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MINERALIZATION OF THE VIRGINIA TITANIUM DEPOSITS*

CLARENCE S. ROSS, *U. S. Geological Survey,
Washington, D. C.*

The Virginia titanium deposits are the world's largest producers of rutile and also contain large supplies of ilmenite. The producing district lies in the central part of the State, about midway between Charlottesville and Lynchburg. It is part of the Piedmont region but lies near the base of the Blue Ridge whose crest is about 12 miles to the northwest.

A study of these titanium deposits has led to the conclusion that they are not magmatic segregations, but have been formed by invading solutions. It will not be possible to give many of the details of occurrence, of mineralogy, and of chemical relationships in a brief paper of this character. However, these will all be included in a more comprehensive report which is planned for later publications by the United States Geological Survey. This paper will present briefly the evidence that indicates the mode of origin and some of the outstanding factors in the chemistry of mineralization.

The dominant country rock of the region is a gneissic quartz monzonite of pre-Cambrian age which has been intruded by a feldspathic rock that was originally composed only of andesine, which contained microscopic lenses of antiperthitic microcline. This intrusive mass is roughly elliptical in shape, being about 13 miles long, $2\frac{1}{2}$ miles in greatest width, and having a total area of about 22 square miles. It is composed of feldspar which everywhere shows a cataclastic structure. Most of it has been very thoroughly granulated, but locally masses up to six inches in diameter have partly escaped granulation. This primary feldspar is light blue-grey in color and contrasts strongly with the white granulated material. After granulation the rock was intruded by a group of ferromagnesian dikes, by numerous small lenses of ferromagnesian minerals, and by quartz.

The contact of the feldspathic intrusive with the country rock is

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marked by a broad zone of injection, or augen gneiss. This injected material seems to represent residual magma forced out of the spaces between the grains of the partly crystallized rock, by filter press action, during intrusion and consolidation. The mono-mineralic character, the intrusion as a mush of crystals, the thorough granulation, and the expulsion of residual magma, all show the relationship of the Virginia rock to typical anorthosites. It differs from these only in the more sodic character of its plagioclase, and therefore the name anorthosite seems to be applicable to this feldspathic intrusive.

The titanium deposits are of two types—one as disseminations in the anorthosite, and the other as lens- or dike-like bodies of a rock called nelsonite. The disseminated ores are all within the anorthosite, as are most of the nelsonite bodies. A few small nelsonite bodies have intruded the country rock.

The disseminated ores are most readily studied in the open cut mine of the American Rutile Company at Roseland, where they are associated with a series of parallel shear zones. Close to these, ilmenite occurs, associated with actinolite, clinozoisite, and biotite. Rutile becomes the dominant titanium mineral in an intermediate zone, where it is associated with tremolite, sericitic muscovite, and clinozoisite. At greater distances—indeed throughout the anorthosite—muscovite and clinozoisite have developed. The mines at Roseland also contain large irregular masses of a blue-grey quartz, for which the district is noted. The color is due to great numbers of minute rutile crystals that are included in the quartz. It forms irregular masses up to a foot or more in diameter, or more rarely definite veins. These masses of quartz tend to be associated with zones where there has been shearing and where ferromagnesian minerals are most abundant. Thus there is a clear relationship between quartz and other secondary minerals.

The nelsonite bodies are composed essentially of rutile or ilmenite, and apatite, but commonly gangue silicates are also present. The nelsonite body being worked by the Southern Mineral Products Company contains some "hard ore" which is about one-third apatite and two-thirds ilmenite. More generally the rock contains varying proportions of ilmenite and apatite, which are associated with biotite, or less commonly with fine grained actinolite. Within the nelsonite body is a large "horse" of typical anorthosite, which has been only slightly mineralized, and contains but a few per cent of ilmenite, apatite, actinolite, micas and clinozoisite. On its border this mass shows a gradual transition to a lean biotited nelsonite. Other bodies contain large proportions of amphiboles associated with apatite, ilmenite, and garnet, and also numerous residual areas of anorthosite.

The titanium minerals and the associated secondary silicates in both types of deposits are believed to have been formed by invading solutions. Evidences of replacement and secondary origin are as follows. The rutile and ilmenite of the disseminated deposits occur only in the granulated portions of the anorthosite, and are totally absent in primary feldspar. Titanium minerals are localized near major fractures which evidently acted as feeders for mineralizing solutions. The distribution of titanium minerals is exceedingly erratic, and varies from rich to barren rock within a few feet. Ilmenite occurs in fractures and cleavage planes in hypersthene which has formed in the parallel shear zones in the anorthosite. Thus both hypersthene and its enclosed ilmenite are later than the anorthosite. The rutile and ilmenite are ungranulated, even where included in thoroughly granulated feldspar. Ilmenite and the same associated silicates that occur in the anorthosite are also found in the country rock along the borders of the anorthosite where only solutions seem capable of introducing them.

