of geologial age, that a great amplitude in age is represented among those Archean granites that are older than the Serarchean group. Apparently, some granites are considerably younger than the rest, and perhaps more closely approach the Serarchean granites. The Filipstad granite, a characteristic petrographic type, is regarded as being of this intermediate age. Its contact relations also appear to be, in a way, intermediate in character between those of the Serarchean and the older granites.

Some authors[3] class in one group with the Filipstad granite a number of other massifs, among them the fairly well preserved granites of Upland, leaving only a number of strongly gneissic granites to form the oldest group. The author has not had enough field experience of the various granites to have formed a definite opinion on these questions, but belives that, for the present study, a slight modification of the classification used by TÖRNEBOHM in his pioneer mapping work in this region[4] will be the best. According to this view, the group of the

[1] Pre-cambrian Geology of Sweden (this Bull., Vol. 10, 1910—11, p. 1).

[2] Compare several papers in Am. Journ. of Science 1903 and 1908, also »The North American Cordillera at the Forty-ninth Parallel» (Geol. Survey Canada, Mem. 38), and »Igneous rocks and their origin», New York 1914.

[3] O. NORDENSKJÖLD, Über die Kontaktverhältnisse zwischen den archäischen Porphyren (»Hälleflinten») und Graniten im nordöstlichen Småland (this Bull., Vol. 5, 1900, p. 1).

HOLMQUIST, Studien über die Granite von Schweden (this Bull., Vol. 7, 1905, p. 77).

TÖRNEBOHM, Geol. översiktskarta över Skandinavien, 1908 (1: 1 000 000).

[4] Geol. Öfversiktskarta öfver Mell. Sveriges Bergslag (Stockholm 1880).

Older Achean granites should comprise all the rocks called by TÖRNEBOHM gneiss granites or »urgraniter» (among which are the older granites of Upland) and also the majority of the rocks mapped by the same author as granite gneisses, which are now known to represent more strongly metamorphosed phases of the »urgraniter». Undeniably, there are among the granite gneisses granitic intrusions considerably older than the bulk of the Older Archean granites, but it is extremely difficult, at the present state of our knowledge of them, always to separate them from the others. Further, for a discussion of the intrusion mechanism, less confusion is caused by this classification than by classing the somewhat differing Filipstad granite with the bulk of the older Archean granites.

In the following, we are going to consider the Older Archean granites, giving to this term the scope just outlined above, and the Serarchean granites. The Filipstad granite does not need to be discussed, as it is intermediate between the extreme groups.

The brief characteristic of the Serarchean granites which was given above, may be sufficient for the present purpose, but the Older Archean granites require a somewhat more detailed description.

The complex, in which these granites are intruded, is in most cases the (ore-bearing) leptite formation, which is often stratified or at least shows a bedding of a higher order of magnitude. The form (in the surface) of the granite massifs belonging to this group generally more or less approaches that of an ellipse; but some massifs may be almost circular, others are strongly elongated. When the directions of strike in the surrounding rocks are plotted on the map, it appears that the boundaries of the granite areas generally run parallel to the strike of the leptites. The actual contact is often masked by a later metamorphism, but where it is discernible it may be found that this parallelism holds true even in details, or there may locally appear cross-cutting under an acute angle. Dikes of the granite are sometimes observed in the leptite, mostly injected parallel to the strike of the latter. Fragments of leptite occur in the granite, but are never numerous.

The granite in most cases is best preserved in the centre of a massif, and becomes more or less gneissic when nearing the contact to the leptite, the schistosity running parallel to the contact. Fig. 1, a reproduction from fig. 11 in HÖGBOM's paper »Pre-Cambrian Geology of Sweden», illustrates the relations between the Older Archean granites and the leptite formation, and also the occurrence of peripheral gneissic zones in the granite massifs.[1]

[1] Recent studies have shown that some changes ought to be made in this map, but they are of no consequence for this discussion (compare G. LINDROTH, Sverig. Geol. Unders. ser. C, n:o 266, p. 2).

