ON THE METASOMATIC PROCESSES IN SILICATE ROCKS.[1]

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CONTENTS.

INTRODUCTION.

Definition.—The term metasomatism, as originally defined by C. F. Naumann, was applied to certain kinds of pseudomorphs, namely, those formed by chemical replacement at the expense of some original mineral. Every transformation of minerals by chemical replacement would be designated as metasomatism, and in this sense, most of the newly formed constituents of the metamorphic rocks would be metasomatic minerals.

Later, however, the conception of metasomatism was narrowed, and was used to comprise those transformations only by which the chemical composition of the whole rock, as well as that of the individual minerals, was essentially changed. Meta-

[1] Manuscript originally transmitted in German and translated by P. Eskola, P. Armstrong, and the Editor.

somatism in this sense would include, for example, the alteration of limestone into dolomite.

The definition of metasomatism as a transformation of a rock with essential changes in its composition is not quite satisfactory either. The transformation of a calcareous sandstone, for instance, into a wollastonite rock by contact metamorphism, whereby carbon dioxide is driven off, is not called metasomatism, in spite of the fact that the composition of the rock is essentially changed through the loss of carbon dioxide. Rather is it customary to apply the term metasomatism especially to those processes which involve an addition of substances into the rock.

We shall base our discussion on the following definition of the term metasomatism:

"*Metasomatism is a process of alteration which involves enrichment of the rock by new substances brought in from the outside. Such enrichment takes place by definite chemical reactions between the original minerals and the enriching substances.*"

According to such a definition the processes of mere impregnation are excluded from the conception of metasomatism. The newly introduced substances may take the form of either gases, aqueous solutions or melts, and their reactions with the original constituents of the rock result in the formation of metasomatic and possible accessory minerals.

Importance.—If no metasomatic replacement accompanied metamorphism, the chemical composition of the metamorphosed rock would not change, except for a possible loss of volatile compounds and subtraction or addition of substances by the ordinary processes of leaching and impregnation. Then, Rosenbusch's rule of the constancy of chemical composition in metamorphism would be valid almost without exception.

The effect of metasomatism, however, introduces many exceptions to this rule. Such processes at first were described particularly only in carbonate rocks, although silicate rocks have also furnished a number of similar examples, as Lindgren has emphasized in his descriptions of the geology of certain ore deposits. Recently others, especially P. Eskola, have called attention to the

important influence of various metasomatic processes in silicate rocks. As examples of such replacements, connected with ore deposits, may be mentioned the formation of greisen, scapolite, and magnesium-silicate rocks. For two reasons, such phenomena have been studied chiefly in the vicinity of ore deposits. In the first place, many ore deposits and the regions surrounding them ha e been the scene of exceptionally intense chemical replacements, partly simultaneous with ore deposition, partly succeeding it. Secondly, the economic importance of ore deposits often calls for detailed chemical and microscopical study of both the deposits and the country rocks.

A critical review of the literature, however, shows that replacement is not necessarily associated with the formation of ore deposits only, but that various metasomatic processes of greatly differing character may also accompany rock metamorphism. A great number of rocks owe their present character to metasomatic replacement, and should be considered in a class by themselves. They are as justly entitled to a separate classification as are rocks of igneous and sedimentary origin, or those formed by " normal " metamorphism, *i.e.,* metamorphism without addition of substances. A distinction should be made, therefore, between the two kinds of metamorphic rocks in the petrographic system :

1. Products of " normal " metamorphism where the chemical composition of the original rock has remained unaltered.

2. Products of metasomatic metamorphism which owe their present composition essentially to the introduction of new substances.

In my report on contact-metamorphism in the Christiania region,[1] I pointed to the existence of these two different types of contact rocks, and I believe that a similar division might prove useful in the case of the crystalline schists. We are not justified in diagnosing the origin of a metamorphic rock from its present chemical composition; attempts to do so have led to many faulty conclusions. In illustration, I may mention that not all antho-

[1] V. M. Goldschmidt, " Die Kontaktmetamorphose im Kristiania-Gebiete," *Vid. Selsk. Skr. Mat.-Naturv. Kl.,* 1911, No. 1.

phyllite schists are metamorphosed igneous magnesium-silicate rocks. In most cases, they were derived from quartzites and other highly siliceous rocks acted upon by magnesia-bearing solutions. Again, nearly all andradite rocks are metasomatic derivatives from limestones, and many gneisses of granitoid composition owe their existence to the metasomatic feldspathization of argillaceous rocks.