The nelsonite bodies show a sequence of mineralization. Reaction rims of garnet surround small residual areas of anorthosite in some occurrences. Apatite is the earliest of the secondary minerals, followed by rutile or ilmenite, which in places form veinlets in the apatite. Biotite forms veinlets in apatite, rutile, and ilmenite. In both the disseminated deposits and in the nelsonites, rutile has been replaced by ilmenite, and magnetite forms veinlets in ilmenite, thus showing a sequence in the composition of the depositing solutions. Post granulation dikes are highly altered, evidently at the same time as the enclosing anorthosite, and contain abundant ilmenite.

Small veins of nelsonite have formed along fractures in the anorthosite in specimens from the mine of the American Rutile Company and from the dumps of the old General Electric Company mine. The pyrogenic origin that has commonly been assumed for the Virginia deposits implies two distinct periods of formation. The disseminated deposits would represent a crystallization from a feldspathic magma, whereas the nelsonite would represent a much later crystallization from an exceedingly basic magma that intruded the earlier one after it was consolidated and fractured. On the other hand, deposition from incoming solutions avoids the improbable assumption of two distinct periods of formation for essentially similar groups of minerals.

Mineral deposits are in general characterized by diverse groups of minerals that have been introduced into rocks of complex chemical composition. In contrast, the Virginia titanium deposits have replaced a rock of very simple composition. The important introduced elements are limited in number and were totally absent in the primary rock. These

relations present an unusually favorable opportunity for studying the chemistry of mineralization.

The physico-chemical factors that control mineral alterations and replacements are in general complex, and inadequately known. In the titanium region, however, the instability of calcic plagioclase and the stability of sodic plagioclase in the presence of hydrous solutions seems to have been the dominant factor in mineralization. This instability and some of its consequences have been discussed by Bowen in the *Lindgren volume*.¹ The reaction principle is, no doubt, the controlling factor in a wide variety of hydrothermal processes just as in magmas, and the Virginia titanium deposits probably differ only in the clearness with which the reaction principle control of mineralization is indicated.

Recently Eskola² has experimentally produced the alteration of calcic to sodic plagioclase in solutions containing an excess of sodium carbonate and silica. He found that albitization was more complete, and the resulting crystals more perfect at 310° to 330° than at 550° or even at 360°. Highly sodic albite developed only at the lower temperatures. In the titanium deposits the reactions between the anorthosite and the incoming solutions has produced plagioclase feldspar ranging in composition from andesine to albite. Thus Eskola's work suggests temperatures ranging down to at least 300° during mineralization in the Virginia deposits.

The primary anorthosite was composed of approximately 3 parts of andesine and 1 of microcline. That is, 2 molecules of albite, 1 of anorthite, and 1 of microcline, or chemically only of SiO₂, Al₂O₃, CaO, K₂O and Na₂O. In the innermost zone of alteration ilmenite, actinolite, biotite, and clinozoisite formed showing the introduction of TiO₂, FeO and MgO. Throughout the anorthosite the new minerals were muscovite, clinozoisite and sodic plagioclase which are composed of SiO₂, Al₂O₃, CaO, K₂O and Na₂O, the same elements comprising the anorthosite. This implies zonal relations, with titanium, iron and magnesium as the essential new elements that were introduced into the zone of most intense alteration. The solutions evidently lost most of their iron before reaching the intermediate zone, and only insignificant amounts of these three elements penetrated into the great mass of the anorthosite. The inner zone which is characterized by titanium minerals and iron bearing silicates is very irregular in width, but in general ranges from a few feet up to perhaps 15 or 20 feet before it gradually merges with the second, or nearly iron free zone. This second zone is wider than the last, and was controlled

¹ Bowen, N. L., Ore deposits of the Western States: *Lindgren volume*, p. 114, 1933.

² Eskola, Penetti, An experimental illustration of the spillite reaction: *Compt. Rend. Soc. Geol. de Finlande*, Extract No. 9, pp. 1-8, 1935.

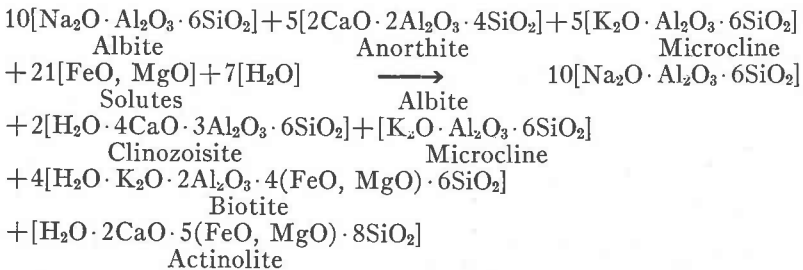
by the permeability of the granulated rock as well as by proximity to feeding channels. In places it probably has a width of some hundreds of feet before it fades out into the altered but nearly unmineralized portion of the anorthosite.

We may now examine these changes by means of chemical equations, neglecting the rutile and ilmenite which were introduced into the anorthosite by the complete removal of the feldspar in the space they occupy. This type of replacement involves relative solubilities, and probably other factors that can not be evaluated and so can not be represented by simple equations.