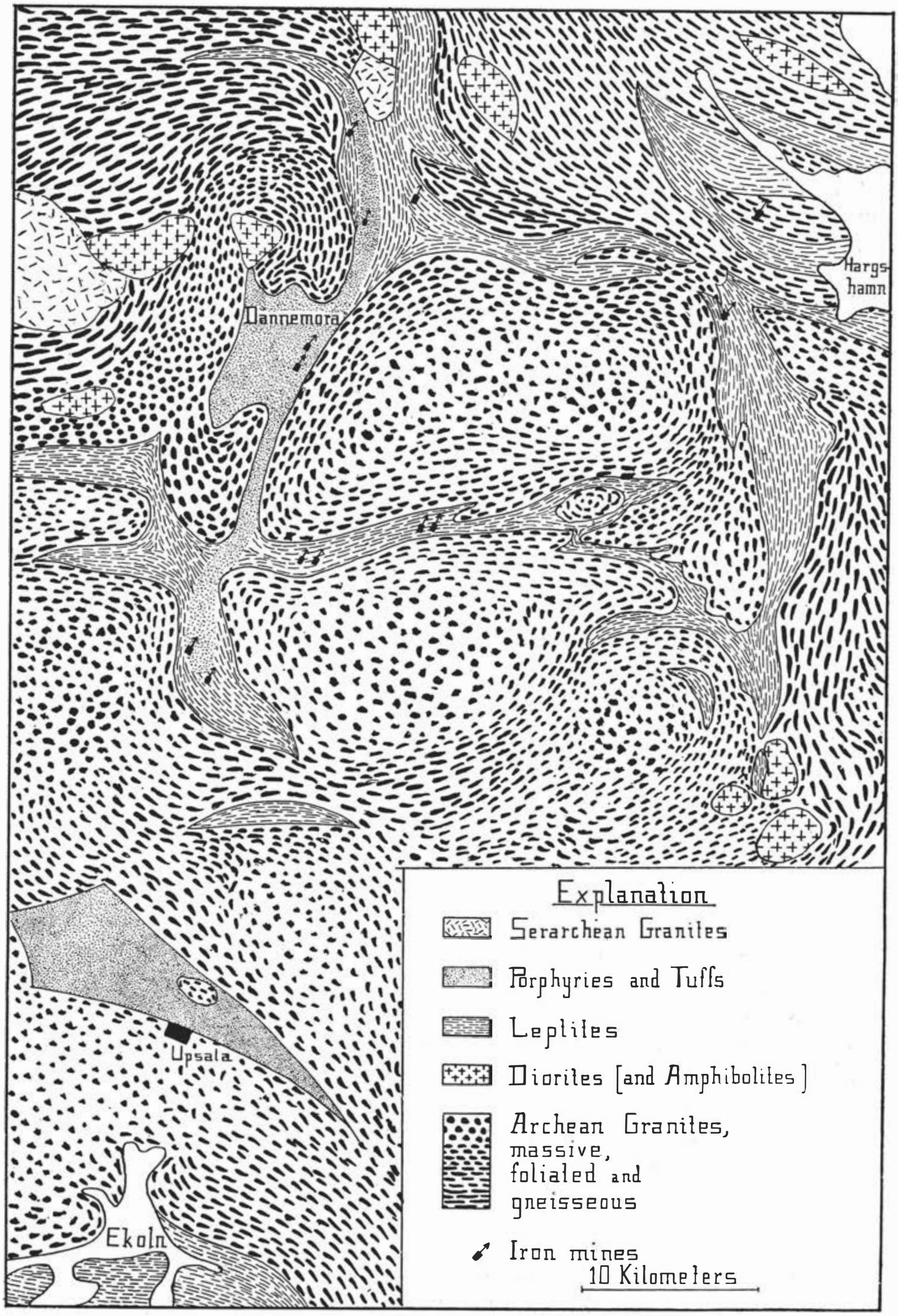

Fig. 1. Sketch-map of the Archean of a part of Upland (after A. G. HÖGBOM).

