4. Felspathization and boudinage in a quartzite boulder from the Västervik area.

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With 5 text-figures.

Introduction.

In the spring and summer of 1938 the author had the opportunity to make some rather detailed field investigations in the coast region around Västervik in S. E. Sweden. The material collected in the course of this work is very extensive, and presents a great many features of interest. For various reasons the laboratory investigation had to be postponed until lately and it may take some considerable time, before a final report of the results can be given. It seems desirable, however, that some of the problems encountered should be subjected to a preliminary treatise and the following brief note is intended as a first contribution.

Megascopical description.

At the S. W. shore of the small island Mjödö (about 5 km S. E. of Västervik) a rather peculiar boulder was found which seems to merit a brief description. The boulder, which has a greatest diameter of about 30 centimetres, is of an irregularly rounded shape and consists mainly of a red, somewhat leptite-like rock, which forms an integral part of the so-called Krokögneiss of the neighbourhood (SVENONIUS 1907). The rock is dissected by several bright red or yellowish-white veins of a width of 1—2 mm and consisting mainly of felspathic material. Attention was drawn to this particular boulder because of a black coating of a peculiar fernlike pattern, which was observed on one of its faces. At a blow from the hammer the boulder parted along an approximately plane surface and similar patterns of still more excellent development were revealed on both of the juxtaposed parting planes (fig. 1). This peculiar design is effected by an alternation of black tourmaline and red microcline. One gets the

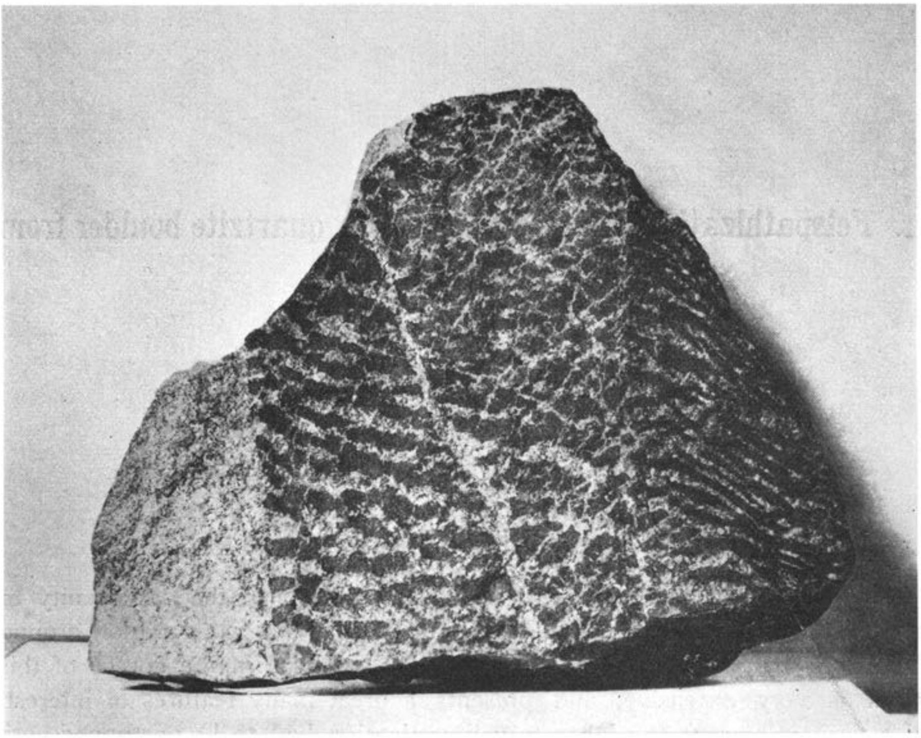

Fig. 1. Frontal view of the fernlike pattern. Black — tourmaline, gray — microcline.

impression that an originally continuous coating of tourmaline has been dissected by an intricate net-work of microcline veins, or that tourmaline has been deposited in the small lenticular depressions of an irregularly rippled or wrinkled surface. It should be noted, however, that the microcline »strings» do not represent sections of veins traversing the main rock obliquely to the parting surface. On the contrary, the microcline-tourmaline zone constitutes a thin sheet of maximum 3 mm width, bordered on both sides by the normal leptite-like rock.

