SVERIGES GEOLOGISKA UNDERSÖKNING

SER. C. Avhandlingar och uppsatser. N:o 392.

ÅRSBOK 29 (1935) N:o 7.

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A fact, which has been known for some time, is that the sulfidic ores, as well as certain types of oxidic iron ore from the archean of Fennoscandia, are generally associated with peculiar quartz-rich or quartzitic rocks containing Mg-, Fe-, and Al-bearing minerals such as biotite, muscovite, cordierite, garnet, andalusite, and amphiboles, poor in CaO, in varying, often great quantities. The first to have recognized this fact was that excellent geologist, the late H. E. Johansson[1]. According to him the only possible interpretation of this kind of regular association was that ore and side rock were formed at the same time and from the same source. According to his general view on the genetic relations of the ore-bearing formation, he considered both ore and the surrounding peculiar rock varieties as special differentiated forms of the surrounding leptites or gneisses which he regarded as true magmatic rocks crystallized *in situ*. No statements of metasomatic changes or late magmatic processes in connection with the formation of the ores and the named minerals are to be found in his publications. That he was not unfamiliar with the conception of processes of this kind is shown, however, by his acceptance of the theory later propounded by the present writer for the ores and ore schists at Åtvidaberg.

In his very suggestive work on the rocks of the Orijärvi region P. Eskola gave in 1914 an explicit and illustrative description of many occurrences of rocks, containing the aforesaid minerals, and ore bodies occurring in this district.[2] As to the genesis of the rock varieties associated with the ores and occurring in their environs, a careful analysis of the circumstances in the field and of the petrographical conditions led him to the conclusion that the ores and their gangue minerals, as well as all the rocks containing the minerals rich

[1] G. F. F., Bd. 29, p. 287, 1907, Bd. 32, p. 272, 275—77, 313, 335, 411. Bd. 36, p. 451—54.
[2] Bull. Comm. Géol. Finl., Nr. 40.

in MgO, FeO, Al_2O_3 and SiO_2, were the result of extensive metasomatic changes brought about by agents probably originating in a neighbouring great body of granite (plagioclase granite). A fact worth mentioning and distinctly shown up by Eskola is the intrusive behavior in certain cases of extreme types of the metasomatic rocks. The problem was again taken up by P. Geijer in his monograph on the Falu copper mine[1]; here new evidence of metasomatic replacements in leptites and other rocks was given. According to Geijer, the ores and the rocks around them which are rich in quartz and mica are due to agents emanating from a magma of the old archean granite group (urgranites) occurring in the mapped area. There has been some discussion as to what is the proper granite body that has supplied the active substances; but most evidence points to a plagioclase-rich granite, immediately adjoining the ore bearing rocks, as being the mother rock.

A related though chemically somewhat different case of metasomatic changes in connection with ore deposition was described somewhat later (1921) by the present writer from the ore schists at the old copper mines of Åtvidaberg.[2] The chemical distinction to be found here is that MgO has been very scarce in the late magmatic solutions. Furthermore the metasomatic changes have been bound chiefly to the very body of the mother rock, signs of metasomatic alteration in the side rock appearing only sparingly.

The minerals of the ore-bearing rocks named above are for the most part unusual, though not wholly unknown in normal eruptive rocks. Nor do they appear to be common as contact pneumatolytic products from other countries or from the contacts of younger intrusives. It is also worthy of note that halogenes, sulphates, and other salts of volatile acids are in most cases very sparingly represented among the minerals suggested as metasomatic. The view of Eskola, therefore, does not appear to have been universally accepted[3]. To those working on the rocks and minerals in question, however, it is clear from their appearance in the field and their relations to the adjacent rocks that they must be of magmatic origin and that metasomatic changes have very often played an important part in their genesis. At present this opinion seems to be held by all working petrographers in Fennoscandia.

Of late years and in different parts of our country a number of new occurrences of the minerals, characteristic of the »metasomatic» rocks, have become known both in association with and without accompanying ores. It has been recognized that the appearance of these minerals is a very widespread phenomenon, and in certain cases it is of a regional and quantitatively great significance. Almost invariably the presence of the minerals has been ascribed to metasomatic changes caused by outside agents. In many cases, where no source of supply is to be found in the vicinity, the theory demands that substances have been carried great distances; and in some cases, where cordierite, garnet, biotite, and silimannite bearing rocks cover great areas, enormous quantities

[1] S. G. U., Ser. C, No. 275.
[2] S. G. U., Ser. C, No 306, p. 85, 1921.
[3] Ann. Acad. Sc. Fenniæ, Ser. A, Vol. XXXVI, Nr. 4, p. 59, 1932.

of oxides in some form must be assumed to have penetrated the rock crust great distances. To processes of this kind, and to occurrences of the said minerals in general, the terms »magnesiametasomatosis» and »magnesiametasomatic products» have respectively been applied. These are not very logical names since the MgO contents of the minerals are as a rule not greater than those of FeO, and in special cases the contents of MgO are even very low. The chief reason for adopting the name, however, seems to be the peculiar appearance of the latter oxide as a pneumatolytic agent.

A matter of considerable importance to the theory of »magnesiametasomatosis» is the question of the very nature of the assumed active agents. A second question of equal importance is that of the differentiation act in the magma through which the active mineral-forming substances have been produced. In general very little is to be found in literature on these subjects. Indeed the real nature of the processes which have resulted in the formation of the said rock species cannot be fully understood without a knowledge of these questions. In a preceding number of Geologiska föreningens förhandlingar[1] the present writer published a short discussion on the »Mg-metasomatic» problem, the chief aim of the paper being to show that a supply of outside agents is not necessary for all occurrences classified as »Mg-metasomatic». Minerals of this kind may also be supposed to separate directly from the magma in the later stages of cooling; furthermore, magmatic differentiation products, corresponding to the quartz-rich and Mg-, Fe-, Al-bearing rocks may be concentrated in a magma as residual solutions and may crystallize *in situ* or be squeezed out in the side rock. Magma parts of this kind must be of a late magmatic nature and enriched in water. In either case, whether intrusive in the side rock or crystallized *in situ*, they may also be supposed to cause metasomatic changes in the older minerals of the enclosing rock.

It should be mentioned that the different opinions as to the genesis of the »Mg-metasomatic» products are due less to contrasting differences in the mineralogical and geological conditions in the separate occurrences, than to different standpoints as to the genesis of the surrounding side rocks; which, whether they are of a leptitic or of a gneissous nature, are necessarily regarded by most geologists as supercrustal metamorphic derivatives. This point of view necessarily excludes any other explanation than that of supply from outside. The mineral assemblages and the appearance of the different occurrences, on the other hand, exhibit very great similarities indicating a similar mode of origin.

The great extension of the »Mg-metasomatic» phenomena makes them one of the most important questions of archean geology in general. The matter has also a practical side of equal interest, since the processes leading to the building of the minerals are the same as those by which important bodies of sulfidic and oxidic ores have been generated. This significance of the problem justifies its treatment from a more theoretical point of view, independent of the varying opinions on rock genesis.