In the leptite formation, stratification and schistosity are nearly always parallel. Thus, the granite-leptite contacts are parallel, not only to the schistosity of the formation, but also to the bedding, and it is excluded that the parallelism should be due to the fact that pressure of the magma has induced a schistosity parallel to the contact in the country rock, or to the granite masses' having acted as resistant and orientating nuclei during a later pressure metamorphism. The latter factor is responsible for the peripheric schistosity of the granite massifs, and it may have accentuated the schistosity of the leptite, but apparently it cannot be the original cause to the parallelism in question.

When the different behaviour of the older and younger Archean granites became known, the intrusive nature of the latter was soon realized, but the concordant relations between the older granites and the leptite formation led the observers to the belief that these granites should represent lenticular layers intercalated in the supposed sequence of sediments of an original crystalline character. The most important contribution from that time is the one given by TÖRNEBOHM in the theoretical chapters published as an introduction to his »Bergslagskarta»[1] (1880), where the granites are regarded as surface flows.

A younger generation of geologists understood the intrusive nature of these granites. An important step forward in the knowledge of the older Archean granites is marked by HÖGBOM's paper on the »urgraniter» of Upland.[2] In this paper, HÖGBOM also mentions the differences between the older and younger granites; as possible causes are mentioned the different degree of metamorphism, or the fact that the present surface may cut the massifs of the two groups at different depths below the surface at the time of their intrusion.

Generally, the massifs of both groups have been called batholiths, despite the lack of sections deep enough to be accepted as definite proofs for this view. However, HJ. SJÖGREN[3] is inclined to regard the Older Archean granites as laccoliths. This author calls attention to the different petrographic characters even in neighbouring granites, and to the fact that differences in age have been proved also among the granites of the Older Archean group. This was uttered in opposition against HOLMQUIST's view[4] of these granites as a »magma bottom». But also typical batholiths composed of various granites of different age are known, therefore this argument, whatever weight it may have in the discussion for which it was directly used, can hardly be cited against the view of a batholithic nature of these granites.[5] As regards the corresponding granites in southwestern

[1] Compare above, p. 48.
[2] Geol. Fören. Förh., Vol. 15, 1893, p. 241.
[3] *Ibid.*, Vol. 30, 1908, p. 129.
[4] *Ibid.*, Vol. 29, 1907, p. 347.
[5] The word batholith is here used in the now common sense of a *subjacent* igneous body (to use DALY's terminology) without any floor of older rocks, and growing wider in depth.

Finland, TIGERSTEDT[1] in 1890 expressed the view that they fill up anticlines in the leptite formation. ESKOLA[2], who has made a detailed study of this region, has proclaimed his agreement to this view.

There is little more to be said about the opinions published by Swedish and Finnish geologists on this subject. In other countries, the mechanics of batholithic intrusion have been vigorously debated. The old view that the batholithic granite has eaten its way upwards by simply fusing the roof cannot muster many adherents nowadays. BRÖGGER[3] has produced many arguments against it (instead advocating the laccolithic hypothesis). More recently, DALY[4] has summarized the causes that make this view in its original form untenable. In a way, its place has been taken by the hypothesis of »overhead stoping», formulated by DALY,[4] BARRELL,[5] and USSING,[6] and worked out with great detail by DALY.[4] The facts that brought forth this hypothesis are the same that once led to that of roof fusing: if we look at the map of a region, where cross-cutting batholiths occur, it appears as if the older rocks had, within certain areas, entirely disappeared, and their place had been occupied by the batholithic rock. DALY's textbook gives a great number of excellent illustrations of this fact (see especially figs. 43, 55 and 64). As the simple fusing of the roof is excluded, another explanation of the displacement had to be found. The three authors believe that the roof of the magma chamber was fissured by tensions caused by the unequal heat, and that the detached fragments sunk in the specifically lighter magma. Employing a mining term, DALY speaks of the process as »overhead stoping».[7] A wealth of facts is cited in favor of this hypothesis. A crucial point is whether the brecciation phenomena fixed by the crystallization of the magma at what became the definite contact of the batholithic granite, may be interpreted as representative of this contact also at the earlier stages of the evolution of the batholith. Some authors have claimed that they belong only to the last phases of the intrusive action.[8] The comparisons given in the following of the general structural conditions accompanying the various forms of batolithic intrusion, may perhaps shed some new light on the process.

