

likewise richer in lime and poorer in alumina than felspar. The vesuvianite aggregates, therefore, are the product of the solution of hornblende crystals in a fluid so viscous that but little diffusion could take place. The interstitial vesuvianite arises through a combination of two causes: (1) The ratio of lime to alumina in the diorite is, as stated above, higher than that required for the formation of epidote. (2) The diorites contain appreciable amounts of magnesia and alkalis. Part of the former crystallizes as spinel, but the remainder, together with the alkalis, would enter the vesuvianite molecule, which can have up to 6 per cent magnesia and 2 per cent alkalis, while epidote rarely has more than a trace of either.

(To be concluded in our next Number.)

V.—ON SATURATED AND UNSATURATED IGNEOUS ROCKS.

By Professor S. J. SHAND, D.Sc., Ph.D., F.G.S., Victoria College, Stellenbosch, South Africa.

OF the various minerals which enter into the composition of igneous rocks, about one-half are capable of forming in presence of free silica, as is shown by their association in rocks with quartz and tridymite. These may, for the present purpose, be termed *saturated* minerals; they include some of the most highly silicated compounds of their respective metallic elements. The remaining rock minerals do not appear in association with free silica, and may be presumed to be incapable of stable existence in its presence; they are mostly the less highly silicated compounds of the same metallic elements which enter into the former group. These may, for the present purpose, be termed *unsaturated* minerals. The unsaturated character of any mineral in the latter group is not affected by the temperature and pressure at which crystallization takes place; this is shown by the fact that quartz and the minerals referred to are mutually exclusive both in plutonic and in effusive rocks. In the case of sodium, potassium, calcium, and magnesium the formation of saturated or unsaturated minerals appears to depend only on the amount of silica available in the magma. Aluminium, ferrosium, and ferricum, elements of feebly basic character, have their combinations largely determined for them by the more strongly basic elements, with which they tend to form either complex molecules or mix-crystals.

In the following table the saturated and unsaturated compounds of each element are placed as far as possible in apposition:—

<i>Saturated.</i>	<i>Unsaturated.</i>
Orthoclase.	Leucite.
Albite.	Nephelite.
	Sodalite.
	Nosean.
	Analcite.
	Cancrinite.
Anorthite.	Hauyne.
	Melanite.
	Melilite.
Pyroxenes. }	Olivine.
Amphiboles. }	Pyrope.
Micas.	Picotite.

<i>Saturated.</i>	<i>Unsaturated.</i>
Tourmaline.	
Spessartite.	
Topaz.	Corundum.
Titanite.	Perovskite.
Magnetite.	
Ilmenite.	
Apatite.	
Zircon.	

I anticipate that objection may be raised to one or two of the minerals classed here as unsaturated. The first of these is olivine. A few dolerites and basalts have been described as containing both quartz and olivine, but I think the experience of most petrographers will show that this association is quite unusual. I have never come across an instance of it in the field, and I think it highly probable that the explanation of such an unusual association is that the quartz is not of magmatic origin. The only example of a quartz-olivine rock in my collection is the 'melaphyre' of Albersweiler in the Rhenish Palatinate, which contains small 'phenocrysts' of quartz. An examination of this rock decidedly suggests that the supposed phenocrysts are really xenocrysts. They are just as often aggregates as single grains, and they are always anhedral, with rounded, fretted outlines. But to be sure of this one would require to study the rock in the field. Harker¹ and Mennell² have both described occurrences of quartz xenocrysts within basalts and dolerites. In the cases described by Harker, basalt sills which were invaded by granophyre have been acidified and impregnated with quartz xenocrysts by the latter. In the dolerite intrusions in the Matopo granite, which Mennell describes, the quartz xenocrysts and the interstitial micropegmatite of the dolerites are due to absorption of granite. In at least one of these intrusions olivine is present. As the latter is a mineral of very early crystallization it is evident that the absorption or incorporation of quartz may occur too late to prevent the partial separation of magnesium in the form of olivine, and hence the two minerals may exist side by side. According to this view such quartz-bearing dolerites would be hybrid rocks, not true magmatic products. For further evidence bearing upon this point I must await the judgment of those who have the opportunity of studying such exceptional rocks in the field.

As regards corundum, I know of no instance where it occurs in association with quartz in igneous rocks; its common hosts are nephelite-syenites, anorthosites, and peridotites. Any excess of alumina over bases in the quartz-bearing rocks always seems to appear as muscovite or topaz, not as corundum.