We may mention still another circumstance pointing to the common occurrence of metasomatic processes in rock metamorphism, namely, that crystalline schists have, in very numerous cases, been explained as derivatives of tuffs. If all these interpretations were true, tuffs would be far commoner within metamorphosed formations than they are among non-metamorphic rocks. Apparently, in many cases, the chemical composition of metasomatic rocks, lacking marked igneous as well as marked sedimentary characters, has been regarded as a proof of tuffaceous origin, and the possibility of metasomatic changes has not been considered.

CLASSIFICATION OF METASOMATIC PROCESSES.

No detailed classification of metasomatic processes has heretofore been attempted, although a preliminary one dealing with metasomatism in silicate rocks was recently published by the writer,[2] and in a later publication somewhat elaborated upon.[3] The purpose of the present paper is an attempt at a classification of metasomatic processes as affecting silicate and silica rocks, examples being given in each case.

Generally, metasomatic processes may be considered under four main headings, based on the character of the rock involved:

> Metasomatism of silicate and silica rocks.
> Metasomatism of carbonate rocks.
> Metasomatism of salt deposits.
> Metasomatism of sulphide deposits.

[2] V. M. Goldschmidt, " Geol.-petrogr. Studien im Hochgebirge d. Südl. Norwegens V., Die Injektionsmetamorphose im Stavanger-Gebiete," *Vid. Selsk. Skr. Mat.-Naturv. Kl.,* 1920, No. 10, 1921.

[3] V. M. Goldschmidt, *Geol. Fören. i Stockholm Förh.,* vol. 43, p. 463, 1921.

The first group is exemplified by the scapolitization of a plagioclase rock, or the formation of anthophyllite at the expense of quartz, the second by the alteration of limestone into siderite, or andradite. As illustrative of the third group may be quoted the change of anhydrite into polyhalite, or glauberite, while various kinds of alteration in the zone of cementation in sulphidic ore deposits typify the fourth group.

Besides these four principal kinds of metasomatism, some others of lesser importance may be mentioned, as, for example, the metasomatism of oxidic rocks, and that of certain coals by enrichment in vanadium.

In discussing each main group, further subdivisions are needed and these may advantageously be based upon the character of the added substances. The first group, which alone of the four mentioned will be discussed in the present paper, may then be considered under two sub-headings:

(*a*) Metasomatism of silicate rocks with addition of metal compounds.

(*b*) Metasomatism of silicate rocks with addition of metalloids or compounds of metalloids.

METASOMATISM OF SILICATE ROCKS WITH ADDITION OF METAL COMPOUNDS.

According to the metal introduced, we may further differentiate between alkali-, magnesia-, lime-metasomatism and others.

Alkali Metasomatism.—Alkali metasomatism is decidedly common in silicate rocks. A reason for this, probably, is to be found in the comparatively high solubility of most alkali compounds, excepting the complex alkaline silicates of alumina and iron. Hence the latter represent the newly formed metasomatic minerals.

The various chemical processes arising in alkali metasomatism and resulting in the binding of the alkalies may be treated specifically as:

A. Metasomatic exchange of the alkalies.

Examples: Formation of myrmekite or " chess-board albite " from potash feldspar.

Formation of adularia from plagioclase (in propylites).

Formation of muscovite from nephelite.

B. Binding of alkali by excess alumina in the precipitating mineral.

Examples: Metasomatic formation of feldspar in the contact zones of injected rocks.

Metasomatic formation of feldspar in the inclusions of hornfels.

Metasomatic formation of feldspar in pyro-metamorphic rocks.

C. Binding of alkali by silicates of Mg, Fe'' and Fe'''.

Examples: Formation of biotite in amphibolites in contact zones.