As is seen in fig. 1 the tourmaline disappears abruptly at an almost perfectly straight boundary line in the left part of the boulder. This is, however, only due to a sudden change of direction of the tourmaline zone, its continuation deviating about 45° towards the observer and thus passing through the corresponding front half of the boulder. The boundary line represents the intersection between the tourmaline zone and a microcline sheet traversing the whole boulder. This microcline sheet appears in parallel section in the leftmost part of fig. 1 and in cross section on the right face of fig. 2 (M—M).

A cross section of the tourmaline-microcline zone is seen in the bottom part of fig. 2.

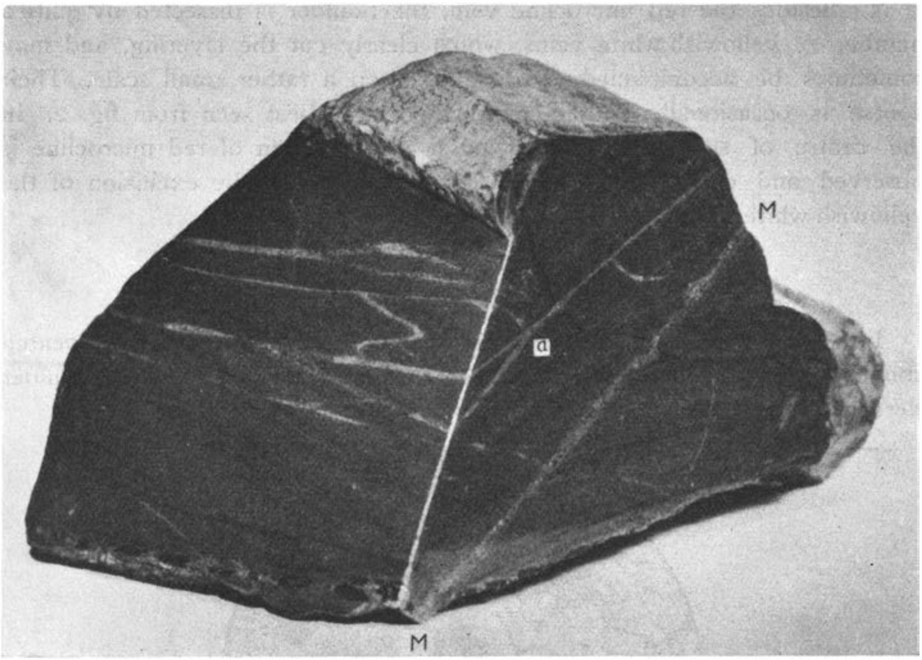

Fig. 2. Polished sections of one half of the boulder. The main tourmaline zone follows the bottom face. M—M=microcline vein.

Turning now to the main part of the boulder, some features of interest should be mentioned, and are moreover illustrated by fig. 2. The salient points may be summarized as follows.

1. The rock shows a distinct layering, which is made prominent by numerous thin black layers alternating with the predominant brownish-red material. As is evident from the right face of fig. 2, this layering is not altogether undisturbed but shows indications of a gentle folding or arching.

2. The tourmaline zone (at the bottom of the figure) cuts the layering discordantly as best seen in fig. 2 (left face). Although not apparent from the figures it seems to have to some extent partaken of the folding. Thus, in the right part of fig. 1 there can be observed a rather distinct break in the direction of the parting surface. This break corresponds exactly to the maximum bend in the layers of fig. 2.

3. From the foremost bottom corner the right face of the boulder is dissected by a remarkably straight microcline vein (M—M in fig. 2), already referred to above. This bright red vein is from place to place bordered laterally by a rather diffuse yellowish white zone, to all appearance corresponding in composition to the veins described under 5 below.

