Geochemistry of Niobium and Tantalum

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By RAYMOND L. PARKER *and* MICHAEL FLEISCHER

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A review of the geochemistry of niobium
and tantalum and a glossary of
niobium and tantalum minerals

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GEOCHEMISTRY OF NIOBIUM AND TANTALUM

By Raymond L. Parker and Michael Fleischer

ABSTRACT

This report on the geochemistry of niobium and tantalum is chiefly a summary of works published since those of Rankama, and it is not a product of original research. It summarizes what is known of the geochemical characteristics of these elements and their occurrence in various types of minerals, rocks, and ores. A glossary of niobium and tantalum minerals and an extensive list of references on the geochemistry and mineralogy of these elements are included.

Niobium (atomic number 41) and tantalum (atomic number 73) occur in nature almost entirely as single isotopes (Nb^{93} and Ta^{181}), and they commonly substitute for one another in minerals because they both have similar ionic radii and occur mostly in the quinquevalent state. A great preponderance of one element over the other rarely occurs in certain types of rocks such as nepheline syenites (niobium-rich) or lithium-bearing pegmatites (tantalum-rich). Both elements are lithophilic and are enriched in the silicate crust of the earth.

Most niobium and tantalum minerals are oxides, although some rare silicates and one borate are known. Many oxide, phosphate, tungstate, and silicate minerals of other elements contain minor amounts of niobium and tantalum in isomorphous substitution for such elements as titanium, tungsten, tin, zirconium, and hafnium. Minerals containing niobium and tantalum are listed in the glossary.

The abundance of niobium and tantalum in the earth's crust according to modern estimates is near 20 and 2 ppm respectively, but abundance of these elements in different types of rocks comprising the crust is highly variable. Crustal abundance as well as abundance in various rock types are subject to considerable uncertainty in accuracy and validity because of limitations imposed by availability of analytical data, by accuracy of analytical procedures, and by adequacy of sampling. Additional limiting factors are improper classification of rocks and geographic bias. A compilation of abundance tables for different rocks shows that niobium is most abundant in alkalic rocks such as nepheline syenite, syenite, alkalic mafic and ultramafic rocks, and sodic and alkalic granite. Tantalum generally accompanies niobium with an abundance of one-tenth to one-fifteenth that of niobium although it is extremely low in some niobium-rich alkalic complexes. (See tables.)

In sedimentary rocks the highest niobium contents are found in deep sea manganese nodules and sediments and in bauxites; the highest tantalum contents are found in marine clays and bauxite, whereas a paucity of tantalum exists in the deep sea environment. Some physically and chemically resistant minerals of niobium and tantalum accumulate locally in placers and are found as rich accumulations preserved in some sandstones and conglomerates.

Niobium and tantalum in meteorites are a fraction of their clarke values, although in tektites the tantalum content is close to that for the earth's crust.

Most univalent, divalent, and some of the larger trivalent ions of trace elements exist free in magma and their crystallization can be interpreted satisfactorily in terms of ionic radius, ionic charge, and electronegativity or ionic potential according to the rules of Goldschmidt and of Ringwood. Ions with charges greater than three and some of the smaller trivalent ions, however, form complexes with oxygen, hydroxyl, fluorine, chlorine, and other anions, and these complexes maintain their identity during the crystallization process. The higher the ionic potential of the element the more stable is the complex formed. Niobium and tantalum have ionic potentials of intermediate values ($Nb^{+5}=7.25$, $Ta^{+5}=7.35$), sufficiently high to form normally stable complexes, although they are also in the range where partial dissociation under certain conditions is possible. Niobium and tantalum probably form tetrahedral complexes, NbO_4^{-3} and TaO_4^{-3}, and octahedral complexes, NbO_6^{-7} and TaO_6^{-7}. The octahedral form is the one found in most niobium-bearing minerals. Neither tetrahedral nor octahedral complexes of niobium and tantalum can be easily incorporated into most silicate minerals according to the rules of Ringwood; hence these elements tend to accumulate as complexes in the magma during crystallization until sufficiently concentrated to allow precipitation, most likely as multiple oxide minerals, or are scavenged during crystallization by accessory minerals of titanium or titanium and iron.

These complex-forming elements can be considered as individual ions for the purpose of examining schemes of isomorphism and the electrostatic balances involved. Two types of isomorphism are prevalent, isovalent and heterovalent. The common substitution of niobium for tantalum is the isovalent type. The substitution of titanium for niobium and tantalum is the heterovalent type.

The geochemical behavior of niobium and tantalum in granitic rocks depends to a certain extent on the paragenesis of the titanium minerals. Monazite-bearing granites containing ilmenite and rutile commonly contain niobium and tantalum in accessory biotite, whereas allanite-bearing granites containing sphene and magnetite commonly have niobium and tantalum concentrated in sphene with only subordinate amounts in the biotite. In some granitic rocks the niobium and tantalum are concentrated in hornblende. Most likely these elements substitute for titanium in the minerals concerned. Some rare granites contain niobium and tantalum in discrete accessory minerals of these elements. Although exceptions occur, niobium and tantalum generally accumulate in the later differentiates during crystallization of granites, and there is a tendency for tantalum to be concentrated relative to niobium in certain albitized or greisenized rocks. The separation of niobium from tantalum and the concentration of tantalum are attributed to changes in alkalinity-acidity of the crystallizing medium and to the complexing of these elements with fluorine, tantalum-fluorine complexes being more mobile and stable than niobium-fluorine complexes.

High concentrations of niobium and tantalum occur in granitic pegmatites both as discrete niobium-tantalum minerals and as minor constituents in the lattices of mica, garnet, tourmaline, ilmenite, zircon, and other minerals. Complexly zoned pegmatites commonly are more intensely mineralized with niobium and tantalum than other types. Those pegmatites having a strong development of albite and lithium- and fluorine-bearing minerals commonly are enriched in tantalum. Tantalum generally tends to be concentrated with respect to niobium in successive later phases of many granitic pegmatites.

Nepheline syenite is well known for its high concentration of niobium. Some Russian nepheline syenite complexes have concentrations of tantalum (Nb:Ta = about 12:1) also, but many alkalic complexes elsewhere are notably poor in tantalum. In miaskitic nepheline syenites ($K_2O + Na_2O:Al_2O_3 = <1$) niobium and tantalum are concentrated in titanium and zirconium minerals and also form independent minerals of niobium and tantalum in late magmatic and postmagmatic derivatives. In agpaitic nepheline syenites ($K_2O + Na_2O:Al_2O_3 = 1$ or more) most niobium and tantalum are fixed in titanium and zirconium minerals even though the average contents of niobium and tantalum in these rocks is greater than in miaskitic syenites.