Formation of ægirite in certain contact zones.

D. Binding of alkali (and alumina) by quartz.

Examples: " Syenitization " of granite in certain contact zones of alkaline rocks.

The two examples quoted under *A,* namely, the formation of myrmekite or " chess-board albite " at the expense of potash feldspar[4] and that of adularia from plagioclase,[5] show quite clearly that the direction, chemically speaking, of metasomatic replacement is not necessarily always the same, but may vary with the concentration of the solutions added and with the temperature and pressure prevailing during the reaction. Such " reversible " replacement has been observed in quite a few pseudomorphs of minerals.

A common case is that mentioned under *B,* namely, the metasomatic formation of feldspar at the expense of minerals and rocks containing " excess alumina," *i.e.,* of those in which $Al_2O_3 : Na_2O + K_2O > I$. A series of similar occurrences

[4] F. Becke, " Denkschriften d. k. Akad. d. Wissensch." *Wien. Math.-Naturw. Kl.,* I., Bd. 75, I. Halbbd., 1913.

[5] W. Lindgren, " Mineral Deposits," p. 469, London and New York, 1919.

has been described by the writer and others.[6]   The formation of adinoles in shales along contact zones of diabases may be considered as belonging to the same group.

Of similar character, evidently, is the replacement of lime by soda in lime-bearing plagioclases, described by P. Geijer[7] and N. Sundius[8] from the Kiruna district.   Such change results in albitization of the plagioclase with addition of soda, as distinguished from common saussuritization which takes place without any change in total composition of the affected mineral.   Quite possibly, also, many glaucophane rocks may owe their present chemical composition to metasomatic addition of soda.

Not less common is case *C* where alkali is bound by the iron-magnesium minerals of the original rock.   The formation of biotite at the expense of amphibole, described by Becke,[9] and the formation in contact rocks of ægirite by metasomatic addition of soda, described by the writer,[10] are examples of this case.

Case *D,* the formation of feldspars from quartz by addition of alkalies and alumina which are brought in either as dissolved alkali aluminates or as nephelite in solution, apparently is common in the contact zones around ijolites and related abyssal rocks rich in nephelite.   It changes granites into syenitic rocks.   An example which my colleague, Professor W. C. Brögger, and I had

[6] V. M. Goldschmidt, "Die Kontaktmetamorphose im Kristiania-Gebiete." Die Injektionsmetamorphose im Stavanger-Gebiete."

E. Becke, "Denkschriften d. k. Akad. d. Wissensch.," *Wien. Math.-Naturw. Kl.,* I., Bd. 75, I. Halbbd., 1913.   "Typen der Metamorphose," *Geol. Fören. i Stockholm Förh.,* Bd. 42, p. 183, 1920.

R. Brauns, "Uber Laacher Trachyt und Sandinit," *Sitzungsber. d. Niederrhein. Ges. f. Nat.- u. Heilkunde,* Bonn, 1911.   "Die Kristallinen Schiefer des Laacher Seegebietes und ihre Umbildung zu Sandidinit," Stuttgart, 1911. "Die chemische Zusammensetzung granatführender krist. Schiefer u. s. w. aus dem Laacher Seegebiete," *N. Jahrb. f. Min.,* Beil.-Bd. XXXIV., p. 85, 1912.

[7] P. Geijer, "Geology of the Kiruna District 2." Stockholm, 1910.

[8] N. Sundius, "Beiträge zur Geologie d. südlichen Teils d. Kiruna-Gebietes," Uppsala, 1915.   "Zur Frage der Albitisierung im Kiruna-Gebiete," *Geol. Fören. i Stockholm Förh.,* Bd. 38, p. 446, 1916.

[9] F. Becke, *Geol. Fören. i Stockholm Förh.,* Bd. 42, p. 183, 1920.

[10] V. M. Goldschmidt, "Uber einen Fall von Natronzufuhr bei Kontaktmetamorphose," *N. Jahrb. f. Min.,* Bd. XXXIX., p. 193, 1914.

the opportunity of studying very closely has been described recently by the former[11] from the Fen Area, in Telemark, Norway, as "Fenite," from Archæan granites in the contact zones of alkaline rocks.