It may seem strange that garnets should fall into two contrasted groups, the spessartites (and probably the almandites as well) being regarded as saturated while others (melanite, pyrope) are unsaturated; yet this is simply an expression of observed facts of distribution. In my own experience of melanite rocks in Sutherlandshire,³ where

¹ *Tertiary Igneous Rocks of Skye* (Mem. Geol. Surv., 1904).

² "Basic Dykes and Rock Genesis": *GEOL. MAG.*, 1911.

³ *Trans. Edinb. Geol. Soc.*, 1910.

quartz syenites pass insensibly into melanite syenites, the first trace of melanite does not appear until the last trace of quartz has been lost, although there is no immediate change in total lime content.

Anorthite, too, appears at first sight to occupy an anomalous position; it is an orthosilicate occurring in a group which is mainly composed of polysilicates and metasilicates. But calcium metasilicate (wollastonite) is incapable of independent existence under magmatic conditions, hence the orthosilicate is the stable form even in quartz-bearing rocks. True quartz-anorthite rocks are probably rare, but the anorthite molecule must have been present as such in the parent magma of every quartz-plagioclase rock.

Magnetite and ilmenite are of course completely unsaturated as regards silica, from the chemical point of view, but as both are capable of stable existence in the presence of free silica under magmatic conditions, they rank here as saturated minerals. (Should it be felt that this new use of a common term is liable to be misunderstood, the reader may at his pleasure read *sated* and *unsated* in place of 'saturated' and 'unsaturated'.)

A rock which contains only saturated minerals may be termed a *saturated rock*; one which contains only unsaturated minerals may be termed an *unsaturated rock*. It will also be desirable to distinguish *partsaturated rocks* (e.g. phonolites, olivine-dolerites) from wholly unsaturated ones; as a general term to cover both partsaturation and unsaturation we may employ *undersaturation*. Any rock which contains free quartz or tridymite of magmatic origin will be termed *oversaturated*.

These distinctions are by no means trivial; they have a very definite chemical significance which has a bearing upon the reaction of the magma towards invaded rock masses, and hence upon magmatic differentiation. They are also capable of useful application in the classification of igneous rocks.

1. An undersaturated magma (i.e. one which on solidifying would give rise to a partsaturated or unsaturated rock) is capable of entering into chemical combination with the silica of invaded rock masses. The reactions thereby induced would be exothermic, and would tend to raise the temperature of the magma. The amount of heat to be gained in this way does not seem to be susceptible of direct measurement at the present time: the difficulties to be overcome would be very great, but as silicic acid is known to be an exceedingly powerful acid at high temperatures, it is probable that the heating effect of the reaction would be considerable. The access of heat produced in this way would in turn enable the magma to perform a further amount of work in the way of mechanical solution.

2. A saturated or oversaturated magma (i.e. one which on solidifying would give rise to a saturated or oversaturated rock) is incapable of combining chemically with silica; its action on the quartz of invaded rocks must be confined to physical solution, which will lower the temperature of the magma.

Other things being equal, then, an undersaturated magma must have a greater action upon invaded siliceous rocks than a saturated or oversaturated magma; as a result of such action it would tend

first to saturate itself chemically, then to oversaturate itself in the physical way. (Reactions with constituents other than silica are for the moment disregarded.) As a consequence of the greater activity of an undersaturated magma, one would expect to find greater variation, both chemical and mineralogical, within a body or complex of undersaturated rocks than in a saturated or oversaturated body or complex. This deduction seems to be confirmed by the enormous number of varietal names which have been coined for different facies of the undersaturated rocks.

3. Towards the aluminium constituents of invaded rocks it would seem that there would be little difference in the behaviour of saturated and undersaturated magmas. The change by which aluminium silicates are converted into micas and feldspars, a change for which the field evidence is overwhelming in amount, could not be effected any more readily by a felspathoidal magma than by a felspathic one, since in both feldspars and felspathoids the ratio of Na, K : Al is the same. This particular conversion must be due to an excess of alkali in the magma, of which no trace remains as such when the rock has solidified and become exposed to investigation. With this point, however, I am not at present concerned. There remains the theoretical possibility that aluminium silicates might be reduced to corundum by reaction with an undersaturated magma.