Alkalic ultramafic complexes, typified by those of the Kola Peninsula, U.S.S.R., characteristically contain multiple phases in concentric arrangement. The phases consist of varieties of olivinite, pyroxenite—including melilite-, perovskite-titanomagnetite-, and nepheline-bearing types, melteigite-ijolite-urtite, and others. In the products of magmatic crystallization niobium and tantalum enter into the titanium-bearing iron-magnesium-silicate and oxide minerals. In products of residual crystallization, such as alkalic pegmatites, niobium and tantalum are concentrated in titanium and zirconium minerals and in independent niobium minerals. In postmagmatic rocks, such as carbonatites, niobium and tantalum are concentrated in independent minerals such as pyrochlore, lueshite, dysanalyte, and others, apparently in part remobilized and reconcentrated in the process of postmagmatic alteration of pyroxenes and other minerals. In general, niobium is progressively enriched in successive phases, and tantalum is depleted relative to niobium.

Niobium and tantalum dissolved during the weathering cycle tend to be concentrated in hydrolyzates; however, an appreciable amount of niobium escapes to the ocean where it precipitates with clays and manganese oxide producing a degree of relative enrichment of niobium over tantalum in this environment. A similar fractionation of niobium and tantalum occurs in clays grading from arid source areas to a basin of marine deposition, as is shown by progressive decreases in the Nb:Ta ratio. Differences in solubility of organic niobium and tantalum compounds formed by weathering and differences in behavior of these elements in solution with titanium, zirconium, and others are possible causative factors. Hydrolyzate minerals derived from rocks originally rich in niobium and tantalum tend to be rich in these elements also.

Commercial recovery of niobium is mostly from columbite-tantalite, pyrochlore, and euxenite ores and possibly from rocks containing loparite and murmanite. The recovery of tantalum is chiefly from columbite-tantalite, microlite, or euxenite ores.

Future advances in the field of niobium-tantalum geochemistry will depend on the availability of a large number of additional, accurate analyses of rocks and minerals from well-studied complexes.

INTRODUCTION

The most comprehensive researches in the field of geochemistry of niobium and tantalum were made by Kalervo Rankama (1944, 1948), and most of the geochemical characteristics of these elements were outlined in these works. In the last 10 years the work on the geochemistry of these elements has been dominated largely by Russian scientists working principally in the Institute of Mineralogy, Geochemistry, and Crystal Chemistry of Rare Elements and the V. I. Vernadskii Institute of Geochemistry and Analytical Chemistry, both in Moscow. Despite the large volume of literature on the subject since Rankama's work, concepts in the field have not changed greatly, although many principles have been verified or modified slightly as a result of the accumulation of greater amounts of data and more accurate data. The chief deterrent in the advancement of knowledge has been the lack of analytical data in the very low levels of concentration of these elements as found in ordinary rocks.

This report is chiefly a summary of works published since those of Rankama and is not a product of original research. Comprehensive works of M. V. Kuz'menko (1961, 1964) and E. M. Es'kova (1964) have furnished considerable substance to this summary. Our purpose has been to review the mode of occurrence of niobium and tantalum and point out characteristics of geochemical behavior under certain geological conditions. No attempt has been made to discuss specific ore deposits or to delve deeply into that subject, but rather to summarize what is known of the geochemical characteristics of these elements and their occurrence in various types of minerals, rocks, and ores. A glossary of niobium and tantalum minerals is included, and an extensive list of references on the geochemistry and mineralogy of these elements is given.

It is hoped that this review will serve to point out weaknesses in the knowledge of niobium and tantalum geochemistry and the areas where further geochemical research is needed.

We wish to express our gratitude to David Gottfried for discussing niobium and tantalum geochemistry many times with us and for making available unpublished data.

GENERAL GEOCHEMICAL CONSIDERATIONS

Niobium is a chemical element of atomic number 41 and atomic weight 92.91; tantalum has atomic number 73 and atomic weight 180.95. In nature both elements consist almost entirely of single isotopes

(Strominger and others, 1958). Niobium has one isotope, Nb^{93}. Tantalum has two isotopes, Ta^{181} and Ta^{180}, although Ta^{180} accounts for only about 0.01 percent of the element (Evans and others, 1955; White and others, 1955).

Niobium and tantalum are a pair of elements with strong geochemical coherence; that is, they are closely associated and are found together in most rocks and minerals in which they occur. Great preponderance of one element over the other more rarely occurs in certain types of rocks such as some nepheline syenites (niobium-rich) and lithium-bearing pegmatites (tantalum-rich) or in some rocks modified by metasomatic processes.

The principal reasons for such coherence are the similar ionic radii and the identical valence states of the two elements, $Nb^{+5} = 0.69$ A and $Ta^{+5} = 0.68$ A, which apparently are fundamental parameters controlling entry of the elements into crystal structures. These elements are found in the quinquevalent state in most naturally occurring compounds. The slightly smaller ionic radius of Ta^{+5} than that of the much lighter Nb^{+5} is a result of the lanthanide contraction. (See Rankama and Sahama, 1950, p. 107–112.)

Both niobium and tantalum are lithophilic elements, showing a strong affinity for oxygen and are enriched in the silicate crust of the earth (Rankama and Sahama, 1950, p. 88). Most niobium-tantalum minerals are oxides, although some rare silicates and one borate of these elements are known. Niobium and tantalum occur also in minor amounts in many oxide, tungstate, phosphate, and silicate minerals of other elements. In these minerals, niobium and tantalum are closely associated with titanium, tungsten, tin, zirconium, and hafnium for which they commonly substitute isomorphously by virtue of the similarity of their ionic radii and other physical properties. Commonly occurring in the same minerals with niobium and tantalum or in coexisting minerals in the same rocks are uranium, thorium, rare earths, iron, manganese, bismuth, and many other elements.

ABUNDANCE OF NIOBIUM AND TANTALUM

CRUSTAL ABUNDANCE

Early estimates of the crustal abundance of niobium and tantalum, which accompanied the abundance figures for many other major and minor elements, were hardly more than guesses and had little analytical basis. It was not until the 1930's that emission and X-ray fluorescent spectrographic techniques were sufficiently developed for practical determinations of these elements in low concentrations. Average percentages of the elements in the earth's crust (clarke values) for niobium and tantalum as estimated by various workers in geochemistry are listed in table 1. The values of Georg Von Hevesy and coworkers, and of Ida and Walter Noddack were the first to be based on real analytical determinations, but these values ranged lower than present day accepted values; however, the Noddacks' values were based chiefly on analyses of meteorites which are now known to contain less of these elements than most crustal rocks. The works of V. M. Goldschmidt and Kalervo Rankama formed the principal basis for modern values, near 20 ppm and 2 ppm for niobium and tantalum respectively. The monumental works of Rankama have been modified only slightly as methods and accuracy have improved. More recently A. P. Vinogradov and S. R. Taylor established clarke values for all the elements by combining the average values for particular elements in granite and in basalt. Vinogradov combined the elements in a 2:1 granite: basalt ratio, whereas Taylor used a 1:1 ratio. Such combinations of granite (or felsic rock) and basalt (or mafic rock) are considered by these geochemists to be representative of the earth's crust, and the values obtained for niobium and tantalum by this method compare favorably with the values obtained by Rankama by averaging analyses.