4. The layering of the rock is distinctly faulted by the microcline vein just mentioned.

5. Besides the red microcline vein, the boulder is dissected by quite a number of yellowish white veins, which clearly cut the layering, and may sometimes be accompanied by a faulting on a rather small scale. Their course is occasionally rather complicated as is best seen from fig. 2. In the centre of some of these veins a narrow seam of red microcline is observed and occasionally it may expand almost to the exclusion of the yellowish-white material (central part of left face).

Microscopical investigation.

In order to get at an explanation of the phenomena briefly delineated above, a number of slides from different interesting portions of the boulder were examined, and an account of the results is given below.

Fig. 3. Microcline penetrating into one quartz grain and afterwards following the boundary between that grain and another.

The main rock is composed predominantly of quartz and microcline, the latter being sometimes slightly perthitic and occasionally somewhat sericitized. A few grains of polysynthetically twinned plagioclase have succumbed to a far more intense sericitization, which makes optical determinations impossible. The grain is rather fine, averaging 0.1—0.2 mm, and the texture typically granoblastic, at least as far as the quartz grains are concerned. The latter show a slightly undulose extinction, are generally tolerably well rounded and isometric, and have distinct boundaries against each other. The microcline grains on the other hand are of a decidedly more irregular shape with ragged and rather diffuse contours. Numerous small portions of the slide are almost exclusively composed of a mosaic of interlocking quartz grains which, except for some quite negligible interstitial microcline fillings, presents the picture of a typical quartzite.

Protuberances of microcline are often seen to penetrate into quartz grains (fig. 3) or to force their way along the grain boundaries (fig. 4). Microcline was in no case observed as inclusion in quartz, whereas small rounded quartz grains are almost everywhere present as inclusions in microcline. Sometimes several such rounded quartz inclusions may show exactly the same optical orientation mutually or even as compared with an adjacent quartz grain outside of the embedding microcline individual. In some cases these inclusions do not consist of isolated quartz grains but of quite an aggregate of interlocking grains, exactly similar to those of the mosaic portions just referred to. The boundary between these quartz grains

Fig. 4. Microcline (cross-hatched) forcing its way along the boundary between two quartz grains.

and the embedding microcline are generally fairly distinct but in a great many cases they become more diffuse. Thus one may find almost every gradation between well-defined quartz inclusions and a sort of blurred, light patches in the microcline which are only just discernible.

The data reported above seem to prove beyond reasonable doubt that the microcline has attained its present position by a replacement process.

Besides quartz and microcline the rock contains subordinate amounts of *biotite*, *tourmaline* and *iron ores*. The following optical properties were determined.

Biotite: α pale straw
β brownish olive
γ dark chestnut
$2 V_{\alpha}$ close to $0°$

Tourmaline: ω dark olive green
ε colourless

The biotite appears as elongated shreds of remarkably uniform orientation. As a matter of fact, in the slide examined no single section has been found that is even remotely perpendicular to α. The iron ores form small isometric grains averaging 0.1 mm across or else somewhat larger elongated shreds of strongly ragged contours. The tourmaline likewise occurs as isometric rounded grains of a maximum diameter of 0.1 mm. All these minerals are rather sparsely scattered all over the rock but are, moreover, conspicuously concentrated in a number of parallel or sub-parallel streaks, obviously corresponding to the black layers observed megascopically. The elongation of the biotite flakes is parallel to the direction of the streaks.

The mutual relations between these subordinate minerals and quartz seem to suggest, that they were originally deposited together with the latter by sedimentation. The scattering of the dark minerals all over the rock shows, that they were present among the material sedimented, and the streaky concentration may probably be explained by slight external variations during the period of sedimentation.

It ought to be mentioned, finally, that even biotite sometimes appears to have been partly replaced by microcline.

The yellowish-white veins were studied in a slide showing the junction of the two branching veins at a, fig. 2. One of the branches is conformable to the layering, the other is cutting it obliquely. These veins are composed of quartz and plagioclase. The quartz is of much the same appearance as in the main rock. The plagioclase, which exceeds the quartz quantitatively, has been so intensely sericitized that optical determinations are greatly hampered. By luck a section exactly perpendicular to β was encountered, which allowed a comparison of the refractive indices to those of quartz, and it was found that N_γ is slightly lower than ω which gives an upper limit of about 12 % An. The albite is intensely twinned.