4. When the invaded rock is a carbonate or other non-silicate rock, or contains much lime, magnesia, or iron in the form of oxide or carbonate, then the advantage as regards absorbing power lies with the saturated and oversaturated magmas, which can yield first their excess of silica, and secondly a further quantity of silica due to the reduction of sodium, potassium, calcium, and magnesium molecules from the saturated to the unsaturated state. In this way a saturated or oversaturated magma may become undersaturated. This case, as regards alkaline rocks, has been presented by R. A. Daly.¹

The above deductions involve no assumption at all as to the *extent* to which absorption takes place in nature; so long as even a few instances arise in which absorption is admitted to have taken place, then it becomes necessary to recognize the essential difference in the absorptive capacity of saturated and undersaturated magmas. The appearance of, let us say, nephelite in a syenitic rock means far more than the mere addition of another name to the list of accessory minerals present in the rock; it involves a real difference, both of kind and degree, in the reaction of the magma towards its environment. By studying the distribution of the saturated and undersaturated members of an igneous complex one may gain a wider view of the process of differentiation than is to be had from the study of minute mineral and chemical differences alone.

With these considerations in view, it is instructive to turn to the distribution of oversaturated and undersaturated rocks in the lithosphere.

1. As regards mere bulk, the oversaturated and saturated rocks predominate enormously over the undersaturated. Daly¹ estimates

¹ "Origin of the Alkaline Rocks": Bull. Geol. Soc. Amer., 1910.

that "all the visible alkaline rock of the world 'probably constitutes less than 1 per cent of the total visible igneous rock". If in addition to the alkaline rocks we consider the olivine, melilite, melanite, and corundum-bearing rocks, it seems likely that the total mass of the undersaturated rocks will scarcely exceed 2 per cent of the total visible igneous rock.

2. Among major intrusions the vast majority consists of oversaturated rocks. Saturated rocks have a much smaller representation, and undersaturated rocks are relatively rare except as marginal facies and differentiated bodies. Where nephelite-syenites occur they are in surprisingly many cases associated with limestones, and Daly¹ makes out a good case for regarding some of them, at all events, as due to absorption of limestone. Thoroughly unsaturated types (e.g. dunite) never form truly major intrusions.

3. Among lavas and minor intrusions the oversaturated types are quite subordinate to the saturated and undersaturated. Thoroughly unsaturated types, though rare, are recognized in dunites and some monchiquites and alnöites. Undersaturated types, such as nephelite and leucite tephrites, basanites, and basalts, olivine dolerites and basalts, picrites, peridotites, and serpentines, are well represented.

4. A curious point, which will, I think, survive the test of statistics, is the very frequent occurrence of undersaturated and unsaturated rocks in the pipes of single-explosion volcanoes. The olivine bombs of the Dreiser Weiher and other volcanoes of the Eifel and Auvergne, and the ultrabasic agglomerate with content of olivine and pyrope which fills the pipes of some of the volcanic necks of Scotland, will serve to illustrate this point, but the most superb examples are the kimberlite and alnöite pipes of South Africa. Kimberlite, with its abundant olivine and pyrope, and its possible melilite,² is emphatically undersaturated; while some of the alnöites, as described by Rogers,³ are entirely unsaturated.

These observations can be reduced to the following form: Those igneous rocks which have been brought up most rapidly from the earth's interior, and have solidified most rapidly in or on the crust, are to a marked extent undersaturated. Those others which have slowly worked their way up into the crust (and have hence had abundant opportunity for absorbing silica) are found to be predominantly oversaturated. We have here a strong suggestion that undersaturation may be characteristic of the deeper zones of the lithosphere, as oversaturation is of the higher. I do not wish to insist upon this point, but merely to show that the distinctions employed here have their uses even in the discussion of the major problems of geochemistry.

The conceptions of saturation and undersaturation are capable of application to the classification of igneous rocks, and provide just those natural distinctions between different types, the absence of which petrographers have been accustomed to deplore. If writers

¹ "Origin of the Alkaline Rocks": Bull. Geol. Soc. Amer., 1910.

² Carvill Lewis, 1897; Mennell, 1909.

³ Trans. S.A. Phil. Soc., 1904; Ann. Rep. Geol. Comm. (Cape of Good Hope), 1911.

like Dr. Hatch¹ and Mr. Menell,² who tie their faith to silica percentages, would instead employ the mineralogical dividing lines which separate the oversaturated from the saturated rocks, and these again from those which are undersaturated (1) with regard to leucocratic constituents, (2) with regard to melanocratic constituents, and from (3) those which are undersaturated or unsaturated in all their constituents, they would find themselves in possession of a much more 'natural' classification of rocks, and one which would be vastly simpler to use than any classification which is based upon silica percentages. The connexion between mineral and chemical composition need not be obscured thereby, but rather the reverse, especially if, as could easily be done, the relative degrees of oversaturation or undersaturation were introduced as subordinate factors in the classification. The fact that, under different conditions of temperature and pressure, one and the same magma may give rise to rocks of different degrees of saturation, is an argument in favour of my contention, not against it. The classical experiment of Fouqué and Michel-Lévy, in which a melt of orthoclase and biotite yielded leucite and olivine on cooling, illustrates this point. The silica percentage, being the same in the product as in the educt, fails to express the difference between these two very different mineral associations; yet the former is saturated, the latter unsaturated, and by making degree of saturation a criterion of systematic position we effect a separation of things formed under unlike conditions, which is at least as important as the separation of things of unlike ultimate composition.