TABLE 1.—*Niobium and tantalum contents in the earth's crust (clarkes) according to different authors*

[Adapted from Rankama (1948)]

Author	Nb (ppm)	Ta (ppm)	Nb : Ta
Vogt (1898)[1]	1.0	1.0	
Clarke and Washington (1924)[1]	30	.000*n*	
Vernadskii (1924)[1]	1–0.1	10–1	
Behrend and Berg (1927)[1]	.04	.012	
Hevesy and others (1929)	40	30	1.33
Hevesy and others (1930)	.32	.24	1.33
Hevesy (1932)	.3	.2	1.5
Noddack and Noddack (1934)[1]	.0769	.0297	2.6
Goldschmidt (1937a)	15		
Goldschmidt (1937b)	20	(15)?	1.33
Van Tongeren (1938)[1]	10	5	2
Rankama (1941)[1]	37	13	2.07
Rankama (1944)		2.1	
Rankama (1948)	24	2.1	11.4
Mason (1958)	24	2	12
Vinogradov (1962)	20	2.5	8
Taylor (1964)	20	2	10

[1] Not listed in bibliographies of present report; see Rankama (1948).

Znamenskii (1957) pointed out that direct analytical determinations by Hevesy and coworkers are low because of (1) their not taking into account niobium and tantalum in biotite, (2) the rocks analyzed were not representative of the crust, and (3) niobium and tantalum were lost during chemical concentration procedures prior to analysis. Rankama's values, on the other hand, are slightly high because he assigned values equal to the limit of analytical sensitivity to samples in which these elements could not be detected.

LIMITATIONS OF DATA

The crustal averages, or clarkes, of niobium and tantalum and abundances of these elements in various rocks are beset with the same uncertainty of accuracy and validity as are those for many other minor elements. Problems involved in the computation of crustal averages and the controversy as to the validity of methods of computation and accuracy of results were reviewed recently by Fleischer and Chao (1960) and Parker (1967). It should be pointed out that no practical method of sampling representatively the entire crust of the earth has yet been devised. Most attempts to approximate the average composition with respect to most elements are subject to criticism on the basis of bias and unrepresentative sampling. The crustal composition of some minor elements such as niobium and especially tantalum is even more in doubt than many others because of the limited availability of accurate analytical data, owing to the difficulty of analysis and other factors.

Limiting factors in the study of the geochemistry of niobium and tantalum are the availability of analytical data, the accuracy of analytical procedures, and the adequacy of sampling. In recent years, certain minor elements have been determined routinely in some analytical laboratories as a supplement to the determination of the major elements. Commonly niobium has been reported among those elements determined, but rarely has tantalum been detected because of its relatively high detection limits and low abundance in ordinary rocks. These routine analyses for niobium, though useful in petrologic studies, commonly have been of insufficient accuracy and sensitivity for geochemical use in establishing the abundance of the element and its geochemical behavior in geologic processes. It has been necessary, therefore, to make analyses of niobium and tantalum specifically for geochemical purposes because the required data for these elements simply do not automatically accumulate as byproducts of other analytical work, as is the case for many of the more easily detected elements. The effect of this limitation, of course, is a considerable reduction in the amount of data that otherwise would be available to geochemists.

Accuracy of analyses has improved considerably in recent years through research on methods and modern instrumentation and through use of standard samples exchanged among laboratories. Techniques of analysis now considered to be satisfactory for determination of niobium at low levels of concentration are: chemical colorimetry (or spectrophotometry) (Grimaldi, 1960), spectrochemical analysis, optical emission spectrography (Herz and Dutra, 1960), and X-ray fluorescence spectrography. Techniques of mass spectrography (Taylor, 1965a, b) have recently been introduced but are used in only a few laboratories on an experimental basis at the present time. Techniques of analysis with the required sensitivity for the determination of tantalum at the level of concentration found in ordinary rocks are X-ray fluorescent spectrography (Rankama, 1944) and optical emission spectrography following chemical concentration, chemical colorimetry (spectrophotometry) (Dinnin, unpub. data), neutron activation analysis (Atkins and Smales, 1960), and mass spectrography. It should be pointed out that various procedures of concentration, purification, or extraction of elements by wet chemical means are common to all of these techniques. The analytical chemistry of niobium and tantalum was reviewed comprehensively by Moshier (1964).

Accuracy among the above named techniques and among different analytical laboratories can be assessed from the compilations (Fleischer, 1965) of analyses of the standard granite G–1 and standard diabase W–1 listed in table 2. Though some deviations occur, most of the niobium and tantalum determinations for G–1 are close to 20 ppm and 1.6 ppm respectively and for W–1 are near 10 ppm and 0.7 ppm respectively. Such correspondence between different techniques and ana-

TABLE 2.—*Analytical determinations of niobium and tantalum in standard granite G–1 and standard diabase W–1*

[Analytical data are in parts per million; a following number in parentheses indicates the number of determinations averaged]

Method	G–1		W–1		References; affiliation
			Niobium		
Chemical colorimetric	22	(10)	10	(10)	Grimaldi (1960); USGS.
Do	22	(3)	9	(9)	F. S. Grimaldi (written commun., 1961); USGS.
Do	23.1	(13)	10.2	(14)	Esson (1965); Univ. Manchester.
Spectrochemical	18				Paul Barnett (written commun., 1955); USGS.
Do	20				A. A. Chodos (written commun., 1955); California Inst. Technology.
Do	[1]19				A. T. Myers (written commun., 1958); USGS.
Spectrographic	18.5				Herz and Dutra (1960); USGS, and Inst. Technologia Indus., Belo Horizonte, Brazil.
Do	27	(18)	20	(20)	Rooke and Fisher (1962); Univ. Leeds, England.
X-ray fluorescence	20		9		T. K. Ball (written commun., 1964); Mineralog.-Geol. Mus., Oslo, Norway.
Mass spectrographic	4		4		Brown and Wolstenholme (1964); Associated Elec. Industries, Ltd., Manchester.
Do	21		5.4		Taylor (1965a); Australian Natl. Univ.
Do	20		4		Taylor (1965b); Australian Natl. Univ.
Recommended values	20		10		Fleischer (1965); USGS.
			Tantalum		
Neutron activation	1.59	(8)	0.48	(2)	Atkins and Smales (1960); Atomic Energy Research Establishment, Harwell, England.
Do	[2]1.33	(2)			Do.
Do	3.0	(8)	.93	(6)	Morris and Olya (1960); Brunel Coll., London.
Do	.9	(5)			Butler and Thompson (1962); Imperial Coll., London.
Do	1.3	(4)	.69	(4)	Hamaguchi and others (1962); Toyko Univ. Education.
Do			.67		G. E. Gordon (written commun., 1967); Univ. California, San Diego.
Mass spectrographic	2		.5		Brown and Wolstenholme (1964); Associated Elec. Industries, Ltd., Manchester.
Recommended values	1.6		.7		Fleischer (1965); USGS.