This vein is practically devoid of microcline, but the relations between albite and quartz are practically identical with those between quartz and microcline in the main rock. Thus one may observe as many as four or five interlocking quartz grains embedded by a single albite individual. Albite protuberances penetrate into quartz grains and may even dissect them completely.

The relations between albite and microcline, along the vein boundaries are rather difficult to decipher and no definite conclusion could be gained as to their relative age.

The bright red microcline vein is composed of quartz, microcline and intensely sericitized albite, which latter is mainly confined to the lateral parts of the vein. The quartz appears as very irregularly formed grains of far greater dimensions than those of the main rock (maximum length about 2 mm). Quite as in the albite veins the quartz grains are often penetrated by albite protuberances which are occasionally seen to fade out diffusely towards the interior part of the grain invaded. Sometimes a large quartz individual is observed to be dissected in two parts by a veinlet of interlocking albite grains. Small rounded quartz relics may also occasionally be observed as inclusions in albite. Even here, then, there seems to be little doubt that quartz has been replaced by albite.

In this vein the interrelations between albite and microcline are more clearly revealed. As was already mentioned the central parts of the vein contain only subordinate amounts of albite and it seems perfectly clear that a replacement by microcline has taken place. Thus irregular albite

Fig. 5. Inclusions of albite (striped) in microcline.

grains are very often observed as inclusions in microcline (fig. 5) in some cases two or more grains in optical continuity. Their boundary against the embedding mineral is diffuse and indistinct and gives the impression of a gradual transition. A still more advanced stage of development is represented by some microcline individuals, that show between crossed nicols a diffuse whitish streakiness that may sometimes pass into a perthite-like structure. These streaks which are, moreover, conspicuous by their intense sericitization are sometimes clearly seen to emanate from half-digested albite grains that have partly still preserved their original contours.

The tourmaline zone was studied in two slides, one parallel to and one at right angle to its plane of extension. The latter shows a vein of maximum 3 mm width traversing the main fine-grained rock and built up of a series of roughly rectangular segments. These segments are composed alternatingly of an aggregate of small rounded tourmaline grains and of rather coarse quartz-microcline material. The parallel section on the other hand shows a number of elongated, roughly lenticular tourmaline aggregates arranged *en échelon.*

The tourmaline is identical with that scattered over the main rock. Its indices of refraction was determined by the immersion method and came out as:

$$\omega = 1.658 \pm 0.002$$

$$\varepsilon = 1.638 \pm 0.002$$

The tourmaline aggregates display three features of special interest. *Firstly* in a narrow zone immediately bordering upon the quartz-microcline segments there is a distinct increase of grain-size. Whereas the tourmaline grains in the interior part of the aggregates rarely exceed 0.1 mm, the grains of the border zone average 0.3—0.4 mm. It should be noted that no corresponding coarse-grained zone is encountered at the boundary against the main rock. *Secondly* at the last-mentioned boundary the tourmaline is seen to send small offshoots into the fine-grained rock, wedging their way along the grain boundaries of the latter. *Thirdly* tourmaline is to some extent represented even in the coarse quartz-microcline segments. Here it generally appears as small aggregates of a few interlocking grains completely embedded by microcline.

Genetical interpretation.

The megascopical and microscopical data recorded in the previous pages allow us to draw some fairly definite conclusions as to the succession of processes, by which this rather peculiar rock has been formed. They had better be given in chronological order, the problem of the primary origin of the tourmaline zones being for the moment disregarded.

1. The primary rock undoubtedly represented a quartzitic sandstone, which was after deposition metamorphosed into a true quartzite without any signs of clastic texture. The metamorphism must, however, have been rather gentle, as the original bedding, indicated by the layers of biotite and iron-ores, is only slightly disturded.