Magnesia Metasomatism.—Magnesia is bound by quartz or acid silicates forming anthophyllite or cordierite. The magnesium-silicate rocks occurring in many contact zones of granites afford an example.

Metasomatism of this kind was first described by P. Eskola in his report on the petrology of the Orijärvi region in Finland.[12] Analogous phenomena were recorded by P. Geijer from the Falun region and other districts in Sweden.[13] Peculiar, and apparently characteristic, is the association of these metasomatic magnesium-silicate rocks with sulphidic ore deposits. From his study of the Orijärvi region and Geijer's investigations of the ore deposits of Falun, Eskola was led to emphasize the great general importance of metasomatism in silicate rocks.

The widespread existence of magnesium compounds in circulating solutions is illustrated by the well-known process of dolomitization of limestones. In connection with magnesia metasomatism, it may be mentioned that aqueous solutions of magnesium salts are capable of dissolving considerable amounts of silica. Analysts have long been aware of this fact, while I have been able to ascertain experimentally that, when olivine is decomposed by dilute acids, a large part of the silica goes into solution.

Lime Metasomatism.—Lime is bound by excessive alumina, as

[11] W. C. Brögger, "Die Eruptivgest. d. Kristianiagebietes, IV., Das Fengebiet in Telemark," *Vid. Selsk. Skr. Mat.-Naturv. Kl.*, 1920, No. 9. pp. 150–167, 1921.

[12] P. Eskola, "On the Petrology of the Orijärvi Region in Southwestern Finland," *Bull. Comm. géol., Finl.*, No. 40, 1914. "Om sambandet mellan kemisk och mineralogisk sammansättning hos Orijärvitraktens metamorfa bergarter," *Bull. Comm. géol. Finl.*, No. 44, 1915. "Om metasomatiska Omvandlingar i silikatbergarter," *Norsk geologisk tidskrift*, Bd. VI., p. 89, 1921.

[13] P. Geijer, "Falutraktens berggrund och malmfyndigheter," *Sveriges geol. Undersökn.*, serie C, No. 275, 1917. "Recent Work on the Sulphide Ores in Fenno-Scandia," ECONOMIC GEOLOGY, vol. 16. p. 279, 1921.

shown by the formation of epidote at the expense of micas. Similar examples of this metasomatic process have been given by the writer from the injection contact-zones of the Stavanger region.[14]

A combined lime-magnesia metasomatism may also occur, giving rise to amphibole or pyroxene at the expense of quartz and lime- and magnesia-bearing solutions. To this group probably belongs the malacolite rock of Skutterud in Norway, to which my colleague, Professor J. Schetelig, called my attention.

Iron Metasomatism.—(*A*) Dissolved iron salts are precipitated by silicates, or quartz, as iron silicates.

(*B*) Dissolved iron salts interact with silicates forming iron oxides or hydroxides.

This kind of metasomatism apparently is represented by those replacements which have changed diabases, greenstones and slates into iron ores. It is possible that many cases thought to belong to this group should properly be referred to replacements of either primary or transitionally formed carbonates.

An example of case *A,* recently described by Sundius,[15] is the metasomatic formation of biotite and almandite at the expense of alkali feldspar. Cases of metasomatic formation of manganese formations, analogous to those of iron, are also known.[16]

Nickel Metasomatism.—Dissolved nickel salts are precipitated by serpentinous silicates as garnierite. Presumably, many garnierite deposits have originated in this manner.

Still other kinds of enrichment in heavy metals might possibly be classed as silicate metasomatism, for example, the precipitation of native metals such as gold, silver, or copper by ferrous silicates. In this case, however, it is the reducing ferrous iron content of the latter, rather than the silicates themselves, which controls the direction in which the chemical reaction proceeds.

[14] V. M. Goldschmidt, "Die Injektionsmetamorphose im Stavanger-Gebiete."

[15] N. Sundius, "Åtvidabergstraktens geologi och malmfyndigheter," *Sveriges Geol. Undersökning,* serie C, No. 306, 1921.