[1] Several.

[2] Samples ground by these authors.

lysts inspires a high degree of confidence in niobium and tantalum analyses from most of the laboratories concerned.

A high degree of confidence, however, does not extend to all previously published analyses. Part of the analytical data on niobium and tantalum published within the last 10 years is of doubtful accuracy. Some of it is presented without any accompanying information on its accuracy, precision, or limits of sensitivity, and in some cases even the analytical method by which values were determined is not given. Such lack of qualifying information shakes the confidence of geochemists in part of the available data and promotes doubt as to the correctness of the geochemical interpretation based on these data.

The adequacy of sampling is a factor that is hardly possible to assess from the literature alone. Whether or not the samples are truly representative of the body or group of rocks that they are claimed to represent rests entirely with the sampler and is a factor of considerable variation. Some types of rocks are represented by averages of a large number of samples, whereas others are represented by only a few. Geochemical interpretation based on the latter can be of doubtful validity especially if, in a group of a few samples, some samples happen to be atypical. Sampling can be misleading if classification of the sampled rocks is erroneous or inaccurate. Complete chemical analyses are not always available for rocks analyzed for niobium and tantalum, so that petrographic classification of various degrees of refinement commonly is used instead of a more exacting chemical classification. The multiplicity of petrographic names and the differences among systems of classification limit the usefulness of the geochemical data derived from such samples.

ABUNDANCE IN ROCKS

QUALIFYING STATEMENT

No attempt has been made in this report to revise the clarkes of niobium and tantalum. Some figures, however, on the abundance of these elements in different types of rocks can be assembled from the data published in the last several years, and these figures, even though beset with the uncertainties mentioned above, give a more accurate picture of abundances than has been available previously. These figures can be expected to be revised subsequently as more complete and more accurate data become available.

As compiled, the abundance figures of this report contain weaknesses and limitations against which the reader should be cautioned:

1. Some analyses probably are of low accuracy and precision.
2. Some rocks are no doubt imprecisely classified.
3. Most averages representing complexes or areas are not weighted according to the relative abundance of the constituent rocks.
4. Some averages of rock types are not based on typical or representative rocks.
5. Analyses from certain regions predominate so that some averages are biased geographically.
6. Averages of most rock types are based on too few analyses.

The contents of niobium and tantalum in different types of rocks have been compiled by several authors. Mentioned here are Goldschmidt (1937b), Rankama (1948), Turekian and Wedepohl (1961), and Vinogradov (1962). The averages obtained by these authors are assembled in table 3.

TABLE 3.—*Average niobium and tantalum contents, in parts per million, in different types of rocks, as given by previous authors*

	Goldschmidt (1937b)	Rankama [1] (1948)			Turekian and Wedepohl (1961)			Vinogradov (1962)		
	Nb	Nb	Ta	Nb:Ta	Nb	Ta	Nb:Ta	Nb	Ta	Nb:Ta
Monomineralic rocks		0. 3	0. 7	0. 4						
Mafic alkalic		14	1	14						
Ultramafic		16	1	16	16. 0	1. 0	16. 0	1. 0	0. 018	56 0
Eclogite		3	. 7	4						
Basalt					19	1. 1	17	20	. 48	42
Gabbro	8. 0	19	1. 1	17						
Diorite	24	3. 6	. 7	5				20	. 7	29
Granite, high Ca	40	21	4. 2	5	20	3. 6	5. 6	20	3. 5	5 7
Granite, low Ca					21	4. 2	5			
Syenite		35	2	18	35	2. 1	17			
Nepheline syenite	160	315	. 8	384						
Clays, shales		15	2. 5	6	11	. 8	14	20	3. 5	5. 7
Sandstone					. 0X	. 0X				
Carbonate rocks					. 3	. 0X				
Deep sea carbonate					4. 6	. 0X				
Deep sea clay		8	<. 8	10	14	. X				
Chemical sediments		. 4	. 2	2						
Organogenic sediments		. 6	. 2	3						

Recomputed from Rankama's data.

A number of modern analyses for niobium and tantalum have been gathered from the literature during the present study. They are assembled under major rock types as follows: granite, quartz monzonite, and granodiorite, and volcanic rocks of similar chemical composition; sodic and alkalic granite and rhyolite of similar chemical composition; syenite and trachyte; nepheline syenite, phonolite, and other nepheline-bearing felsic rocks; other feldspathoidal rocks; gabbro, basalt, and alkalic basalt and gabbro; ultramafic rocks; sedimentary rocks; and meteorites and tektites.

IGNEOUS ROCKS

The abundance tables are useful in bringing out the relations between niobium and tantalum contents and the various types of rocks. Niobium is most abundant in alkalic rocks; namely nepheline syenite, syenite, and feldspathoidal rocks, and in alkalic mafic and ultramafic rocks. Niobium content is also high in sodic or alkalic granite. Within the alkalic group of rocks, nepheline syenite and mafic alkalic rocks carry the most niobium. Tantalum generally accompanies niobium, but the amount is about one-tenth to one-fifteenth that of niobium in most rocks other than some nepheline syenites and related alkalic rocks. The abundance of tantalum is high in some of the Russian alkalic rocks but is extremely low in some niobium-rich alkalic complexes in other parts of the world.

Another factor of interest suggested by abundance tables is the variation of the niobium-tantalum content in similar types of rocks from massif to massif. In some comparisons there is actually greater difference between the content of these elements in rocks of the same general class from different massifs than between the average contents of contrasting rock types. As an example, nepheline syenite from the Lovozero massif, U.S.S.R., reaches niobium values of over 1,000 ppm, whereas nepheline syenite from the Shonkin Sag, Mont., ranges from 15 to 56 ppm. Averages in contrasting rocks range from 17 ppm in gabbro-basalt to 173 ppm in nepheline syenite. Variations among alkalic complexes are shown by the average contents of niobium and tantalum in some nepheline syenite massifs of the U.S.S.R. (table 22). Niobium and tantalum contents range from about 900 ppm and 70 ppm respectively for the Lovozero massif as a whole to 100 ppm and 8 ppm respectively for the Il'men Mountains. Values near 100 ppm niobium are averages for the Khibina and Koisk massifs. All of these nepheline syenite massifs have niobium and tantalum contents that considerably exceed the clarke values.