2. The quartzite was invaded by a number of quartz-veins. These were most probably intruded along fissures generated during the metamorphism of the sandstone. This seems to be proved by the distinct though slight faulting phenomena previously referred to (fig. 2 right face). Such a secondary pneumatolytic (or even hydrothermal) veining would explain *i. a.* the conspicuous difference in grain-size between the veins and the main rock.

3. The rock was next exposed to metasomatic alterations which were effected in two successive stages:

a) In the first stage alumina and sodium were introduced. This process was not very intense and mainly affected the coarse quartz veins, where quartz was to a considerable extent replaced by albite. In the fine-grained quartzitic mass on the other hand only rather insignificant amounts of albite were generated.

b) In the second stage the sodium of the material introduced was succeeded by potassium, and now the metasomatism became far more intense. During this stage not only the primary quartz but even the newly-formed albite were largely replaced by microcline, and the replacement process was no longer confined to the veins, but was as intensely effected all over the rock. The destruction of the albite seems to have been initiated by a rather abundant formation of sericite.

The microscopical data thus seem to show, that the alkalies were introduced in the order 1) Na 2) K. It is of interest to note, that such a succession is in good agreement with the probable degree of mobility of the two elements, the ionic radius of Na being 0.95, that of K as much as 1.33.

4. The microclinization obviously implied a considerable increase of volume (= 60 % of the volume of the newly-formed microcline) which can only to a rather small degree have been counterbalanced by possibly pre-existent pore spaces. As pointed out by WEGMANN (1932, p. 487) such an increase of volume is likely to be compensated by lateral stretching. This will in its turn lead to tensional forces setting up in any intercalated sheet or layer that is not directly affected by the felspathization. The result will be, that such layers will assume a boudinage structure, and it is thought that this explanation is valid for the segmented tourmaline zone. The problem of the original genesis of the tourmaline will be discussed below, but it seems rather certain, that the segmented zone once represented a continuous sheet within the quartzite, and that it was torn asunder by the tensional stresses appending felspathization. The interfragmentary spaces were then invaded by the surrounding quartzo-felspathic material, which will have had the opportunity, in these places of relaxed pressure, to recrystallize rather coarsely. Such a coarse or even pegmatitic crystallization is in complete accordance with the experience gained from boudinage structures in granitized regions (*cf.* for instance WEGMANN *loc. cit.*). Most probably the slightly coarser grain of the tourmaline at the boundaries against the interfragmentary spaces is also caused by a recrystallization effected under these favourable conditions.

Now fig. 1 shows that the microcline stripes dissecting the tourmaline zone do not belong to a single parallel system, but form a sort of network. The most conspicuous stripes are roughly parallel, running in an approximately horizontal direction in the figure. Another system of less well-developed stripes stands at an angle to the first. Most probably these two systems represent a MOHR set of tensional fissures. This is of some interest, inasmuch as it seems to indicate that shearing rather than single tension has been at work.

As was already mentioned above, the rock forming the main part of the boulder is met with elsewhere as a rather wide-spread component of the so-called Krokö gneisses. The problem of the genesis of these very interesting rocks, which I hope to be able in the near future to discuss in some detail, was some time ago touched upon by H. G. BACKLUND (1936, p. 316). He concluded, from tectonical and structural observations, that at the time of their formation tensional stresses must have been operating. It is of interest to note, then, that the present investigation from a somewhat different point of view tends to confirm this conclusion.