[1] G. F. F., Bd. 57, p. 93, 1935.

Pneumatolytic Agents and the Oxides in the »Mg-metasomatic» Products.

In describing occurrences of »Mg-metasomatic» rocks and minerals the different authors have sometimes used the name »pneumatolytic» for the agents working the metasomatosis. In some cases a vaporous state is also supposed, especially in connection with presumed long transports. There is no discussion of the chemical forms in which the gaseous transfer should have occurred, and on the whole the problem of transport is almost entirely ignored.

The relations in a magma, when pneumatolytic distillates are discharged, have recently been discussed by N. L. Bowen[1] and C. N. Fenner[2]. Principal parts of the following account refer to these two papers and especially to the systematic survey of the former. If we imagine the case of a magma in the state of progressive crystallisation, a certain differentiation of its constituents will in most cases occur. The higher melting minerals, which in most cases are also anhydrous, separate as crystals, whereas the low melting compounds, chiefly alkalic feldspars, quartz and hydroxyl-bearing compounds of different kinds are concentrated to the residual solution. To the latter are also gathered substances characterized by low melting temperatures and high vapour pressure, such as water, hydrocarbons, acids, and various salts, chiefly of HF, HCl, N, S, CO, CO_2, B_2O_3, and others. Some forms of phosphorus in combination with hydrogen, or as alkalic phosphates, may also belong here. The contents of these substances may vary in different cases but as a rule it may be concluded that the magmas always contain some greater or smaller quantity of these substances. As a consequence of the progressive crystallization, a relative enrichment of these more volatile substances will generally occur in the residual solution and a tendency for them to escape in gaseous form is thereby induced. If the conditions of the magma are appropriate, the vapour pressure of the »volatile» substances is raised to equal or to exceed the external pressure, and a boiling off from the magma of a distillate of volatile compounds will then occur. From now on the residual solution is divided into two parts: the vaporized substances and the remaining solution which contains the remainder of the »volatile» constituents and compounds with low melting points but hardly evaporated. Of the latter the alkalic feldspars, quartz and hydroxyl-bearing compounds undoubtedly play the incomparably greatest part under normal conditions. The chemical character of the residual solution must therefore be alkaline. The fraction boiled off from the magma, on the other hand, contains water and a mixture of acids and their salts corresponding to the most volatile combination under the conditions governed by the composition of the magma and the prevailing temperature and pressure. Free, strong acids, and salts formed by them, as well as metals with weak basic properties, enter into this combination as important components. The chemical character of the

[1] The broader story of magmatic differentiation, briefly told, Ore deposits of the western States, Am. Inst. min. and metall., Engin., 1933, part II, chapter III, pp. 106—128.

[2] Pneumatolytic processes in the formation of minerals and ores, Ibid. part I, chapter III, pp. 58—106.

vaporized substances must therefore be acidic and strongly aggressive. If we imagine the further events in the history of the vaporized substances, it is evident that the new conditions set up in the side rock must soon cause rearrangements within the escaped complex of gases, with an accompanying deposition of heavy metal compounds and of substances such as silica, fluorite, and others. It is also evident that a rapid and strong attack on the part of the pneumatolytic agents will be made on the traversed neighbouring rocks, the result of which will be a leaching out from the latter of more soluble substances, chiefly alkalies, and above all of Na_2O, at the same time as other substances are introduced into the decomposited residue, forming new minerals. In consequence the pneumatolytic agents will soon be neutralized and alkaline. The final result of the pneumatolytic action will therefore be the formation of alkaline solutions, whose capacity for further decomposition or metasomatosis is highly reduced. Furthermore, in consequence of the high initial temperature and the acidity, the actions leading to this result will begin soon after the entrance of the vaporized substances in the side rock. This is important in view of the expressed opinion that a gaseous state of the working agents should facilitate long transports of the various metals in the rock masses. In reality the contrary will be true, since the substances supplied in the »Mg-metasomatic» products cannot be imagined otherwise than as salts of strong acids, provided they are in a gaseous state.

In the following table a number of boiling points, at one atmosphere, have

	Boil. p.	Melt. p.
CaO	2850°	
MgO	2800°	
CaF_2	2451°	
MgF_2	2239°	
Ca_2SiO_3		2130°
Mg_2SiO_3		1890°
$CaCl_2$	1600°	
PbO	1470—1495°	
KCl	1411—1420°	
$MgCl_2$	1412°	
NaCl	1412°	
PbF_2	1285—1292°	
$MnCl_2$	1190°	
Mg	1100—1120°	
$MgNaF_3$	1030°	

	Boil. p.
$PbCl_2$	954°
$PbBr_2$	916°
$CaBr_2$	806—812°
$ZnCl_2$	732°
CaJ_2	708—719°
$SnCl_2$	623°
$BiCl_3$	442°
$FeCl_3$	315°
$HgCl_2$	304°
$SbCl_3$	220°
$AlCl_3$	177°
$AsCl_3$	121°

been collected from chemical handbooks and from the researches of C. G. Maier[1]. No determinations on the vapour pressures of silicates of MgO and CaO are known to the writer, but the vapour pressures of these silicates are generally assumed to be negligible up to and above the melting points quoted for orthosilicates. The significance of the figures in the table is only relative, but they make it possible to conclude that the substances chiefly entering into the vaporized fraction of the magmas must be those in the right-hand column. Magnesia and calcium would be practically absent. Some small amounts of bromide

[1] U. S., Bur. Mines, Techn. pap. 360, 1925.

or iodide of Ca might be supposed to be present, but in the magmas the amounts of these acids are generally small. A certain amount of some ternary compounds containing Mg, such as $MgNaF_3$, might also be realized; but in the competition for the fluorine, compounds which have such a low volatility when compared with other salts of this acid would have no great chance of being more than sparingly represented.

If we apply these considerations to different mineral and ore occurrences, and if the mineral contents of the latter are taken into consideration; it is evident that the theory of a pneumatolytic origin will agree with depositions of those types which are represented by the important lead-silver dykes in western America, or in Saxony and Harz in southern Germany, with their great contents of As, Sb, and Bi, and their richly represented gangue minerals of fluorite, baryte, quartz, and carbonates. Other examples of ores rich in pneumatolytic substances are the tin occurrences; the apatite dykes with their aureoles of scapolithized rocks also exhibit related traces. A peculiar phenomenon of pneumatolytic nature is the wide-spread scapolitization in Lappland in northern Sweden. This is of a special kind, since the alteration process is distributed regionally and therefore seemingly contradicts the considerations stated above. However, in this case we have no formation of ores or of other minerals which require a transport of heavy metals. The only substances that are necessary for the mineral changes that have occurred are solutions of NaCl and Na_2CO_3.

On the other hand it is evident that the circumstances about the pneumatolytic agents do not fit in with the »Mg-metasomatic» mineral assemblages and ore occurrences, the characteristic properties of which are a scarcity of minerals containing volatile substances and an accumulation of MgO, FeO, and SiO_2. On the whole this scarcity of volatile substances is not unique for the »Mg-metasomatic» minerals and ore occurrences, but it is a universal feature of almost all skarn and ore occurrences of the archean of Sweden. In this respect our archean ores exhibit a fairly strong contrast to the more pneumatolytically accentuated ore occurrences mentioned above.