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[1] Unpublished work, quoted by ESKOLA in »On the Petrology of the Orijärv Region» (Bull. Comm. géol. Finl. n:o 40), p. 5.

[2] L. c., p. 15.

[3] Die Eruptivgesteine des Kristianiagebietes, II, p. 151.

[4] In the works quoted above p. 48.

[5] The Marysville Mining District, Montana (U. S. Geol. Survey, P. P. 57).

[6] Geology of the country around Julianehaab, Greenland. Meddelelser om Grönland, Vol. 38.

[7] It may be noted that the mechanism of the process is closely related to that of the old method of mining by fire-building.

[8] Compare LINDGREN, Igneous Geology of the Cordilleras, p. 282 (in »Problems of American Geology», New Haven 1915).

Some of the best arguments for the stoping hypothesis were gathered by DALY during his work in the North American Cordillera along the 49th Parallel. It is unfortunate that the section so carefully examined does not include any batholiths showing the same characters as those

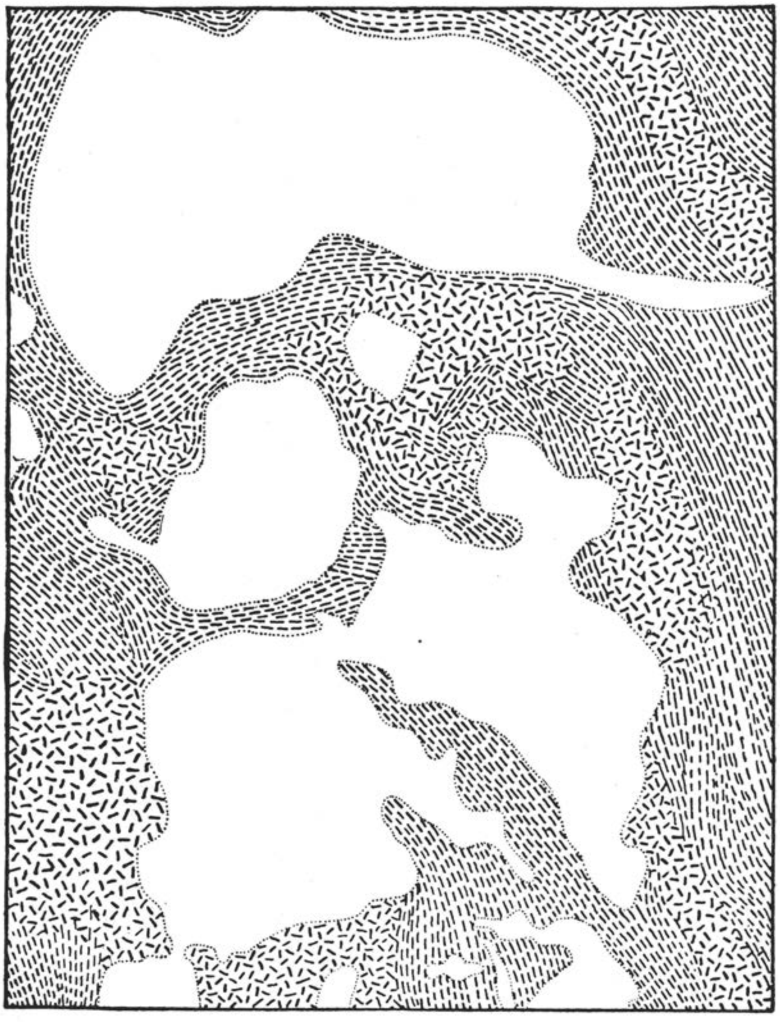

Fig. 2. Map showing the relations between the granite massifs and the structure of the older rocks, Bidwell Bar. After TURNER. Scale c:a 1 : 500 000. White is granite, divergent hachures represent massive, parallel lines schistose (and stratified) older rocks.