There remains the question of the origin of the tourmaline. At first sight one is inclined to interpret the boudinaged zone as an original sedimentary intercalation. This seems the more probable, as in the boulder there is observed another zone paralleling the main one and being of essentially the same character. A closer examination shows, however, that this explanation cannot be correct. As is evident from fig. 2 (bottom part of left face) the system of thin black layers, which was earlier referred to, and which is developed all over the rock, is obliquely cut by the tourmaline zone, and there is even an indication of a slight faulting of the layers along the plane of intersection. Now it can hardly be doubted that the thin black layers indicate the original bedding planes, and, consequently, the boudinaged zone cannot possibly represent a layering. This conclusion is furthermore strengthened by the textural relations within the tourmaline »lenses». The tourmaline grains form a completely interlocking mosaic and show no indications of such rounded contours as would be expected, were they the result of simple sedimentary deposition. Finally, the tourmaline »off-shoots» penetrating into the adjoining quartz-felspar mass, seem rather inconsistent with the idea of a sedimentary origin. The necessary conclusion seems to be, that the tourmaline of the boudinaged zones is authigenous, that is, represents a crystallization in a set of parallel joints or fissures. This, however, opens two more questions. Firstly, does the same explanation be valid even for those tourmaline grains, that are finely disseminated all over the rock and to some degree concentrate within the black layers? Secondly, from where does the material emanate, that is responsible for the formation of the authigenous tourmaline? As to the first question it is rather difficult to arrive at a definite conclusion. There are some facts, however, that seem to speak in favour of an allothigenous, that is, a sedimentary origin of this tourmaline. One is the distinct concentration of the mineral within the black layers. Further, it is known that tourmaline is rather wide-spread within the quartzites of the adjoining sedimentary areas. Finally, the shape of the grains does not speak against a sedimentary deposition, fairly well-rounded contours being rather frequently encountered. Angular grains are, however, also very common, indicating that the transport cannot very well have been a long one. From these reasons — circumstantial as they may appear — I am inclined to interpret the disseminated tourmaline as syngenetic with the original sediment.

Now, as to the origin of the tourmaline material within the boudinaged zones, there are two possibilities to be considered. Either it was introduced from extraneous sources, or else it leads its origin from the supposed primary tourmaline content of the quartzite. There seems to be no decision between these two alternatives. The latter one, however, as being the simplest and involving no auxiliary hypothesis, should perhaps be considered the most probable one. That would imply, that this primary tourmaline was for some reason or other mobilized and subsequently deposited in its present *milieu*. It may appear a little far-fetched to assume a migration of such a very complex compound as tourmaline. We must keep in mind, however, that actually only a migration of boron has to be effected. All the remaining components of the mineral may be expected to be present in smaller or greater quantities at almost any place where this boron might »choose» to settle down.

In this connection attention should be called to the black sinuous vein, which is plainly visible on the right face of fig. 2. This vein, consisting mainly of tourmaline, cuts discordantly across the layering but is itself traversed by the microcline vein, as well as by the yellowish-white albite veins. This seems to prove that boron was actually, at some time or other, mobile within the rock. It is obvious, that this must have happened before those fissures were formed, which are now occupied by the microcline and albite sheets. It seems most probable that the formation of the tourmaline of the segmented zones is to be referred to the same period, especially as one of these zones is also cut by the biggest microcline sheet. This goes to show, that fissures or joints were generated at least at two distinctly different periods. As the tourmaline sheet shows indications of having partaken of the gentle folding or arching previously referred to (p. 391), the latter must have been effected between the two periods of fissuring. The first system of fissures must, consequently, have been generated at a rather early stage, probably soon after the diagenesis of the sediment and at no great depth.

After these joints had been formed, but before the younger system of fissures was generated, there was effected a recrystallization, a migration of boron, leading to the formation of discordant tourmaline veins, and a gentle folding. Most probably these processes took place in the order just mentioned, but they may very well have been essentially contemporaneous.

From these considerations it would appear, then, that the present rock owes its formation to the following succession of events:

1. Psammitic sedimentation, including the deposition of small amounts of tourmaline, biotite and iron ores. — Diagenesis.

2. Jointing, effected at no great depth.

3. Recrystallization, migration of boron, gentle folding. Of these processes the recrystallization and the folding were probably due to the increasing load of superimposed sediments. The breaking down of tourmaline may have required still more intensified p-t-conditions, and it seems probable that the boron may possibly lead its origin from still deeper parts of the sedimentary pile, which had already been subjected to a more intense metamorphism or even a beginning rheomorphism (BACKLUND 1936).

4. Fissuring.

5. Infiltration of quartz in the fissures.

6. Rheomorphism, involving the introduction of, firstly, Na and, secondly, K. This leads to an increase of volume, which in its turn effects

7. lateral stretching, causing tensional stresses and boudinage of the tourmaline zones.

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