[16] Beyschlag-Krusch-Vogt, "Die Lagerstätten der nutzbaren Mineralien und Erze," 3, Bd. II., p. 348.

The copper deposits of the Lake Superior type well illustrate this case.

In this connection also might be mentioned the deposition of cinnabar in sandstones and quartzites, probably according to the following reaction: Alkaline solutions of alkali-mercury sulpho-salts react with quartz forming alkali silicates and mercury sulphide, the latter separating in solid form.

METASOMATISM IN SILICATE ROCKS OF METALLOIDS OR THEIR COMPOUNDS.

Among the processes of silicate metasomatism with addition of metalloids or compounds of metalloids, we may again discriminate, according to the substances brought in, between halogen-, sulphur-, phosphorus-metasomatism, and others. The following mode of grouping seems to be appropriate:

Fluorine-Chlorine-Boron Metasomatism.—(*A*) Fluorine or boron (or both) are bound by excess alumina.

Examples: Formation of topaz in hornfels. Formation of tourmaline in hornfels.

(*B*) Chlorine or fluorine (and water) are bound by feldspars.

Examples: Formation of scapolite at the expense of feldspars. Formation of greisen in pneumatolytic tin deposits and by analogous pneumatolytic or hydrothermal processes.

In case *A,* it is noteworthy that topaz and tourmaline seem to form preferably in rocks containing an excess of alumina, especially in slates.[17] When, however, these two minerals are found as metasomatic products in feldspar rocks without an original content of excess alumina, we may suspect that micas carrying excessive alumina had been formed as transitional products.

Case *B,* as well as *A,* is of widespread occurrence. The formation of scapolite at the expense of feldspars, especially of plagioclase, takes place under varying geological conditions. It may attain regional distribution, as described by Sundius from

[17] H. Rosenbusch, " Physiographie der massigen Gesteine," Bd. II., i, pp. 124-126, 1907.

the Kiruna district,[18] it may be limited to contact zones, as observed by the writer in the Christiania region,[19] or it may occur in the immediate vicinity of apatite veins, as those of southern Norway.

As is well known, greisen is generally associated with tin veins and related mineral deposits, and more or less gradually merges into rocks containing sericite, formed by hydrothermal alteration of the feldspars. The formation of typical greisen is frequently accompanied by the addition of lithia, a process apparently related to the metasomatic exchange of alkalies.

Sulphur Metasomatism.—(*A*) Formation of sulphides at the expense of iron-bearing silicates.

Example: Impregnation of rocks, originally iron-bearing, with pyrite and pyrrhotite in many contact zones.

(*B*) Sulphatization of feldspars and feldspathoids.

Example: Formation of alum-rock by volcanic exhalations.

An example of case *A* is afforded by " impregnation " deposits of pyrite in slates near intrusive rocks, recently described by Vogt[20] as of metasomatic origin. He believes them to have been formed by reactions between chlorite or biotite rich in iron, and hydrogen sulphide. To this class belong certain sulphide minerals which were formed by reduction of sulphates by ferrous silicates, for example, the impregnation of basic lavas with chalcocite as observed in many contact zones of the Christiania region. This case is analogous to the precipitation of native metals by ferrous silicates.

Case *B* is common in volcanic districts. Here, the active substances apparently were SO_2 and SO_3, while in most cases water vapor or water was probably also present.

Water and Carbon Dioxide Metasomatism.—Water and carbon dioxide are bound either during diaphthoresis or weathering, often with simultaneous leaching of primary constituents from the silicates.

[18] N. Sundius, " Beiträge zur Geologie d. südl. Teils d. Kiruna-Gebietes," Uppsala, 1915.

[19] V. M. Goldschmidt, " Kontaktmetamorphose im Kristiania-Gebiete."

[20] Th. Vogt, " Geol. Fören. i Stockholm Förh.," Bd. 43, p. 480, 1921.

Examples: Formation of serpentine, talc, sericite, chlorite, kaolin, laterite, zeolites, saussurite, prehnite, carbonates, etc., at the expense of primary silicates.