If Dr. Hatch and Mr. Menell had considered the natural criterion of undersaturation, in place of the artificial one of silica percentage, they would not have been led into the paradoxical positions of classifying borolanite, a rock which typically contains neither plagioclase nor augite, with "alkali-gabbro" and "dolerite" respectively. In my opinion both these gentlemen have erred by committing themselves to classifications which are neither definitely chemical nor definitely mineralogical. A chemical classification, to be of any value, must have regard to *all* the molecules present in a rock, not to one alone. If a classification is to be mineralogical, let it be consistently so. I believe that both chemical and mineralogical classifications are necessary, but of hybrid classifications I would go so far as to say, as Harker says of hybrid rocks, "like other hybrids, they are barren."

The recognition of the essential difference between saturated and undersaturated rocks ought to lead to the avoidance of such loosely-used terms as shonkinite, monzonite, and esséxite. We read in Dr. Hatch's textbook, for example, that "nepheline and leucite occur occasionally in monzonites"; that esséxites contain a variable quantity of nepheline; and that nepheline and sodalite "may be present in small quantities" in shonkinite. The older petrographers always drew a sharp distinction between the syenites and the nepheline-syenites; however small the proportion of nepheline, it was considered sufficient to justify the removal of the rock from the former to the

¹ *Textbook of Petrology*, 1909.

² *Manual of Petrology*, 1913.

latter class. The same procedure, with regard to olivine, is followed to this day in the application of the names tephrite and basanite, nephelinite and nepheline basalt. The distinction between the saturated and the unsaturated minerals is a real one, with important consequences in the chemistry of rock magmas; and petrographers who shut their eyes to a natural distinction of this kind deserve the fate that awaits them at the hands of inventors of arbitrary classifications.

The present paper is an argument for the importance of the above distinction, and a plea for its recognition in petrographic nomenclature.

VI.—SEPTARIA: A DEFENCE OF THE 'SHRINKAGE' VIEW.

By T. CROOK, A.R.C.Sc. (Dublin), F.G.S.

A CONTRIBUTION to the March number of the GEOLOGICAL MAGAZINE by Dr. A. M. Davies, and another in the August number by Mr. J. E. Todd, support a view formerly held by Professor H. G. Seeley, viz. that the cracks of septaria are due to expansion, during growth, of the outer layer of the nodule.

For several reasons this view appears to me to be untenable. It seems to be based on an erroneous conception of what takes place during the growth of a septarian nodule. It exaggerates the significance of crystallizing force in material deposited from solution. In a rudimentary way a nodule is a crystalline growth, but the manner of this growth speaks of a force of crystallization that has been thwarted and not allowed free play. A nodule is of the nature of an imperfectly crystalline precipitate, rather than a robust crystalline growth. It consists of a mass of shapeless microcrystalline granules, each of which was presumably deposited from solution in such a way as to accommodate itself quietly to the surface on which it grew. Surely Mr. Todd makes a mistake when he compares the crystallizing force of material deposited from solution to the expansive force manifested by water in solidifying. There is no analogy between the two processes.

I think we are justified in asserting that the growth of a septarian nodule in a clay has at least this in common with the growth of a crystal from solution: it presents a sharply defined surface to the medium in which it is growing, and it grows by addition of material to the surface. And if material can be deposited on the faces of a growing crystal without the interior being ruptured by the crystallizing force when that force displays its full vigour, why should the addition of shapeless and accommodating microcrystalline granules to the surface of a growing nodule result in internal rupture?

Moreover, nodules are septarian only when they have incorporated within their substance a considerable amount of colloidal clayey matter. If a nodule consists of fairly pure carbonate, or if it contains sandy matter to the exclusion of clay substance, it does not become septarian. How is this fact explained by the 'expansion' view?

Again, I fail to see how we can allow the last added shell of the nodule to crack the enclosed mass without cracking itself; and if the outer shell did expand during growth without cracking itself,