As an alternative explanation of the transport of the oxides contained in the »Mg-metasomatic» products, it may be supposed that vaporized water could transfer substances which themselves are not volatile but are held in solution in the water vapour. If this is so then the substances which above all would be carried off from the magma in this way would be those which are easily soluble in water, such as the alkalies and presumably also hydrates of SiO_2, but only in a minor degree the less soluble combinations of heavy metals and MgO. Furthermore, the quantity of substances transferred in this way would not be great.

We will now return to the residual solution remaining in the crystallizing magma. In a late stage of crystallization it has the composition referred to above, namely: chiefly alkalic feldspars, quartz, and some hydroxyl bearing compounds. In addition to these there are the remainder of the volatile substances which have not escaped as vapours, and among them water undoubtedly plays the dominant part under normal conditions. From this residual

solution the pegmatite and aplite dykes have been supposed to be derived and this deduction may, generally speaking, be right. On the other hand, the fact has often been referred to that oxidic or sulfidic ores are seldom directly combined with pegmatites, though combinations of this kind are by no means unknown. For this reason most authors seem to be disinclined to bring together genetically pegmatites, ores, and skarns. On the whole this is probably right. Nevertheless, in the opinion of the present writer, a very important part of ore and skarn occurrences owe their origin to residual solutions from magmatic rocks, or to salic magmas of corresponding composition. In fact, most of the Swedish ores, and among them the »Mg-metasomatic» products with their contents of sulfidic and oxidic ores, may have been thus formed.

If we wish to form an idea of the conditions in a magma which have given rise to products comparable with the »Mg-metasomatic» formations, the starting point would be instances of rocks in which the metasomatically active substances clearly originate from the rock itself and have been fixed *in situ* in its very body, or have escaped into the side rock only in subordinate quantities. Examples of this kind are to be found in some granitic rocks in southern and central Sweden the details of which are fairly well known geologically and petrographically. For the following discussion three rocks of this kind have been chosen, namely: the alkalic quartz syenite granite to the west of Åtvidaberg holding the old copper mines of this country[1], the Silverknut granophyre[2] from the Grythytte district, and the helsinkite at Stavsjö[3]. Of these the first two belong to the oldest archean granite group (the urgranites), while the last named is regarded by its describer, B. Asklund, as a younger archean granite. Other examples of the same phenomenon are exhibited by gabbroic rocks and the segregations of aplitic and quartzitic rocks, genetically belonging to them, which often contain sulfidic ores and minerals chemically corresponding to those in the »Mg-metasomatic» occurrences. But these rocks and the ores belonging to them play a subordinate part and the circumstances about them are not of equal interest to those about the granites.

The Åtvidaberg Granite and the Metasomatic Products contained therein.

Under 1 in the Table on p. 12 is shown an analysis of the Åtvidaberg granite. The rock is built up of 20.8 % quartz, 63.4 % alkalic feldspar, 2.7 % anorthite, 8.8 % biotite, 3 % magnetite, titanite, and apatite, 0.7 % epidote, and traces of some carbonate. The chief constituent of the rock is a microperthite which appears in the form of large isometric individuals. These grow more pure from perthitic albite inclusions towards the margins. Quartz, albite, and some perthite-free microcline form irregular and more fine-grained aggregates between the perthite individuals. Here the epidote and the other accessories also appear. Some traces of fluorite have been seen in slides of the rock. The rock

[1] S. G. U. Ser. C, N:r 306, p. 34 and 85, 1921.
[2] Ibid. N:r 312, p. 220, 1923.
[3] Ibid. N:r 325, p. 40, 1925.

is rather strongly deformed, and the deformation has all signs of having occurred at the close of the crystallization of the magma. Thus the microperthite individuals are to a great extent crushed at the edges and are in many cases also broken along the crushing zones in the rock. Of special interest in this connection is the behavior of the biotite. This is a deep green variety, very

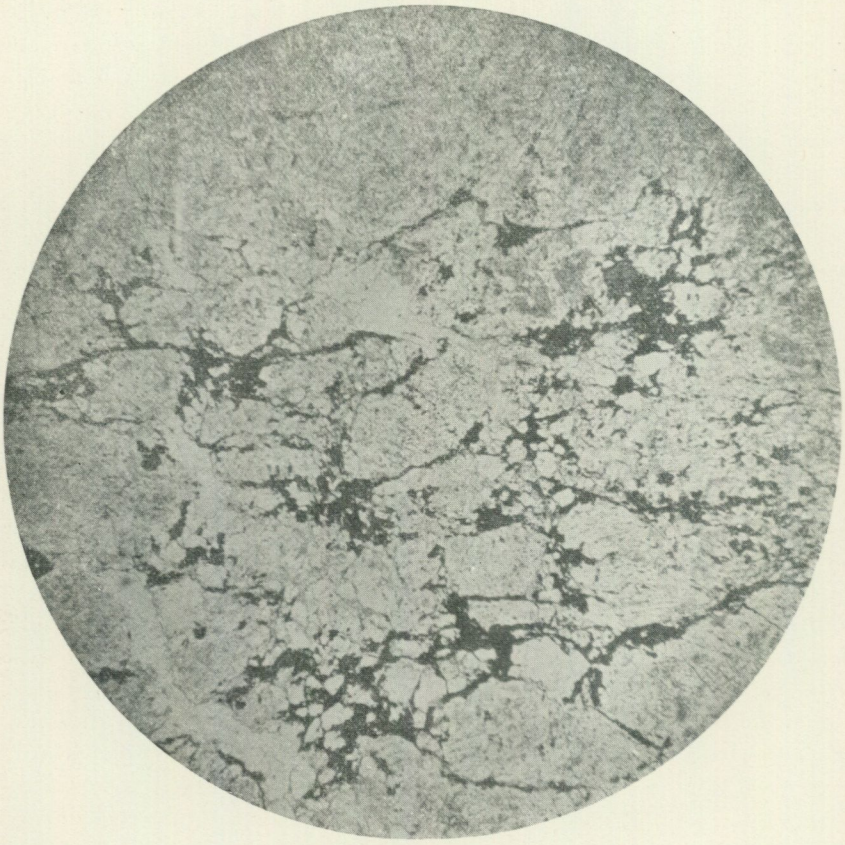

Fig. 1. Åtvidaberggranite, ord. light, magn. 16 times, showing the schlieric breccia like distribution of the biotite.

poor im MgO (MgO: iron oxides = 3,7 : 27,8). It appears generally in the form of small flakes which are gathered to the crushing zones in the rock and are here bound to the feldspar. Apparently the biotite has been formed at the expense of feldspar substance. Biotite can hardly be discovered in the quartz aggregates of the rock. In this way the rock gets a gneissous appearance with a schlieric arrangement of the biotite-rich stripes. The distribution of the biotite is in general rather even, but locally a greater concentration of the mineral can be seen, the rock in such cases having larger and more numerous biotite-schlieren.