According to our definition of metasomatism, many important alteration processes, all of which take place with the addition of substances and may properly be regarded as metasomatic phenomena and thus come into this particular class, give rise to the above cited secondary minerals. The formation of sericite from anhydrous silicates frequently is due to metasomatism by hydration, possibly with simultaneous abstraction of some of their original constituents. Furthermore, another special type of sericitization of plagioclase involving the addition of potash is found in the vicinity of many gold-quartz veins.[21] Processes of this kind apparently are closely related to the formation of muscovite from nephelite.[22] We are dealing here with a combination of alkali- and hydration metasomatism.

Phosphorus Metasomatism.—(*A*) Phosphorus halogens interact with silicates rich in lime, forming apatite.

Example: Formation of apatite in contact zones of basic igneous rocks.

(*B*) Soluble phosphates interact with silicates rich in alumina forming aluminium phosphates.

Example: Alteration of silicate rocks under guano deposits.

The example mentioned under *A* often shows, at the same time, replacement characteristic of case *B* of " Chlorine Metasomatism," namely, the formation of scapolite at the expense of plagioclase. Phosphorus metasomatism as illustrated by case *B* has been described from many guano deposits in the tropics.

Carbon Metasomatism.—(*A*) Precipitation of carbon through interaction of silicates rich in iron with CS_2 or COS, forming graphite, iron sulphides and quartz.

Example: Formation of graphite in pyrite impregnations.

The frequent association of pyrite and graphite, both secondary, especially in silicate rocks rich in iron—amphibolites, for

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[21] W. Lindgren, " Mineral Deposits," p. 544, 1919.
[22] W. C. Brögger, " Das Fengebiet in Telemark," p. 144.

instance—points decidedly towards their common metasomatic origin. Experimental investigations of the reactions involved in such processes have been carried on for several years at the University of Christiania.

Silica Metasomatism.—Transformation of silicate rocks into opal or quartz with addition of silica.

Silicification of silicate rocks has been reported from many localities[23] and apparently may take place under various conditions. The chemical reactions which lead to silicification are still very little understood. In many cases alumina, a substance whose mobility is generally small, has no doubt been carried away, probably in the form of alkali aluminates.

To the cases of silicate metasomatism described above numerous others might be added. However, this synopsis does not aim at completeness, but only to give an idea of the great variety of metasomatic processes which may occur in silicate rocks.

The various cases of silicate metasomatism described above may occur either alone or in combinations of two or more. Certain of the latter are especially common, as for instance the formation of apatite and scapolite, the simultaneous formation of tourmaline, topaz and greisen, or the metasomatic " syenitization " of granite and the metasomatic formation of ægirite. It may be possible to develop an essentially geological classification of metasomatic processes, operative in silicate rocks, with groups like " Greisen metasomatism " or " Apatite vein metasomatism."

Many cases of silicate metasomatism may properly have to be classed under several headings. Thus metasomatism of muscovite from nephelite may be due to alkali-exchange as well as to hydration.

In classifying "special" cases of metasomatism, a scheme differing in its chemical point of view from the one employed here may be used, as for example, one differentiating between processes of metasomatism involving an exchange of bases, neutralization by acid or basic minerals, or reduction, although in my

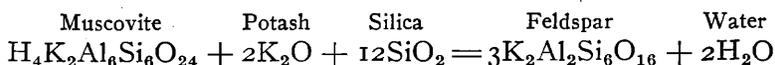[23] W. C. Brögger, "Das Fengebiet in Telemark," p. 544.

opinion, such a grouping would not have any essential advantages.

A PHYSICO-CHEMICAL THEORY OF METASOMATISM.

Considering the great variety of metasomatic processes taking place in silicate rocks, the question naturally arises whether they are controlled by any general laws; and to answer this important question, recourse must be had to physical chemistry. It seems especially important to search for the physico-chemical laws of metasomatism. The law of mass action would seem to apply also to replacements in the world of minerals, and we may ask in what form it might be used to greatest advantage.