of Sierra Nevada and the British-Columbian and Alaskan Coast Range, as such a batholith would have furnished an example of another intrusion mechanism. In fact, geologists familiar with the Sierra Nevadan granites and granodiorites have always considered roof doming through the pressure of the magma as the dominant factor in batholithic intrusion. This was pointed out very clearly in 1898 by H. W. TURNER.[1] Fig. 2 is reproduced from TURNER's works. TURNER writes: »It vill be observed that at nearly all points the lines of schistosity, which are also largely coincident with the bedding of the sedimentary rocks, are parallel to the outlines of the granitoid areas. To this, however, there are abundant minor exceptions, as where narrow tongues of granite cut across the lines of schistosity, and it would appear that the schistosity in the main was developed at a period antecedent to the granite intrusions, and that the parallelism of the lines of schistosity to the contacts of the entering granite is due to these masses being forced aside by the intrusive rock.»

Recently, LINDGREN has called attention to TURNER's work and pointed out that the features described by him are characteristic of the

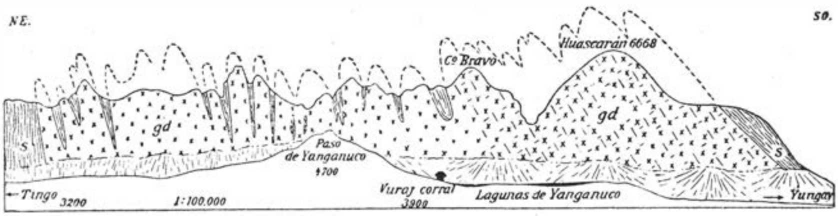

Fig. 3. Section through the Cordillera Blanca, Peru (after STEINMANN). Height greatly exaggerated; gd = granodiorite, s = contact-metamorphic slates and sandstones.

whole Californian Gold Belt. »Everywhere the strata bend around the intrusive masses. Even in the large batholith of the High Sierra this is evident by the strata following the general trend of the contacts. The sedimentary rocks have been pushed aside bodily to accommodate the slowly rising intrusive.»[2]

STEINMANN[3] has found similar relations between the Tertiary granodiorites of the Cordillera Blanca of Peru and the Mesozoic sediments. The cross-section reproduced in fig. 3, with narrow folds of the stratified roof folded down into the magma, is closely similar to the hypothetical sections through the Swedish terrain of leptite formation and Older Archean granites, which are constructed with the aid of the relative positions of the rocks at the surface, as no sections occur that are comparable in depth to those in Peru. The undulating character of the batholithic crest line is also described. At the upper surface of these batholiths, according to STEINMANN, the relations are concordant, but in their walls the granodiorite is often seen to truncate the Mesozoic strata.

A good example of similar relations in the Alps is given by the

[1] Bidwell Bar Folio, United States Geol. Survey.

[2] L. c., p. 283.

[3] Gebirgsbildung und Massengesteine in der Kordillere Südamerikas (Geol. Rundschau, Vol. 1, 1910, p. 13).

tonalite of the Riesenferner, according to the descriptions by LÖWL[1] and BECKE.[1] In a cross-section, this massif shows a regular arch, covered by an almost concordant roof of older (contact-metamorphic) sedimentaries. BECKE says that it would be an ideal case of a laccolith, if a plane floor were exposed. However, the general structure of the district, and the very steep dip of the contact plane make it more probable that it is a concordant batholith.

Several of the batholiths quoted here as examples of concordant relations are found to send out apophyses into their country rock, and to contain fragments of the latter, but none of this features is more conspicuous than at our Older Archean granites.

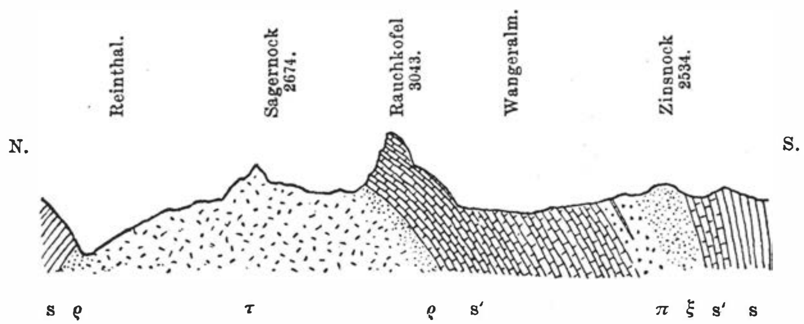

Fig. 4. Section through part of the Riesenferner (after LÖWL and BECKE). Scale 1 : 100 000. τ central tonalite; ρ marginal phase of tonalite; ξ quartz-mica-diorite; π pegmatite; s schists; s' schists with pegmatite layers.