The appearance of the biotite has been more particularly treated on account of the related features which are shown by the ore-bearing zones. In the gran-

ite body the ores (chalcopyrite, pyrite, and pyrrhotite; locally also some magnetite) occur as lenticular stocks and as a rather poor impregnation in zones of 0.5 m to a maximum of 7 m in width, striking concordantly with the schistosity of the granite and located near to its contact, about 1 km therefrom at most. In the ore-bearing zones the rock is chiefly made up of schlieric or banded quartz-biotite schists, which represent metasomatic alteration products of the granite and hold varying amounts of the more or less changed remnants thereof. All transition forms, from pure biotite-quartz schists and feldspar-bearing varieties, to little changed granite, can be found. These ore-bearing zones represent more strongly developed planes of schistosity in the granite to which the ore material and the metasomatically active substances have been concentrated. Similar zones without ores are known, and no definite differentiation can be drawn between the ore schist zones and the instances where the biotite stripes occurring normally in the granite, are more richly concentrated. The chief minerals of the ore schists are quartz and biotite. Some feldspar is present in most cases, but only in subordinate amounts if the metasomatic change has been strong. Other minerals locally observed in the schists are hastingsitic amphibole and almandine. Tourmaline and fluorite can be present, but only locally. The same is the case with epidote.

From the facts quoted it is evident that no general differentiation can be made between the origin of the biotite in granite and its origin in the ore-bearing zones. The deposition of the very ore substance, however, seems to be of a somewhat later date than the generation of the ore schists, since the ores partially form veinlets or schlieren in the schists. It should be noted that the biotite of the ore schists is, as a rule, optically identical with the biotite in the granite. Analytically the former is shown to be very poor in MgO and almost identical with the latter. (Comp. the table on p. 12, the figures under 3 and 4.)

All the metasomatic changes described above have occurred in the granite itself. Nevertheless, the active substances have not been entirely bound to the mother rock. Thus locally one finds in the vicinity of the contacts in the adjacent rock — a leptite, chiefly composed of acidic feldspar, quartz, and some biotite — clear signs of metasomatic changes which have developed here also, though on a smaller scale. In these cases large flakes of muscovite have developed in the leptite. More pronounced changes are exhibited by zones or patches where the rock is transformed into a muscovite-biotite-quartz schist, in its most extreme form free from feldspar. Fibrolite, too, is to be found in the rock. In connection with these rock varieties, and independent of them, small dykes or somewhat diffuse veinlets of quartz-tourmaline are sometimes seen. Evidently the metasomatic changes in the leptite have chiefly consisted of a decomposition of the feldspar and a generation of mica and silimannite from the products of decomposition. An addition of FeO and silica, though undoubtedly rather small quantitatively, may possibly have taken place.

If the course of the crystallization in the granite be considered, it is possible to state a fair boundary for the metasomatic stage of the rock. This must be at the time when the feldspars finished separating. Some quartz can still have

been deposited from the remaining solution, possibly also some small amounts of albite, since this feldspar is more stable than microcline under the conditions prevailing during the late magmatic period; but the latter feldspar must have been unstable and its constituents could no longer have been separated as feldspar. That the quantities of the ingredients of Or in the solution were restricted may also be deduced from the fact that the biotite was formed at the expense of already crystallized microcline. Naturally it cannot be stated that no biotite was deposited directly from the residual solution; but from the appearance of the biotite in the granite and in the ore schists it is evident that decomposition of the already formed feldspar has proceeded on an extensive scale simultaneously with the formation of the biotite. Thus it is possible to conclude that the remaining solution in the granite chiefly consisted of the basic oxides of biotite and, in addition to these, probably some silica. The chief ingredients of the small quantities of epidote and carbonate, and the contents of fluorite and tourmaline found in the rock and the ore schists, are also to be included. This late magmatic solution was present throughout the granite, and it must have been contemporaneous with the corresponding solution in the ore-bearing zones in which a more ample concentration of the same constituents occurred.

A more quantitative estimation of the oxides contained in the residual solution is possible from the data at hand from the ore schists. For this calculation we will start from the conception that the ore schists are to be regarded as metasomatically altered zones of granite. Furthermore, a variety of ore schist that is very thouroughly altered and contains only insignificant amounts of feldspar is chosen. The chemical composition of a specimen of this kind is shown by the figures under 2 in the Table. Under 3 and 4 are shown the calculated compositions of the biotite in the granite (from analysis 1), and in the ore schist (from analysis 2). The percentage of mineral composition of the ore schist is calculated as 44.3 quartz, 41.0 biotite, 1.1 microcline, 6.3

	1	2	3	4
SiO_2	68.06	66.65	39.34	37.59
TiO_2	0.45	0.16		
Al_2O_3	14.86	9.80	19.39	17.30
Fe_2O_3	1.57	4.59	5.90	7.73
FeO	2.31	11.14	20.75	23.64
MnO	0.10	0.30	1.13	0.73
MgO	0.33	0.46	3.73	1.12
CaO	1.20	1.11		
Na_2O	3.02	0.48		
K_2O	7.02	4.14	6.92	9.69
H_2O	0.48	0.93	2.83	2.20
P_2O_5	0.14	0.11		
CO_2	0.36	—		
F	—	—		
	99.90	99.87	99.99	100.00

plagioclase (An_{35}), 1.1 magnetite, 1.7 epidote, 2.0 garnet (almandine), 0.24 apatite, and 0.39 titanite. A calculation of the chemical changes, which are

produced when the granite under 1 is changed to the mineralogical composition shown by the ore schist, is possible from these data and gives as a result that the following oxides have thereby been adsorbed in the granite: $SiO_2 = 7.0$, $Fe_2O_3 = 3.2$, $FeO = 10.6$, $MnO = 0.31$, $MgO = 0.45$, $H_2O = 0.90$, or, together, 22.4 %, calculated on the weight of the original granite. At the same time 3.4 Al_2O_3, 2.5 Na_2O, 2.5 K_2O, or, together, 8.4 % have been removed.[1] Indeed, these figures, with the addition of some small amounts of fluorine and boric acid, give an indication of the chief oxides and their proportions present in the late magmatic solution at the beginning of the metasomatic stage. Naturally variations may occur and, on the whole, the contents of quartz in the ore schists seem to be somewhat greater than in the analysed specimen. Locally a greater quantity of epidote is present. As an average, however, the figures may be taken as representative of the residual solution at the beginning of the metasomatic stage. The absolute quantities have of course varied at different places, but the relative proportions of the oxides seem to have been fairly constant.