Not to make the following considerations too abstract, let us take a concrete example, namely, the metasomatic formation of feldspar at the expense of potash mica. This case belongs to subgroup *B* of alkali metasomatism and has been studied carefully by the writer in the injection contact rocks of the Stavanger region.[24] Metamorphic derivatives of shales have here been subjected to metasomatic feldspathization. The muscovite of the shale reacted with solutions of alkali silicates, forming alkali feldspars. The solutions of alkali silicates added,—a kind of "water-glass,"—were derived from the mother liquors of muscovite-bearing magmas.[25]

The reaction may be expressed by the following equation:

$$\underset{\text{Muscovite}}{H_4K_2Al_6Si_6O_{24}} + \underset{\text{Potash}}{2K_2O} + \underset{\text{Silica}}{12SiO_2} = \underset{\text{Feldspar}}{3K_2Al_2Si_6O_{16}} + \underset{\text{Water}}{2H_2O}$$

In other words, this is a case where alkali is bound by the "excess alumina" of the precipitating mineral (see above).

[24] V. M. Goldschmidt, "Die Injektionsmetamorphose im Stavanger-Gebiete."

[25] The old distinction between "granite" and "granitite" gains added significance from this. The presence of primary muscovite in a granitic abyssal rock would mean that hydrolysis of the potash feldspar molecules had taken place before the rock was completely consolidated, and was sufficient to cause the separation of muscovite, the residual solution containing free alkali silicate. Metasomatic feldspathization of shales is therefore met with especially around muscovite-bearing abyssal rock masses.

This equation, however, may be somewhat simplified. Water is always present in excess, as we have to deal with reactions in aqueous solutions. Its concentration may therefore be regarded as constant, the solubility of the participating minerals, muscovite and feldspar being at any rate small. We may also presume that there is an excess of silica present, the newly formed as well as the original rocks in the case under consideration containing considerable amounts (about 30 per cent.) of free quartz. Therefore we do not have to deal with a variable ratio of silica to the potash added, but may lump potash and silica together as forming an "alkali silicate." Our equation thus assumes the following simpler form:

$$X \text{ mica} + Y \text{ alkali silicate} = Z \text{ feldspar,}$$
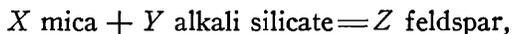
and we are, at the same time, not bound to any definite stoichiometric mica formula or any stoichiometric equation whatever. Water is, as pointed out, present in excess.

We may then assume that the alkali silicate solution attacks the original mica which proceeds to dissolve until its total solubility is reached, while alkali feldspar begins to separate out either before or not until this point is reached. As the solubility of the minerals in question is never so great as to permit of all of both minerals, mica as well as feldspar, to go into solution simultaneously, there will at first result a condition of equilibrium with both minerals present. To enable the feldspar to separate out, its concentration in solution must at least equal its solubility, and likewise the concentration of mica, so long as it is present in the original solid state, must also equal its solubility. The concentrations of mica and alkali feldspar in the solvent, during the process of metasomatic replacement, will equal the sum of their individual solubilities in the same solvent. The following equation, as an expression of the law of mass action, must therefore be valid for the condition of equilibrium assumed to prevail during the metasomatism:

$$K = \frac{(\text{Solubility of the mica})^x \times (\text{Concentration of the alkali silicate})^y}{(\text{Solubility of the feldspar})^x}$$

where K is the equilibrium constant for the reaction at the existent temperature and pressure.[26]

The equation may also be written in the following form:

$$\text{(Concentration of alkali silicate)} = \sqrt[y]{\frac{(\text{Solubility of the feldspar})^z \, K}{(\text{Solubility of the mica})^x}}$$

This means that at a given temperature and pressure, a minimum concentration of the alkali silicate is necessary to cause the separation of feldspar at the expense of mica. If this minimum concentration of alkali silicate does not exist, the circulating solution can only leach mica, but not separate any feldspar.

This important result may be expressed in a more general form valid for any kind of metasomatism: A solution, in order to effect metasomatism, must contain the substances to be added in concentrations at least equal to a minimum, which is definite for each case.

Analogous reasoning may be applied to metasomatism caused by addition of substances in gaseous form; here a certain minimum partial vapor pressure of the substance added is a condition necessary for replacement.