In the evolution of the concordant batholiths, the magma must have pressed upward, lifting the roof. It is a matter of words whether one puts it so that the action of the intrusive magma has caused the uplift, or that the uplift and the intrusion have one common cause.[2]

If the relations are concordant, it follows that the batholiths are overlaid by anticlines in the invaded stratified formations, while depressions in the intrusive correspond to synclines. The undulating crest lines of the anticlines cause the intrusive to appear — in a section through its upper part — as chains of rounded batholiths instead of long bands. These features are particularly well brought out in STEINMANN's paper. The term *anticlinal batholiths* may be used to designate these batholiths apart from those which show transgressive relations to their country rock.

[1] Petermanns Mitteilungen, 1893, p. 73, and Tschermaks M. P. M., XIII 1893, p. 380.

[2] Compare WEINSCHENK, Z. d. deutsch. geol. Gesellschaft, 54, 1912, p. 441, and LINDGREN, l. c. SUESS' view (Antlitz d. Erde I, p. 218) that the magma was injected into hollows opened by the tangential pressure, does not seem to have any adherents to-day.

The examples cited above show that these anticlinal batholiths are found where magma masses have been forced upward into a stratified series which, at the same time, has been folded into strongly compressed and steeply dipping folds. As already mentioned, the authors who have studied such districts, as WEINSCHENK,[1] LINDGREN,[1] and STEINMANN,[1] agree in regarding intrusion and folding as simultaneous processes, brought forth by the same prime cause. The peripheric schistosity of many of these batholiths bears witness that the folding movements have continued with the same general character during and some time after the crystallization of the magma.

LINDGREN[2] has pointed out that there is evidence of roof doming also at some of the type localities for »stoping», as at Marysville, but it must be admitted that in other districts, for instance at Ilimausak, the evidence in favor of the stoping hypothesis seems fully convincing, although it may be questioned, how deep down from the exposed level these relations remain the same.[3] Therefore, the existence of a considerable a mount of stoping must be admitted, and we must try to find out, why abatholithic intrusion sometimes takes this form instead of anticlinal batholiths.

Ilimausak, and the Castle Peak stock described by DALY, show that some of the best examples of the features regarded as characteristic of stoping can be found in districts where the invaded older formation is a stratified one. Thus, differences in the character of the country rock cannot be the causes of the differences between the anticlinal and the transgressive batholiths,[4] nor is the explanation to be found in a different depth for the sections available for examination, as the concordant relations are even more characteristic of the top of the anticlinal batholiths than of their walls. However, if not the *character* of the invaded formation is different, at least its *structure* seems to be. Rather open folding, often combined with faulting, seems to be the most common structure around the transgressive batholiths. Where the country rock of a batholith of this type shows a structure similar to that accompanying anticlinal batholiths, there is generally reason to believe that this structure is essentially older than the intrusion.[5] Folding contemporaneous with intrusion is never proved, but faulting may be very closely associated with it. This is the case

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[1] In the papers quoted above.

[2] L. c., p. 283.

[3] It may be unfair to make this remark, but it must be remembered that the Ilimausak rock group is a very unusual one, and one that would not be expected to form »bottomless» batholiths like those of granite or granodiorite.

[4] If we confined our attention to the granites of Sweden, it would lie near at hand to seek the explanation in the fact that the (transgressive) Serarchean granites have invaded a very inhomogeneuos rock crust, but the older, concordant ones a more homogeneous formation.