In the above calculation an idea has been obtained of the fair proportions of the substances present in the residual solution which have been fixed in the granite and the ore schists. Other substances, which neither were fixed in the rock nor left any traceable signs therein, may naturally have been present. Substances of this kind are hydroxyl-bearing compounds of the alkalies and of Al-Si-components. Very probably compounds of this kind were present in the solution. Of these the former would have been carried away together with the substances removed from the granite. The latter would have been fixed in the biotite, though this is at present impossible to prove. If some quantity of Al-Si-compounds in the residual solution be admitted, it would somewhat affect the calculation of the Al_2O_3 removed from the rock, but it would have little significance as to the other oxides. Another essential constituent of the solution, the content of which we can not decide upon, is water. This, when calculated from the above figures, corresponds to 4 per cent. of the whole residual solution. This plainly cannot represent the whole water content, for the oxides that have been removed during the metasomatosis must have been brought out, and this cannot have been performed by any other agent than water. Furthermore, it is unlikely that the metasomatic changes occurring in the adjacent leptite have been occasioned by any other agent than water. No more is known of the actual content of water in the residual solution at the beginning of the metasomatic stage than that it must have been greater than 4 per cent. of the solution. If the experiments of Goransson be applied an approximate upper limit would be found at about 7 per cent. But this author's experiments were made on granite, or on glass of granitic composition, whereas the residual solution in the Åtvidaberg granite was of a rather different composition and certainly contained hydroxyl-bearing compounds as its chief constituents. The water content may therefore be supposed to have been considerably greater, though it was

[1] A fuller account of the calculation is given by the writer on p. 104, referred to above.

certainly not so great as to permit a classification of the solution as a dilute water solution.

According to the statements made above, the granite at the beginning of the metasomatic stage contained a residual solution chiefly made up of SiO_2, iron oxides, principally in the ferrous state, some MnO and MgO, some CaO, some minor quantities of fluorine and boric acid, and a considerable quantity of water, probably amounting to more than 7 per cent. of the solution. In addition there were probably some alkalic compounds and hydroxyl-bearing Al-Si-compounds present; possibly also a little carbonic acid not fixed in the rock. As to the absolute quantity of the whole solution we are not able to give any definite figure, but possibly the assembled quantity amounted to perhaps twenty per cent. on an average in the ore bearing zones, and to some 2—3 per cent. in the normal granite. If taken as evenly distributed throughout the granite, the proportion of residual solution can hardly have exceeded 3—4 per cent.

As to the temperature at the beginning of the metasomatic stage, there is a starting point in the fact that the alkalic feldspars at the end of their crystallization showed strongly restricted miscibility. According to the compilations of H. E. Johansson, E. Mäkinen, and B. Asklund, this would correspond to the conditions in adular druses or ore veins. Definite temperature for this stage can hardly be given at present, but about 500 degres may be taken as an approximate upper limit.

When considering the aggregate condition of the residual magmatic solution it is very improbable that the substances therein have ever been in a vaporous state; otherwise one would expect to find clear signs of the evaporated substances in the country rock. With the exception of the small quantities that may have been supplied in the metasomatically altered mica schist varieties of the leptite, this is not the case. Water, on the other hand, can have boiled out from the liquefying magma already before the metasomatic period. This has possibly not occurred; but if it is accepted as likely that an evaporation of water has occurred during the proper magmatic period or later, it is also likely that the metasomatic changes in the adjacent leptite have been produced through emanations of this kind. The veinlets of tourmaline-bearing quartz, on the other hand, can hardly be considered as formed through gaseous emanations of this kind on account of their appearance as veinlets or cutting dykes. It is more probable that they represent late intrusions from the residual solution enriched in silica and boric acid during the formation of the ore schist.

On the other hand, it is evident that an enrichment in water, alkalies, and Al_2O_3 (alkalic aluminates?) must have occurred in the residual solution as the mineral reactions proceeded, and that a water solution, rich in these substances, must have escaped from the rock mass. SiO_2 can also have been present. Nothing can be said as to the fate of this escaping water solution. It is possible that it has contributed to the metasomatic changes in the adjacent leptite, though the rather strong alkaline character of this solution would not be favourable to mineral decompositions of this kind.

The Silverknut Granophyre.

This rock forms a rather great intrusive body in the hälleflintas of the northern part of the Grythytte district. Chemically the granophyre contrasts strongly with the Åtvidaberg granite in being extremely rich in albite and very poor in K_2O. The rock is chiefly made up of quartz (38 %) and albite (54 %), which to a large extent appear as graphically intergrown individuals, but in

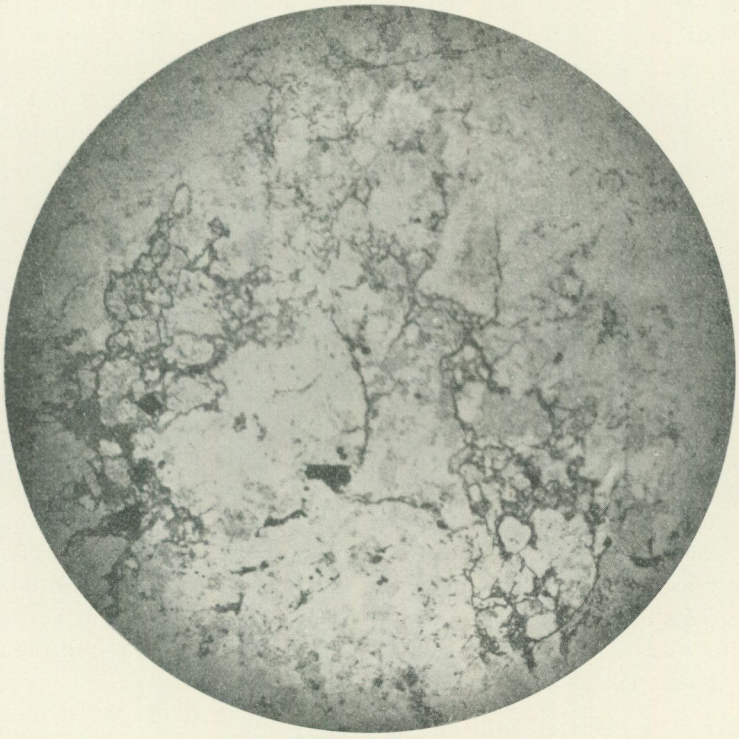

Fig. 2. Silverknut granophyre, ord. light, magn. 16 times, showing the breccia like distribution of the micas.

parts they appear as fine-grained aplitic aggregates. A few isolated phenocrysts of the same minerals are usually present also. Of interest in this connection is the distribution of the femic minerals which exhibit very great similarities to the biotite in the Åtvidaberg granite. In the Silverknut granophyre the femic minerals consist chiefly of chlorite, usually combined with a little biotite. An amphibole, rich in iron, can also be present locally. Occasionally some silimannite has been noticed, and a small amount of muscovite may also frequently appear. None of the minerals mentioned are developed as greater idiomorphic individuals, pointing to a separation during an earlier stage of the cooling; but in the studied slides they are invariably developed in a fine-grained, scaly form, and are distributed as mesostatic aggregates between feldspar and quartz, or as stripes along the contacts of the minerals. In this way they form an irreg-

ular network in the rock similar to the analogous phenomenon in the Åtvidaberg granite, although the schistosity exhibited by the latter rock is not developed in the granophyre (fig. 2). Clear signs of crushing cracks along which the femic minerals have gathered can be seen in exceptional cases, but generally cataclastic phenomena are rare. On the other hand, it is evident from the distribution of the micas that they have been formed also in this case during decomposition of the feldspar and at the expense of substance taken from this mineral. The quantity of the femic minerals is generally small, amounting in most cases to some 3 or 4 per cent., though this may vary: locally the minerals have accumulated fairly abundantly. In the latter case, the rock appears as a breccia similar to the skarn breccias in the ore occurrences. It should be mentioned that this peculiar distribution of the dark minerals is only found in the intrusive granophyre, but not in the surrounding hälleflintas which are almost devoid of femic constituents and must therefore be a feature genetically belonging to the granophyre itself.