In the following chemical equations the name of the mineral represented is placed immediately below its chemical formula. The mineral molecules of the original rock, and the introduced solutes precede, and the new minerals formed by the reactions follow the arrow. The proportion of the albite, anorthite and microcline molecules comprising the original anorthosite are fixed in approximately the ratio 2:1:1 and so when the same molecules reappear among the new minerals on the right of the equation they are not canceled. The proportion of the new elements introduced as solutes is determined by balancing the equation, but their character is clearly indicated by the new minerals formed. Some of the secondary minerals—notably amphiboles and micas—do not have definite formulas. However, variations in their composition introduce only slight changes in proportions and do not affect fundamental relations. The following equations are representative of chemical reaction in the three zones of mineralization.

Equation No. 1 represents the inner zone of most intense alteration. The new elements introduced form only about 10 per cent of the resulting rock, although there has been a very thorough change in the mineral composition.

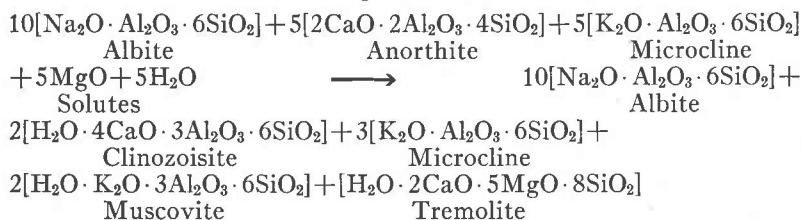
Equation No. 1



Equation No. 2 represents the intermediate zone where about 2.5 per cent of new material has been added and a slightly smaller proportion

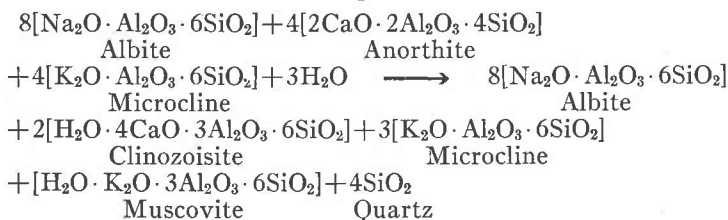
of new minerals developed than in the zone represented by the last equation.

Equation No. 2



Equation No. 3 represents relations throughout the anorthosite. Here only a little water has been introduced, and a marked change in mineral composition has been produced merely from a re-arrangement of the materials of the primary rock. Albite and the elements that recrystallized into clinzoisite were released from the andesine, and some of the microcline has formed muscovite.

Equation No. 3



These equations are no doubt a simplification of the chemical processes within the anorthosite. The rock itself shows incomplete alteration of feldspar to new minerals and much of the plagioclase has become only moderately more sodic. Thus varying proportions of the anorthite molecule should in fact appear on both sides of the equations, and the new plagioclase should vary from albite where alteration was most complete to sodic andesine where it was less so.

The fluorine that proxies water in micas has been omitted. The equations assume that new material entered the system in each zone but that none was removed. No doubt a small proportion of the least readily fixed elements tend to move from one zone to the next. These would be largely alkalis and potassium would in general move the farthest. Geologic observation shows the strong tendency for albitization to fix sodium and drive out potassium.

Such equations as these obviously can not fully represent chemical relations, but nevertheless they seem to present an approximate and

significant picture of the chemistry of mineralization in the Virginia deposits. They enable us to visualize the reactions, and indicate that these were less complex than might otherwise be assumed. They also show that the simplest possible re-arrangement of SiO_2 , Al_2O_3 , CaO , K_2O and Na_2O plus incoming H_2O into new groupings results in the three minerals albite, muscovite and clinozoisite.

The evidence of a simple recrystallization presented by equation No. 3 suggested the desirability of analyzing material that had undergone extreme alteration for comparison with an analysis of the unaltered primary feldspar that had previously been made. A specimen showing a maximum proportion of albite, muscovite, and clinozoisite was selected and the two analyses are given in the following table.

CHEMICAL ANALYSES OF FRESH AND ALTERED FELDSPAR

	Fresh	Altered
SiO_2	61.44	59.62
Al_2O_3	23.47	24.06
Fe_2O_3	0.20	0.49
FeO } as FeO		0.09
MgO	0.05	0.07
CaO	5.00	4.54
Na_2O	5.94	5.47
K_2O	3.92	4.53
BaO	0.19	n.d.
$\text{H}_2\text{O}-$	0.03	0.03
$\text{H}_2\text{O}+$	0.20	1.19
TiO_2	0.10	0.09
	<u>100.54</u>	<u>100.18</u>

These analyses are strikingly similar. Sodium and calcium are a little lower and potassium a little higher in the altered rock, and water and a little ferric iron have been introduced. Otherwise the two rocks are essentially the same. As suggested before, a little potassium has evidently been introduced from zones of more intense alteration. Equations representing this could be given, but will be omitted here.

SUMMARY

In summary it may be stated that a study of the Virginia titanium deposits has shown that they occur within a rock of the anorthosite type that was introduced as a mush of crystals. The ores and associated gangue minerals were deposited by invading solutions that are believed to have been derived from a highly ferromagnesian rock that was probably a differentiate from the same primary magma as the anorthosite. Some of the chemical factors of mineralization are indicated and prove to be rather simple in character.