[5] For example, USSING writes (l. c. p. 307): »The Palæozoic Plutonic rocks of South Greenland — — have invaded the upper part of the earth crust at a time much later than that of the latest foldings of the country.»

at Ilimausak, although USSING finds that there the batholithic invasion »is in all essentials independent of the subsidence of the earth crust, while faulting, on the other hand, may have played some part in the localization of the intrusion.»[1]

In some cases, the »stoping» batholiths occur in regions of what HARKER[2] has called plateau structure,[3] in others these relations are not so typically developed, but always the structural conditions are those of the »zone of fracture», in a strong contrast to the conditions controlling the development of anticlinal batholiths.

Conclusions.

We have found that, among younger batholiths, two structurally different types can be discerned, the anticlinal and the transgressive or »stoping» batholiths, and that the factor controlling these types lies in the nature of the tectonical forces that are the prime cause of the intrusion. We shall also have found, I think, that the controversy between the advocates of roof doming or of »stoping» as the dominant factor in batholithic intrusion is largely due to the fact that the examples have been chosen from districts of a different geological structure. We shall now return to the Archean granites of Central Sweden, and see if any of the conclusions resulting from the preceding discussion can be applied to them.

The examples of anticlinal batholiths cited above have all their essential features in common with our Older Archean granites, and it is clear that the massives of the latter normally have the character of anticlinal batholiths, thus TIGERSTEDT's view has been confirmed. It is also apparent from the same comparison that the relations between the leptite formation and the granites are the same as exist between the folded sedimentaries (including volcanics) and the invading batholiths in typical mountain chains of a Mesozoic or Tertiary age. This correspondence is of a considerable interest, for, although the territory in question has long been regarded as representing the root of a denuded mountain chain (sometimes spoken of as »the Sveco-Fennian range»), there are some features that seem incompatible with this view, as the lack of any clear direction of the supposed range within certain areas, and the remarkable absence of signs of metamorphism under one-sided pressure often met with in the narrow tongues of leptite rocks bordered by granite. It is also of interest for the discussion of »anatexis» and the phenomena of magmatic assimilation in general. As is well known, almost exactly the same relations between granitic batholiths and an older supra-crustal formation are encountered in the Canadian Archean.

[1] L. c., p. 301.
[2] Natural History of Igneous Rocks (London 1909).
[3] For southern Greenland this has already been pointed out by USSING (l. c.).

With regard to the Serarchean granites, little more can be said beyond that directly contained in the above discussion of the transgressive batholiths in general. It seems most probable that the intrusion of these granites took place during a regional sinking of the region in question, probably of at least a large portion of the Fenno-Scandian shield, accompanied by faulting rather than folding. The next work to do is to find out whether any connection can be traced between these granites and still discernible fault lines.