It is evident that metasomatic processes follow the law of mass action; this has also been emphasized by many authors (*e.g.*, by Niggli in his "Lehrbuch der Mineralogie"). The principle of minimum concentration (or minimum vapor pressure), first published by the writer in the spring of 1921,[27] might aid in the interpretation of metasomatic phenomena by the law of mass action.

We can now understand why metasomatic processes are common, but, lacking in minimum concentration, not universal. Although all the water circulating in the rock crust contains traces of alkali silicate, the potash mica is by no means everywhere changed into feldspar; under definite geological conditions only do the solutions contain so much alkali silicate that the limit concentration of this reaction is reached.

[26] Here we disregard electrolytic dissociation and hydrolysis, as these factors, though of influence in the quantitative relations, are of no consequence in the present, purely qualitative, considerations.

[27] V. M. Goldschmidt, *Geol. Fören. i Stockholm Förh.*, 43, 1921.

Such a use of the law of mass action enables us to conclude what kinds of solutions have been active in a metasomatic process.

The minimum concentration of the solutions naturally differs in different reactions and varies with temperature and pressure. To replace a limestone at high temperatures by chlorides of heavy metals, only a very small concentration of the latter is required, as most of the oxides of the heavy metals are by far less soluble than calcium carbonate.

In some cases of silicate metasomatism we are able to make certain deductions regarding the concentration of solutions involved. Thus we may conclude, from petrological evidence, that a larger concentration of alkalies is needed to convert ferric minerals into ægirite than aluminous minerals into feldspar. This is supported by the fact that ægirite is formed only after all the alumina of a rock has gone to form feldspar.

In this way, certain minerals or mineral associations may be arranged in a definite order regarding their behavior towards definite solutions.

An analogous mode of treatment may be fruitful in cases of minerals formed by non-metasomatic rock-metamorphism.

It is also possible experimentally to establish data important in gaining an understanding of metasomatic processes. Thus, since 1918, I have had made, in this University, a series of determinations of equilibria existing between the sulphides of iron and the common magmatic gases at temperatures between 600° C. and 900° C., the results of which are intended for an early publication. This work will furnish numerical data which throw light on a number of metasomatic reactions in which iron sulphides take part.

It would be of great importance to know whether metasomatic processes in rocks have any tendency towards a definite end-condition. Generally it seems that there is an inclination towards equalization of rock types of " extreme " composition, rocks, with " excess alumina " especially, leaning towards a " saturation " of alumina. Metasomatism, in this way, tends to make rock-masses more homogeneous. The common occurrence of relatively

" indifferent " gneisses among the old crystalline schists, without those marked variations characteristic of non-metamorphic rocks, may possibly be due to such a metasomatic equalization. But this tendency is not general; several metasomatic processes, especially such connected with diaphthoresis, even give rise to " non-saturated " rocks, as in the formation of sericite from feldspars.

What is the motive energy of the metasomatic processes? Its source apparently lies in all those geological agencies which bring rocks of different chemical characters into proximity, or set up potentials between different parts of the earth's crust by variation in temperature and pressure. Hence we find proof of intense metasomatism, especially in contact zones, in the crystalline schists, around ore deposits, and in the zone of weathering.

In still another respect, geological processes have an important bearing on metasomatism. Faults may open convenient passages for circulating solutions, mylonitic crushing of rocks may make quick leaching of large rock-masses possible. Petrology appears here as always to be a geological science.

Metasomatism not only represents a phenomenon whose correct interpretation is of interest to the petrologist and the student of ore deposits; it is also of great geological importance as an essential factor in what we may term the metabolism of the earth.

We may look on geological phenomena as a whole as outward expressions of metabolism on a grand scale, as a perpetual wandering and replacement of material. Two chief groups of phenomena may be distinguished:

An outer metabolism, represented by weathering (in part metasomatic), selective erosion, and sedimentation.

An inner metabolism, resulting in the movements of solid rock-masses and liquid magmas, in gravitative assortment, and finally in metasomatic processes. Thus the metasomatism of silicate rocks is no isolated phenomenon of only local interest, but rather an important link in the metabolism of the earth.

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