The contents of niobium and tantalum in granites, quartz monzonites, and granodiorites are given in table 4 and summarized in table 5. Twenty-eight plutons or occurrences have an average niobium content of 16 ppm, ranging from 0.9 to 39 ppm. This average value is slightly lower than those near 20 ppm calculated previously by Rankama, Turekian and Wedepohl, and Vinogradov (table 3). Only a few granitic plutons have been analyzed for tantalum; 13 of them listed in table 4 average 1.3 ppm tantalum. These same 13 plutons average only 12 ppm niobium and their average Nb:Ta ratio is 9.2. Znamenskii (1964) proposed weighted values for Russian granites (Nb =14 ppm; Ta =1.1 ppm) which are close to these figures. Rhyolite, rhyodacite, and quartz latite from nine localities average about 28 ppm niobium and seem richer in niobium than their chemically equivalent plutonic rocks.

Sodic and alkalic granites represented by 20 plutons throughout the world range from 14 to 350 ppm niobium and average about 110 ppm (tables 6, 5). Twelve of these in which tantalum has been determined, however, average only 47 ppm niobium and 3.9 ppm tantalum and have an average Nb:Ta ratio of 12. Inasmuch as the analyses from the eight plutons excluded from the latter averages include some of the highest niobium values, their tantalum contents, if known, probably would raise the tantalum average considerably. Alkalic rhyolites from four localities range from 30 to 260 ppm niobium and average 97 ppm. Granites and rhyolites of these types are certainly enriched in niobium and the granites are enriched in tantalum. Although data are lacking, the rhyolites are probably enriched in tantalum also.

Considerable analytical data are available for niobium in nepheline syenites and phonolites, but a limited amount is available for tantalum. The latter element is almost entirely dominated by tantalum analyses from the Lovozero massif, U.S.S.R., and is subject to considerable regional bias. The Nb:Ta ratio shown at Lovozero may not be typical of other alkalic complexes. In fact, some minerals from complexes such as Magnet Cove and the Kaiserstuhl suggest that a much higher Nb:Ta ratio exists, but sufficient analyses are not yet available to show that the relation holds true for the alkalic rocks as a group. A great variation in niobium content in these rocks is shown in table 7, ranging from 17 to 1,053 ppm; a meaningful average is difficult to obtain from such a spread of values. The average niobium content of nepheline syenite from 20 listed plutons or complexes is 173 ppm, but the average is about 149 ppm if the rich Lovozero rocks are excluded (tables 8, 5). Three plutons or complexes in which both niobium and tantalum analyses are given average 135 ppm Nb and 11 ppm Ta, and the Nb:Ta ratio is 12. These niobium values are considerably less, and the tantalum is greater than the values of Rankama (1944, 1948) for

Table 4.—*Niobium and tantalum contents of some granites, quartz monzonites, and granodiorites, and volcanic rocks of similar chemical composition*

Rocks, location	Number of analyses or samples represented	Nb (ppm)	Ta (ppm)	Nb:Ta ratio	References
Plutonic rocks					
Granite, granodiorite, Kalba, U.S.S.R	3		[1] 2.0		Kuz'menko (1964, table 203).
Kulinda, Baikal region, U.S.S.R	1		[1] 16		Do.
central Kazakhstan, U.S.S.R	1		[1] 8.2		Do.
Susamyr batholith, U.S.S.R	190	24.0	1.9	12.0	Gerasimovskii and Karpushina (1965), Znamenskii (1964).
Alaskite granite, Slyudyanka, U.S.S.R	9	2.4	[2] <0.8		Znamenskii (1964).
Granite, Mamsk-Chuesk, Bodaibensk, U.S.S.R		0.9	<0.4		Do.
Mamsk-Oronskii complex, U.S.S.R		1.2	<0.5		Do.
Konkudero-Mamakanskii, U.S.S.R	11	1.0	<0.5		Do.
Kalbin, E. Kazakhstan, U.S.S.R	14	17	2.1	8	Do.
Korosten, Ukraine, U.S.S.R	7	10	<1.1		Do.
Urik-Oka, E. Sayan Mtns., U.S.S.R	4	12	<0.8		Do.
Kaibsk, Kazakhstan, U.S.S.R	20	16	1.1	15	Do.
Quartz monzonite, Rubidoux Mtn., Calif	2	5.4	0.42	13	Gottfried, David (U.S.G.S.; written comm., 1965).
Granite, G–1 standard		20	1.6	13	Fleischer (1965).
Fennoscandian	12	7	[3] 5.8	1.2	Data averaged from Rankama (1944, 1948).
Granite (rapakivi), Finland	9	39	[3] 1.7	23	Do.
Granodiorite, granite, etc., Kokchetav uplift, U.S.S.R.	99	25.4			Podol'skii and Serykh (1964).
Do	31	20			Do.
Alaskite, leucogranite, etc., Kokchetav uplift, U.S.S.R.	68	37			Do.
Granite and microgranite, S. Rhodesia	6	[1] 96			Cox and others (1965).
Granite, Paraguay	1	10			Eckel (1959).
Aplite, Paraguay	2	20			Unpub. data, U.S.G.S.
Granite aplite, Montana	4	13			Do.
Quartz monzonite, Montana	4	7			Do.
Quartz porphyry, Idaho	1	28			Do.
Granite porphyry, Idaho	1	28			Do.
Alaskite, Idaho	1	15			Do.
Granite, Idaho	1	20			Do.
Granodiorite, California	2	20			Do.
Quartz monzonite, California	5	20			Do.
Granite, California	2	15			Do.
Granodiorite, Johnston County, Okla	5	20			Do.
Average		16			
Average, analyses with both Nb, Ta reported.		12	1.3	9.2	
Volcanic rocks					
Rhyolite, S. Rhodesia	3	[1] 110			Cox and others (1965).
Pitchstone, Iceland	31	23			Carmichael and McDonald (1961).
Rhyolite porphyry, Paraguay	1	10			Eckel (1959).
Rhyolite and quartz latite, Oregon	3	30			Unpub. data, U.S.G.S.
Rhyolite, eastern Idaho	7	56			Hamilton (1966).
northwestern Wyoming	8	30			Hamilton (1963).
New Mexico	12	33			Unpub. data, U.S.G.S.
Rhyodacite-dacite, quartz latite, New Mexico	15	29			Do.
Rhyolite, Nevada	15	26			Cornwall (1962).
Quartz latite, Craters of the Moon, Idaho	2	[1] 300			Unpub. data, U.S.G.S.
Quartz latite porphyry, Nevada	9	18			Do.
Average		28			

[1] Not included in averages.
[2] Figures shown as < are averaged at half value.
[3] Some figures given by Rankama asl ess than a certain value were averaged at half that value.