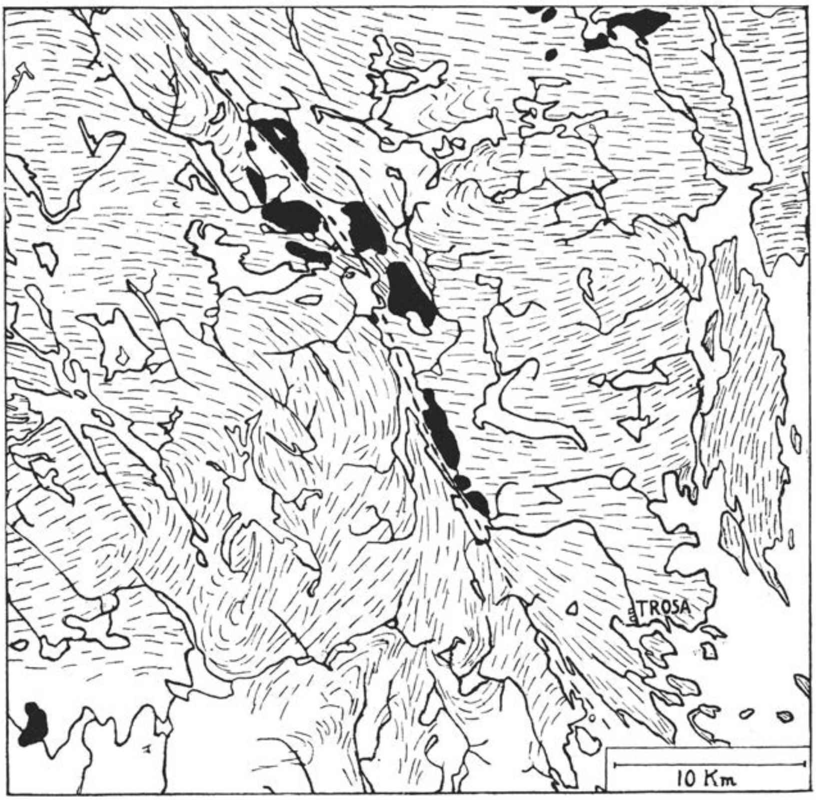

Fig. 5. Sketch map of the Archean of a part of Södermanland. Scale 1 : 400 000. The strike directions of the gneisses are shown. Serarchean granites are black, the fault line Klemmingen-Sillen-Hållsviken is shown by the broken black line, other fissure and fault lines are not marked, but their course may be inferred from the drainage. (Geology compiled from maps published by the Geological Survey of Sweden.)

In one district, at least, there are good reasons to suspect a relation of this kind. Along the Klemmingen-Sillen-Hållsviken valley in Södermanland, there are scattered a number of small massifs of Serarchean granite of the Stockholm type (fig. 5). This valley belongs to the NW-SE system among the straight, narrow fissure and fault line valleys that intersect this part of the country. Some of these fissures may not have been the loci of any movements, but in this particular case the strike directions in the gneiss territory seem to indicate a considerable displacement.

The author has not had the opportunity to study the district in the field, but the data available in the maps and descriptions by the Geological Survey, from which fig. 5 has been compiled, allow the drawing of certain conclusions. Thus, it is plain that the association of the granite with the valley can not be due to the deeper erosion along the fissure, because the granite is largely exposed on the plateau at a little distance from the fissure valley. Nor is there any reason to seek the explanation in the possibility that faulting may have caused a tilting of the faulted blocks and thus enabled erosion to expose the edges of »flatlying laccolithic masses», as SEDERHOLM thinks to be the case in certain other districts, where there is a connection between granite massifs and fault lines.[1] The intrusion mechanism of the granite massifs shown in fig. 5 is typical of batholithic »stoping», and they are radically different from laccoliths.[2]

Undoubtedly, the most natural explanation of the relations between the Klemmingen-Sillen-Hållsviken fault valley and the Serarchean granite massifs is this one: The line of this fault was a line of weakness in the earth's crust already at the time when the Serarchean granites where intruded. It does not make any difference if there should be found signs of faulting younger than the granite, as all evidence points to the fact that, in regions undisturbed by folding, such lines (or rather planes) of weakness may show a remarkable persistence in time. It is possible that the granite itself will furnish proofs that it has been injected during movements along the line in question. HUMMEL, in the description of the map sheet »Trosa», published in 1874,[3] points out that the granite along lake Sillen (the southeasternmost massifs in fig. 3) shows a well developed and regular schistosity in NW—SE, parallel to the fault line and cutting obliquely across the strike of the gneisses. It is not clear whether this schistosity is a fluidal structure or really a schistosity, but apparently there is some reason to suspect that it may be a protoclastic one. HUMMEL calls attention to the peculiar distribution of the granite massifs along the fault line, but does not attempt any explanation. He remarks, however, that the fault is younger than the granite, without

[1] Geol. Fören. Förh., Vol. 38, 1916, p. 36. In the districts described by SEDERHOLM, faulting is later than the granite intrusions.

[2] Naturally, this does not exclude that SEDERHOLM's explanation may hold good in other cases.

[3] Sveriges Geol. Undersökning, ser. Aa, n:r 52.

citing any observations to prove it. Yet it is highly probable that the fault marked by the present valley is younger than the granite, although it follows a line of weakness that existed as such already at the time for the granitic intrusions. A re-examination of the region in question ought to give interesting results. It is also made probable that the fissure and fault structure, which is so conspicuous a feature in southern Sweden, was beginning to develop already in Archean times.

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