An analysis of the granophyre is given under 1 in the following Table. The analysed specimen corresponds to a common type of the rock containing rather a small amount of femic minerals (chlorite, some biotite and muscovite). Under 2 are the calculated oxides belonging to the chlorite quoted, the small amount of biotite being disregarded. An exact calculation of the solution from which the femic minerals have been deposited is impossible in this case, but the figures under 2 show its essential features; the greatest departure from reality being the figure for Al_2O_3, which undoubtedly is too high, since a replacement of feldspar has occurred during the formation of the chlorite. The content of water, when calculated on the total under 2, is 12 %. Apparently this is too low as some muscovite (0.88 %) has been formed in addition to the chlorite. This deficiency is balanced to some extent by neglecting the biotite in the calculation. All that can be said of the actual water-content of the residual solution is that it was at least 12 %.

	1	2
SiO_2	78.22	0.77
TiO_2	0.22	
Al_2O_3	12.11	0.54
Fe_2O_3	0.57	0.07
FeO	0.89	0.66
MnO	0.01	
MgO	0.60	0.60
CaO	0.16	
Na_2O	6.38	
K_2O	0.53	
H_2O	0.40	0.36
P_2O_5	0.01	
BaO	0.02	
S	0.01	
	100.13	3.00

Chemically the contents of the granophyre residual solution are similar to those of the Åtvidaberg granite in that both consist chiefly of bivalent femic oxides, silica, and water. On the other hand, a distinct difference is shown when comparing the femic oxides: the biotite in the Åtvidaberg granite is very poor in MgO and rich in FeO and MnO, whereas the quantities of these two groups of oxides are about equal in the granophyre. This is one of the numerous examples from our ore-bearing formation of the regular chemical distribution of the named femic oxides in rocks of different contents of alkalies.

The Helsinkite at Stavsjö.

When turning to the helsinkite at Stavsjö somewhat different relations are encountered. The helsinkite forms a smaller body covering an area of some 20,000—30,000 square meters. It borders on one side on a quartzsyenite, and on the other on salic aplite rocks. According to the mineralogical and chemical relations the helsinkite is evidently genetically nearly related to the quartzyenite and may be regarded as a derivative from its magma. The characteristics of helsinkite are the absence of quartz and the appearance of large quantities of an iron-rich epidote and chlorite. Both the last mentioned minerals are partially distributed along cracks and crushed zones in the rock, and a similar distribution of both minerals also occurs in the adjacent rocks, their boundaries being indistinct. Thus there has been a certain spreading out of the two late crystallizing minerals. According to Asklund, the process of crystallization of the rock minerals has been as follows: At an early period some plagioclase, of a composition somewhat richer in An, was separated, this feldspar later becoming unstable, the anorthite splitting up in epidote and albite. The bulk of the feldspars crystallized later as perthite with a restricted amount of albite. Free albite in small grains is partly enclosed in the perthite, and occurs partly between the individuals of this mineral. Some biotite also crystallized at this early period in the form of large tabular individuals. Epidote and chlorite separated later than the feldspars, partly filling up the drusy cavities between the feldspar individuals, partly being deposited along cracks and crushing zones. At this period the older biotite became unstable and was converted into chlorite. Thus the crushing of the rock must also in this case be of an early date, occurring during the later stages of the rock crystallisation. No replacement of feldspar by chlorite and epidote is reported by Asklund. According to him, the chloritized biotite is a chlinoclore, whereas the younger chlorite has the character of a pennine. However, in a slide of the analysed specimen (kindly placed at my disposal by Dr. Asklund) the optical differences between the two kinds of chlorite is not pronounced, and, furthermore, a tendency to chemical equalization of both chlorite species may have been active at the time of the separation of the later chlorite. Judging by the analysis, the bulk chlorite must be rather rich in sesquioxides (Sp: at about 2 : 3.8). A considerable amount of Al_2O_3 may therefore be contained also in the younger chlorite and some replace-

ments of feldspar have probably taken place. Signs of this can also be seen in the slide.

The analysis of the predominant type of helsinkite is referred to below under 1. Besides this type there is a variety richer in albite present in the rock area, but only in a subordinate amount. The type rich in albite also holds epidote and chlorite, though the amount of the former is less.

The appearance in the helsinkite of a residual solution, rich in water, at the close of the crystallization of the feldspars, is quite evident. An exact estimation of the substances contained in it is impossible, but from the analysis, and with the aid of the mineralogical determinations made by Asklund, a calculation of the bulk composition of epidote and chlorite in the rock can be made. The figures obtained from this calculation are given under 2.

	1	2	3
SiO_2	57.29	6.27	4.78
TiO_2	0.75		
Al_2O_3	18.50	4.72	3.75
Fe_2O_3	2.43	2.43	2.43
FeO	2.22	2.22	1.11
MnO	0.09	0.09	0.05
MgO	1.06	1.06	0.53
CaO	4.09	3.17	3.17
BaO	0.38		
Na_2O	2.65		
K_2O	8.69		
P_2O_5	0.61		
H_2O	1.23	1.31	0.79
	99.99	21.27	16.61

A rough estimate of the amount of the older chlorite shows that it is at least half of the quantity of chlorite. Admitting the two varieties to be similar chemically, a more accurate conception of the oxides of the residual solution would be gained if half of the substances included in the bulk chlorite be subtracted from 2. The rest is shown under 3. The remainder obtained in this way certainly contains too much Al_2O_3, but otherwise it is representative of that part of the residual solution that has been fixed in in the rock. The content of water, calculated on the total under 3, is 4.7 per cent.

In this case also we find a water-rich residual solution remaining after the separation of the normal magmatic rock minerals, feldspar and biotite. The solution was also in this case rather mobile and partly squeezed out from the rock during the crushing effect at the end of the crystallization period. On the other hand, the metasomatic actions found at Åtvidaberg are not so conspicuous here, though phenomena of this kind are not absent.

The conditions as to the temperature of the crystallization of the helsinkite have been discussed fairly explicitly by Asklund. On account of the restricted miscibility of the alkalic feldspars, their crystallization must have occurred at a lower temperature than usual with granites; and for the beginning of the separation of the chlorite and epidote a still lower temperature must be pre-

sumed, possibly even lower than that at the beginning of the metasomatic stage in the Åtvidaberg granite.