TABLE 5.—*Abundance of niobium and tantalum in different magmatic rocks*

Rocks, location	Nb (ppm)		Ta (ppm)		Nb:Ta
	Range	Average	Range	Average	
Granites, quartz monzonite, granodiorite (table 4):					
28 plutons or occurrences	0. 9–39	22			
13 plutons	. 9–39	12	<0. 4–5. 8	1. 3	9. 2
Rhyolite, quartz latite, rhyodacite, and pitchstone (table 4):					
9 different areas	18–56	28			
Sodic and alkalic granites (table 6):					
20 plutons	14–350	109			
12 plutons (included above)	14–150	47	1–9. 2	3. 9	12
Sodic and alkalic rhyolites (table 6):					
4 different areas	30–260	97			
Nepheline syenite and related rocks (tables 7, 8):					
20 plutons or complexes	44–628	173			
5 plutons or complexes			4–52	21	
3 complexes (excluding Lovozero)	44–250	135	4–21	11	12
Lovozero (average for massif)	320–1053	628	29–94	52	12
19 plutons or complexes (excluding Lovozero)	44–410	149			
Syenites and trachytes (table 9):					
15 analyses	20–210	95			
4 analyses, different areas	105–210	154	8. 7–18	14	11
Gabbroic and basaltic rocks, tholeitic, etc. (table 11):					
16 analyses or averages, different areas	2. 3–35	17			
7 analyses or averages, different areas	2. 2–29	9	. 19–2. 8	. 9	10
Gabbroic and basaltic rocks, alkalic (table 11):					
10 analyses or averages	20–113	73			
Feldspathoidal rocks (table 10):					
20 analyses	13–1016	199			
Ijolite-meltiegite		1016		90	11. 3
Ijolite-urtite (Lovozero)		572		54	10. 6
Ultramafic rocks (table 12):					
Kimberlites, 3 areas	94–240				
Olivinites, Kola Peninsula	. 6–1050		<. 6–82		
Pyroxenite, Kola Peninsula	5. 4–379		. 55–47		
Pyroxenite, Iron Hill, Colo		255			
Alkalic ultramafic rocks, Kola Peninsula	134–518		13. 2–59. 6		

TABLE 6.—*Niobium and tantalum contents of some sodic and alkalic granites and rhyolites of similar chemical composition*

Rocks, location[1]	Nb (ppm)	Ta (ppm)	Nb:Ta	References
Plutonic rocks				
Alkalic granite, Kola Peninsula, U.S.S.R	14	1. 3	10. 7	Gerasimovskii and Karpushina (1965).
Do	30	2. 3	13	Do.
Alkalic granite, Kiev, Kola Peninsula, U.S.S.R	26	2. 5	10. 4	Do.
Do	35	3. 5	10	Do.
Soda granite, Lunyo, Uganda	350			Knorring (1960).
Alkalic granite, Liruei, Nigeria	80	6. 5	12	Butler and Smith (1962).
Amo, Nigeria	70	5. 1	14	Do.
Mount Tremont, N. H	150			Do.
Hastingsite granite, Jackson Falls, N. H	50	8. 1	6. 2	Do.
Alkalic granite, Kungnät, Greenland	275			Do.
Rockall, N. Atlantic	150	4. 3	35	Do.
Biotite granite (Conway), Redstone, N. H	50	9. 2	5. 4	Do.
Alaskite, Ognitskii complex, U.S.S.R. (3)	17. 3	1. 6	10. 8	Kovalenko and others (1964).
Riebeckite granite, Ognitskii complex, U.S.S.R. (3)	13. 7	1. 0	13. 7	Do.
Ognitskii complex, U.S.S.R. (4)	22. 7	1. 0	22. 7	Do.
Albite granite, Attu Islands, Aleutians (1)	30			Unpub. data, U.S.G.S.
Riebeckite(?) granite, Wichita Mountains, Okla. (20)	71			Do.
Riebeckite granite, Brewster County, Tex. (1)	250			Do.
Mount Rosa, Colo. (3)	267			Do.
Conway, N. H. (2)	225			Do.
Average	109			Do.
Average, analyses with both Nb and Ta reported	47	3. 9	12	Do.
Volcanic rocks				
Alkali rhyolite, soda rhyolite, New Mexico (20)	61			Unpub. data, U.S.G.S.
Alkali rhyolite, Oregon	30			Do.
Riebeckite rhyolite, Brewster, County Tex. (7)	260			Do.
Jeff Davis County, Tex. (2)	35			Do.
Average	97			

[1] Numbers in parentheses refer to number of analyses averaged.

TABLE 7.—*Niobium and tantalum contents of some nepheline syenites, phonolites, and other nepheline-bearing felsic rocks*

Rocks, location [1]	Nb (ppm)	Ta (ppm)	Nb:Ta	References
Miaskite, Vishnevye Mts., U.S.S.R.	250	21	12	Es'kova (1959).
Nepheline syenite, Borsuksai, U.S.S.R.	410	20	20	Kuz'menko (1964, table 203).
Il'men Mts., U.S.S.R.	110	8	13	Do.
hydrosodalite syenite, Lovozero, U.S.S.R. (18).	320	29	11	Gerasimovskii and others (1966).
Foyaite, Lovozero, U.S.S.R. (20)	702	49. 5	14. 4	Do.
Lujavrite, Lovozero, U.S.S.R. (21)	607	59	10. 3	Do.
Amphibole lujavrite, Lovozero, U.S.S.R. (7)	760	52	14. 6	Do.
Eudialyte lujavrite, Lovozero, U.S.S.R. (16)	1053	94	11. 2	Do.
Porphyritic lujavrite, Lovozero, U.S.S.R. (5)	440	33	13. 3	Do.
Do	980	85	11. 5	Do.
Poikilitic sodalite syenite, Lovozero, U.S.S.R. (6)	490	32	15. 3	Do.
Phonolite, Lovozero, U.S.S.R.	399	37. 5	10. 6	Do.
Pseudoleucite phonolite, Lovozero, U.S.S.R.	530	50	10. 6	Do.
Nepheline syenite, Karasyrsk, U.S.S.R.	160	<10		Es'kova (1960).
Tatarsk, U.S.S.R.	140			Do.
Karsk, U.S.S.R.	100			Do.
Foyaite, Khibina, U.S.S.R.	140			Borodin (1955).
Khibinite, Khibina, U.S.S.R.	56			Do.
Rischorrite, Khibina, U.S.S.R.	56			Do.
Nepheline syenite, Kishingar, India	44	4	11	Gerasimovskii and Karpushina (1965).
Shonkin Sag, Mont.	25			Gottfried and others (1961).
Aegirine syenite, Shonkin Sag, Mont.	42			Do.
Aplitic syenite, Shonkin Sag, Mont.	43			Do.
Transition rocks, Shonkin Sag, Mont. (3)	20			Do.
Mafic phonolite, Shonkin Sag, Mont.	22			Do.
Nepheline syenite, White Mountain Plutonic–Volcanic Series, N. H.	179			Do.
Sericitized syenite, Bearpaw Mts., Mont.	400			Pecora (1962).
Sericitized syenite dike, Bearpaw Mts., Mont.	60			Do.
Nepheline syenite, Iron Hill, Colo.	150			Temple and Grogan (1965).
Nepheline syenite, Arkansas bauxite region	200			Gordon, Tracey, and Ellis (1958).
Do	100			Do.
Pulaskite, Arkansas bauxite region	90			Do.
Feldspathic trachyte, Magnet Cove, Ark.	200			Erickson and Blade (1963).
Pseudoleucite syenite, Magnet Cove, Ark.	74			Do.
Nepheline syenite, Magnet Cove, Ark.	99			Do.
Pseudoleucite syenite, Magnet Cove, Ark.	96			Do.
Nepheline syenite, Magnet Cove, Ark.	87			Do.
Tinguaite, Magnet Cove, Ark.	220			Do.
Sodalite trachyte, Magnet Cove, Ark.	200			Do.
Nepheline syenite, Monchique, Portugal [2]	420	. 8	525	Rankama (1944, 1948).
Phonolite, Unterwiesenthal, Germany [2]	200	. 8	250	Do.
Kaiserstuhl, Germany (5)	400			Wambeke and others (1964).
tinguaite, Kaiserstuhl, Germany (10)	285			Do.
Nepheline syenite, Greenland (6)	73			Upton (1964).
Wheatland County, Mont. (3)	44			Unpub. data, U.S.G.S.
Marathon County, Wis. (3)	175			Do.
Fremont County, Colo. (3)	107			Do.
Phonolite, Chouteau County, Mont. (4)	20			Do.
Meagher County, Mont. (2)	75			Do.
Leucite phonolite, Sweetwater County, Wyo. (17)	58			Do.
Average	235			
Average, Lovozero massif	628	52	12	
Average excluding Lovozero massif	134			