Between the two cases of residual solutions treated before and the helsinkite rather great chemical differences occur, the most conspicuous of them being the low SiO_2 content in the helsinkite solution and the presence in it of rather much CaO. Mineralogically this latter quality is manifested by the presence of large quantities of epidote. However, if we accept the quartz syenite as being the mother magma of the helsinkite, the nature of the late minerals in the latter is better understood. This rock shows strong signs of alterations and is partly interwoven with veins of epidote and chlorite. These phenomena, which are peculiar to the quartzsyenite, may best be understood if they be taken as the result of late magmatic processes similar to those described for helsinkite. Of course, the theory could be put forward that the helsinkite is nothing but a part of the quartz syenite enriched in epidote and chlorite. That this cannot be the case is clearly shown by the different qualities of the magmatic rock minerals occurring in the two rocks: in the quartz syenite, microcline perthite, andesine, quartz, and amphibole-biotite; in the helsinkite, microcline perthite (poorer in albite inclusions), free albite, and biotite. The helsinkite, therefore, is formed from an individual magma, and if we suppose, on the strength of all the indications, that this magma forms a part of the quartz syenite magma which has been enriched in the late crystallizing constituents of the latter, a satisfactory conception of the chief qualities of the rock may be gained.

On the Origin of the Residual Solutions.

When searching for a reasonable cause of the storing up in the magma of late crystallizing substances of the nature shown in the examples referred to, it will be convenient to choose as a starting point the qualities particularly characteristic of the residual solutions. As such we have in the first place to point out the richness in water and the presence of bivalent femic oxides together with silica as the chief constituents. Water has no doubt played an important part in reducing the temperature of crystallization, in making the solutions mobile, and facilitating their gathering to tectonically preferable places in the rocks. Other substances present in the magma, such as acids and salts of acids, also play a similar part, but their proportions have been inconsiderable compared with that of the water.

But water must also be the chief cause of producing in the magma late magmatic solutions of the kind described. As is well known, water at higher temperatures is rather aggressive. Dissolved water in a magma will not be inactive; its influence may form compounds such as H_2SiO_3, NaOH, KOH, $HAlSi_3O_8$ and others. Corresponding femic combinations may also be produced in the form of hydroxides or even as hydroxyl-bearing silicate molecules. When separation of the magmatic minerals proper occurs, an enrichment of the water and the hydroxyl-bearing compounds will in most cases take place. An attack on the crystallized minerals on the part of the water my now be expected, but,

on the other hand, the hydrolyzing effect of the water is diminished by increasing alkalinity. In all cases the hydroxyl-bearing products, and among them hydrates or hydroxyl-bearing silicate molecules of (FeMn)O, MgO, and CaO, will not disappear from the solution, but their concentration will increase as crystallization proceeds. The quantity of these substances depends chiefly upon the water content of the magma. If this is small the hydroxyl-bearing substances are negligible. On the other hand, in the case of a water-rich magma the remaining magma solution can be enriched by greater quantities of the said substances. In most cases a separation of the hydroxyl-bearing femic minerals, amphibole and biotite, will occur during the magmatic period proper. This plainly has been the case in the Stavsjö helsinkite. The separation during this period of the minerals otherwise regarded as metasomatic (cordierite, garnet, cummingtonite, *et cetera*) may also be possible. But the time of separation of the femic hydroxyl-bearing substances depends upon the concentration of the residual solution. If this is rich in water, and the amount of femic substances in the magma is moderate, this will counteract the separation of the minerals named and a greater or lesser part of the substances will be stored up in late magmatic residual solutions, the oxide contents of which will not be deposited until at a very late stage, later than the magmatic period proper. In water-rich magmas or magma parts one may therefore, as a rule, expect the appearance of solutions containing hydroxyl-bearing compounds of all the named kinds, and among them also those of the femic oxides, (Fe Mn) O, MgO, and CaO.

The composition of solutions of this kind has been illustrated above in three special cases, the composition in each case having been calculated as accurately as is possible from the facts at hand. To the constituents so found should be added, for the Åtvidaberg granite, the ore substances consisting chiefly of sulfides of iron and copper, and a small amount of magnetite. That ore substances are not necessary components in solutions of this kind is shown, however, by the two other occurrences described, as also by the conditions in the quartz biotite schists in the Åtvidaberg granite itself, which for the greater part are not ore-bearing, or are poor in ore substances.

It has been concluded that the residual solutions remaining in the rocks at the close of the crystallisation of the alkalic feldspars — a stage which can fairly be assumed as the close of the proper magmatic period of the solidification of magmas of the present type — were water-rich solutions containing hydroxides and other hydroxyl-bearing compounds, probably silicates, possibly also aluminates and ferrites. The real chemical combination in a mixture of this kind cannot exactly be determined, but it is important that there must have been a solution, and this must have existed in the form of a melt or a magma. Otherwise substances of this kind could not be kept in solution. Moreover, it is probable that this type of melt cannot hold dissolved unlimited quantities of water but that there must be a certain maximum limit for the content of water, differing somewhat according to variations in external pressures, above which an evaporation of water will occur. Finally the relations in the three occurrences

described are in no case such as to indicate depths of such magnitude as to exclude the escape of water vapour from the cooling magmas. Thus the solutions most probably are to be regarded as water-rich magma solutions and not as water solutions.

When the temperature of the magma is reduced below that of the proper magmatic stage, the relations of stability of the minerals already separated will be altered. A change of this kind, important in this connection, is the diminished stability of the feldspars in the presence of water-bearing solutions. It cannot be supposed that the feldspars are in all cases unstable in the presence of water at low temperatures, since alkalic feldspars have been formed under circumstances that exclude temperatures of greater height at their generation (e. g. adular druses, alkalic feldspars grown in unmetamorphosed sandstones, orthoclase, described by Daly and others from unmetamorphosed limestones)[1]. On the other hand, it is evident that the formation of feldspars in such cases must postulate some special conditions in the water-bearing solutions from which they have been deposited, and a factor of great significance in this connection seems to be the alkalinity of the solution. But petrographical experience indicates that, very generally, a decomposition of the feldspars occurs in the postmagmatic period if water is present, and that the feldspars under the conditions of this period generally are metastable. The feldspar that as a rule first becomes metastable is the anorthite, and its alteration products are the widely spread minerals epidote and sericite. Of course, the appearance of epidote in a magmatic rock need not necessarily postulate the earlier presence of anorthite. As is known in many instances, epidote does occur in a manner which apparently shows it to be directly deposited from the remaining solution of the magma. An example of this kind is the helsinkite from Stavsjö. In these cases the ingredients of the epidote in some hydrolyzed form must have been contained in residual solution.

The orthoclase and microcline grow metastable as a rule during a later stage. The resulting products of decomposition are, as is well known, sericite and quartz. The most stable feldspar is the albite, but this feldspar, in the presence of water, can also be shown to have been decomposed in mica and quartz. Apparently this is not a mere decomposition, but an alteration which requires the access of some K_2O.

Undoubtedly the decomposition of the feldspars has in some cases been still more effective, and still more alkalies have been removed, the substances left being rich enough in Al_2O_3 to produce silicates of this oxide. In this way may be explained the silimannite found in the altered leptite at Åtvidaberg and in the Silverknut granophyre.

The diminished stability of the feldspars in the presence of water at low temperatures is important in connection with the water-rich late magmatic residual solutions, since it will induce metasomatic actions on the part of the solutions. If these at the same time contain compounds of FeO, MnO, and MgO

[1] R. A. Daly, Low-temperature formation of alkaline feldspars in limestone, Nat. Acad. of Sc., Vol. 3, pp. 659, 1917.

possibilities are obtained for the formation of the minerals known as »magnesia-metasomatic», i. e. biotite, chlorite, cordierite, cummingtonite, anthophyllite, garnet, muscovite, andalusite, and silimannite. Which species will be formed in each case depends upon the chemical conditions in the solution, and also partly on the nature of the rock in which the mineral reactions take place. The extent of the metasomatic processes must also be dependent upon the mode of distribution of the residual solution, in so far as these processes will be more intensive and more wide-spread if the solutions are generally distributed in the rock mass, than if they are more homogeneously accumulated.

It should be emphasized that the mineral reactions will, in the main, be identical, irrespective of whether a residual solution reacts with the minerals of the mother rock or has been squeezed out in the side rock; supposing that the chemical relations of both rocks are not too unlike.

In the above we have treated cases of residual solutions corresponding to the »Mg-metasomatic» products. Naturally, solutions of this kind are not formed in all cases, it being possible for other compositions to occur. Undoubtedly in many cases a concentration of carbonic acid and carbonates has occurred, and oxidic ore occurrences may also be formed in a similar way. But this type of phenomena does not belong to the subject of this paper.

Applications to other Metasomatic Occurrences.

A survey of the literature on »Mg-metasomatic» occurrences shows that in all better-known cases the chief substances that have been supposed to be supplied are MgO, FeO, and SiO_2 besides the ingredients of the ores. Chemically the content of the acting solutions is evidently exactly identical with that of the residual late magmatic solutions calculated in the examples treated above. The objection can be raised against the helsinkite that the residual solution in this rock contained an unusual amount of CaO and Al_2O_3, and this is, indeed, correct. However, this rock shows, on the whole, the same phenomenon as the other rocks. On the other hand, the high contents of FeO in the Åtvidaberg granite, and its deficiency in MgO, are by no means discriminative features; and the residual solution in this case shows the same deficiency in CaO as is usual in the »Mg-metasomatic» products. As a matter of fact, the three cases chosen here as examples demonstrate variations which are due to characteristic differences in the bulk composition of the mother magmas.

A rigorous application of the theory developed here is not advisable. The conditions in crystallizing rock magmas are complex and may vary in individual cases. Although, in the rocks treated here, volatile acidic substances have played a subordinate part, they may in other cases have been present in greater quantities. In such cases a vaporization of metallic compounds from the magma or from the late residual solution may have played a more prominent part, and it should then be possible to show the presence of agents of this kind through the compounds formed from the acidic part of the vaporized substances. Such cases may occur, though no instances have as yet been clearly revealed.

This may nevertheless not exclude the existence of contemporaneous residual magma solutions which have represented the chief bulk of the ore bearing agents.

To the considerations above some remarks about the mode of appearance in the field at some better known occurrences should be added. Illustrative examples are the quartz cordierite rocks, cordierite gneiss, cordierite anthophyllite gneiss, and other rock varieties described by Eskola from the Orijärvi field, which form intrusive-like layers, or stocks, and in one case are shown to behave as a cutting mass against the side rock (leptite). In such cases a squeezing-out of the residual solution and real intrusions thereof is a reasonable explanation[1]. The writer has also referred to the intrusive-like form of the whole cordierite quartzite-mica schist area at Falun, being as it is the immediate continuation of a protruding wedge of the urgranite which most probably represents the source of supply of ore and gangue rocks. In this case a gathering of the residual solution at this point and an injection thereof into the adjacent leptite rocks is very suggestive. In this connection the »ore conglomerates» deserve to be remembered. They are found in many of the Swedish sulfidic ores, the »pebbles» of them consist of the gangue rock, usually quartz, though other rock varieties are also met with, whereas the cementing mass is made up of sulfides. The origin of these peculiar formations has long been unexplained, but through the recent researches of S. Landergren at the ore occurrence of Saxberget[2] it evidently appears that this type of ore represents a true ore magma which has brecciated the earlier formed skarn ore and ore quartzite. This explanation is well consistent with the theory that the ore-bearing agents are residual magma solutions of which parts of the ore substance represent the last remaining fluids.

In the leptitic rocks in central Sweden, with their abundance of rock varieties, extremely poor in Ca, and of an aplitic and partly quartzitic nature, containing minerals of the kind characteristic of the »Mg-metasomatic» formations, residual solutions similar to those described here must have played an important part, though the general opinion as to the genesis of the leptite has complicated the right understanding of the ores and ore-bearing rocks.

An example of still greater regional extent, and quantitatively of very great importance, is the great gneiss formation in central Sweden, called garnet gneiss, which in certain types of acidic composition is characterized by the presence of large quantities of the minerals biotite, cordierite, garnet, and silimannite. As previously shown by the writer[3] the only theory that from a geological point of wiew reasonably accounts for the appearance of these peculiar rock varieties in the gneiss formation is that the substances of the said minerals belong to the magma of the gneiss itself, and that the gneiss varieties abounding in these minerals have been enriched through magmatic differentiation in solutions containing the corresponding substances.

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[1] A similar explanation is also given by B. Asklund. Comp. the earlier paper of the present writer in G. F. F., Bd 57, p. 93, 1935.

[2] G. F. F., Bd 53, p. 324, 1931.

[3] G. F. F., Bd. 57, p. 104.

When this had already been written the attention of the writer was called to the interesting work by J. E. Spurr on »The ore magmas».[1] The views presented by this author have much in common with the theory propounded in the present paper. According to Spurr the ore-forming substances are, as a rule, in a state of fluid magmas, more or less aqueous, and, like rock magmas in general, in a state of gaseous tension »by virtue of which they possess intrusive power». On the other hand, the ore magmas are supposed by Spurr to be differentiated not as residual solutions but as special magmas »developed at the deep zone where rock differentiation takes place» and intruded at the same time and in the same ways as other rock dikes or veins. This is evidently impossible in the cases described here in detail, though the relations of the helsinkite clearly show it to have formed a special magma part of the quartz syenite, enriched already in fluid state in the late crystallizing components. Cases of this kind in reality may play an important part as, for example, in the case of the garnet gneiss, and in many instances in the leptites. Moreover, the whole of the ore-bearing granite at Åtvidaberg and the Silverknut granophyre can be regarded as late crystallizing magmas enriched in volatile substances and compounds of low melting point. But the ore-forming substances, and the solutions containing the substances of the late formed femic minerals, are always later than the bulk of the mother magma, and generally later than the magmatic period proper.

According to Spurr's views, gaseous emanations play a much smaller part in the ore-forming processes than has generally been supposed. This fully agrees with the opinions here presented.

[1] J. E. Spurr. The ore magmas, New York, 1923.

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