[1] Numbers in parentheses refer to number of analyses averaged.
[2] Values for these rocks not included in averages.

nepheline syenite, which incidentally are based on analyses of only two samples.

Syenites and trachytes also have niobium and tantalum contents which are considerably higher than clarke values (tables 9, 5). Analyses from 16 different occurrences give an average niobium content of 95 ppm; however, for four different areas, analyses in which both niobium and tantalum are given average 154 ppm niobium and 14 ppm tantalum, and the Nb:Ta ratio is 11. Most of these analyses are of rocks from alkalic complexes and perhaps should correctly be averaged with the nepheline syenites.

Melanocratic and leucocratic feldspathoidal rocks such as ijolites, urtites, and others, characteristically are high in niobium, but some of these rocks from Magnet Cove, Ark., for example, contain as little as 20 ppm niobium (table 10). Twenty analyses or average analyses from different alkalic complexes average about 200 ppm and range from 13 to 1,016 ppm niobium. The average tantalum contents of ijolite-urtite and

TABLE 8.—*Niobium and tantalum contents of nepheline syenites and phonolites from different massifs*

[Data summarized from table 7]

Massifs represented [1]	Nb (ppm)	Ta (ppm)	Nb:Ta
Lovozero, U.S.S.R. (10)	628	52	12
Kishingar, India (1)	44	4	11
Vishnevye Mts., U.S.S.R. (1)	250	21	12
Borsuksai, U.S.S.R. (2)	410	20	21
Il'men Mts., U.S.S.R. (1)	110	8	13
Shonkin Sag, Mont. (11)	25		
White Mountain Plutonic-Volcanic Series, N. H. (1).	179		
Bearpaw Mts., Mont. (2)	230		
Iron Hill, Colo. (1)	150		
Arkansas bauxite region (3)	130		
Magnet Cove, Ark. (7)	140		
Karasyrsk, U.S.S.R. (1)	160	<10	
Tatarsk, U.S.S.R. (1)	140		
Koisk, U.S.S.R. (1)	100		
Khibina, U.S.S.R. (3)	85		
Kaiserstuhl, Germany (10)	285		
Tugtutôq, Greenland (6)	73		
Wheatland County, Mont. (3)	44		
Marathon County, Wis. (3)	175		
Fremont County, Colo. (3)	107		
Average	173		
Average excluding Lovozero massif	149		

[1] Numbers in parentheses refer to number of analyses or types of rocks averaged.

ijolite-melteigite rocks from the Lovozero massif are 54 ppm and 90 ppm, respectively, and the Nb:Ta ratios average about 11.

Two groups of gabbroic and basaltic rocks are distinguishable by their niobium contents (table 11). One group, which includes tholeiitic basalts, contains an average niobium content of 17 ppm (16 occurrences). Seven occurrences in which both niobium and tantalum were determined have averages of 9 ppm niobium and 0.9 ppm tantalum, and a Nb:Ta ratio of 10. The other group, which includes alkalic basalts and gabbros, contains a much higher average niobium content of 73 ppm. Values range from 20 to 113 ppm. No tantalum analyses are available.

Ultramafic rocks show considerable variation in niobium and tantalum even in similar types from the same province (table 12). It is difficult to distinguish alkalic and nonalkalic types. Peridotites tend to contain very low contents of both elements. A Kola Peninsula peridotite contains 5.5 ppm niobium and 0.49 ppm tantalum and has a Nb:Ta ratio of 11. Olivinites from Kola range from a fraction of 1 ppm niobium and tantalum to 1,050 ppm niobium and 82 ppm tantalum, the latter rocks containing abundant titanomagnetite. Pyroxenites range from 5.4 ppm niobium and 0.55 ppm tantalum (Nb:Ta≈10) from the Kola Peninsula to 255 ppm niobium from Iron Hill, Colo. Kimberlites contain high abundance levels of niobium, averaging 94 and 160 ppm for parts of the U.S.S.R. and 240 ppm for Basutoland.

SEDIMENTARY ROCKS

The abundance figures of niobium and tantalum in sedimentary rocks are listed in table 13. Highest niobium contents are found in deep-sea manganese nodules and sediments and in bauxites. Highest tantalum contents are found in marine clays and bauxite, although the high Nb:Ta ratio in deep-sea deposits indicates the paucity of tantalum in the deep-sea enviromnent. Because of the chemically resistant nature, high specific gravity, and hardness of some of the common niobium-tantalum minerals, as well as the similar nature of some common minerals of titanium and zirconium, these minerals commonly are locally enriched in sand-

TABLE 9.—*Niobium and tantalum contents of some syenites and trachytes*

Rock, location [1]	Nb (ppm)	Ta (ppm)	Nb:Ta	Reference
Biotite syenite, Vishnevye Mts., U.S.S.R.	170	16	11	Es'kova (1959).
Aegirine syenite, Vishnevye Mts., U.S.S.R.	130	12	11	Do.
Nordmarkite, Greenland	105	8.7	12	Gerasimovskii and Karpushina (1965).
Syenite, Kola Peninsula, U.S.S.R.	210	18	12	Do.
Trachyte, Guadalupe Island	120			Engel and others (1965).
Do	140			Do.
Trachyte, Hocheifel, West Germany (5)	95			Huckenholz (1965).
Trachyte, Magnet Cove, Ark.	100			Erickson and Blade (1963).
Do	20			Do.
Biotite syenite, Il'men Mts., U.S.S.R.	77			Es'kova (1964, table 187).
Syenite, Chouteau County, Mont. (4)	20			Unpub. data, U.S.G.S.
Brewster County, Tex.	88			Do.
Fremont County, Colo. (4)	25			Do.
Trachyte, Meagher County, Mont. (2)	20			Do.
Brewster County, Tex. (6)	100			Do.
Potash trachyte, Uganda	[2] 400			Sutherland (1965).
Average	95			
Average with both Nb and Ta reported	154	14	11	

[1] Numbers in parentheses refer to number of analyses averaged.
[2] Not included in average.

TABLE 10.—*Niobium and tantalum contents of some feldspathoidal rocks*

Rocks, location [1]	Nb (ppm)	Ta (ppm)	Nb:Ta	Reference
Essexite, Illamaussaq, Greenland	440			Gerasimovskii and Karpushina (1965).
Jacupirangite, Magnet Cove, Ark	20			Erickson and Blade (1963).
Ijolite, Magnet Cove, Ark	50			Do.
Do	150			Do.
Do	20			Do.
Melteigite, Magnet Cove, Ark	140			Do.
Ijolite-melteigite, Lovozero massif, U.S.S.R. (2)	1016	90	11. 3	Gerasimovskii and others (1966).
Ijolite-urtite, Lovozero massif, U.S.S.R. (11)	572	54	10. 6	Do.
Ijolite, Khibina, U.S.S.R	210			Borodin (1955).
Iron Hill, Colo	250			Temple and Grogan (1965).
Essexite, Kaiserstuhl, Germany (3)	128			Wambeke and others (1964).
Tephrite, Kaiserstuhl, Germany (5)	115			Do.
Essexite porphyry, monchiquite, Kaiserstuhl, Germany (5)	105			Do.
Bergalite, Kaiserstuhl, Germany (2)	430			Do.
Mondhaldeite, gauteite, shonkinite, Kaiserstuhl, Germany (5)	140			Do.
Olivine nephelite, Kaiserstuhl, Germany (5)	75			Do.
Shonkinite, Shonkin Sag, Mont. (2)	15			Do.
Do	13			Do.
Shonkinite, Paraguay (2)	65			Eckel (1969).
Chouteau County, Mont. (2)	20			Unpub. data, U.S.G.S.
Average	199			
Range	13–1016			

[1] Numbers in parentheses refer to number of analyses averaged.

TABLE 11.—*Niobium and tantalum contents of some gabbroic, basaltic, and alkalic basaltic rocks*

Rock, location [1]	Nb (ppm)	Ta (ppm)	Nb:Ta	Reference
Gabbro and basalt				
Basalt, Bombay, India	29	2. 8	10	Gerasimovskii and Karpushina (1965).
Olivine basalt, Guadalupe Island	30			Engel and others (1965).
Gabbro, Skaergaard, Greenland (9)		. 92		Atkins and Smales (1960).
Gabbro (San Marcos), southern California (3)	4. 7	. 19	25	Gottfried, David (written commun., 1965).
W–1 diabase, Centerville, Va	10	. 7	14	Fleischer (1965).
Tonalite, southern California (2)	5. 3	. 45	12	Gottfried, David (written commun., 1965).
Gabbro-diorite, Chernogor massif, Siberia	9. 8	1	10	Gerasimovskii and Karpushina (1965).
Gabbro, Kokchetav uplift, U.S.S.R	7			Podol'skii and Serykh (1964).
Diabase, Victoria Land, Antarctica (2)	20			Hamilton (1965).
Diorite pegmatite, Victoria Land, Antarctica (1)	30			Do.
Gabbro, Victoria Land, Antarctica (3)	20			Do.
Basalt, andesine basalt, New Mexico (8)	26			Unpub. data, U.S.G.S.
Diabase, Nevada (2)	35			Do.
Basalt Nevada (2)	25			Do.
Snake River, Idaho (5)	14			Do.
Dolerite, Siberian Platform, U.S.S.R. (10) [2]	3. 2	. 46	7	Znamenskii and others (1965).
Basalt, Siberian Platform, U.S.S.R. (18)	2. 2	. 48	4. 6	Do.
Average	17			
Average in which both Nb and Ta are reported	9	. 9	10	
Alkalic basalt and gabbro				
Alkalic basalt, eastern Pacific Ocean (4)	75			Engel and others (1965).
Alkalic olivine basalt, Hocheifel, Germany (7)	65			Huckenholz (1965).
Hawaiite, Hocheifel, Germany (4)	69			Do.
Mugearite, Hocheifel, Germany (3)	84			Do.
Hauyne alkalic basalt, Hocheifel, Germany	110			Do.
Analcime olivine metagabbro, Magnet Cove, Ark	20			Erickson and Blade (1963).
Theralite, Meagher County, Mont	61			Unpub. data, U.S.G.S.
Basalt, Southern Rhodesia (4)	91			Cox and others (1965).
Paraguay (2)	45			Unpub. data, U.S.G.S.
Trachybasalt, Tristan da Cunha (14)	113			Baker and others (1964).
Average	73			

[1] Numbers in parentheses represent number of analyses averaged.
[2] Weighted average representing 162 samples.

TABLE 12.—*Niobium and tantalum contents of some ultramafic rocks*

Rocks, location [1]	Nb (ppm)	Ta (ppm)	Nb:Ta	References
Olivinite, Kola Peninsula, U.S.S.R	0.6	<0.6		Rankama (1944, 1948).
Titanomagnetite olivinite, Kola Peninsula, U.S.S.R	1050	82	13	Do.
Olivinite, Kola Peninsula, U.S.S.R	7	.62	11	Gerasimovskii and Karpushina (1965).
Kola Peninsula and Karelia, U.S.S.R	394	45.6	8.7	Kukharenko and others (1965).
Biotite olivine rock, Harzburg, Germany	56	4.2	13	Rankama (1944, 1948).
Peridotite, Kola Peninsula, U.S.S.R	5.5	.49	11	Gerasimovskii (1965).
Alkalic ultramafic rocks, Kola Peninsula, U.S.S.R	134–518	13.2–59.6	8.7–10.2	Kukharenko and others (1961).
Pyroxenite, Kola Peninsula and Karelia, U.S.S.R	379	47.3	8.0	Kukharenko and others (1965).
Pyroxenite, Kola Peninsula, U.S.S.R		25		Kuz'menko (1964, table 203).
Do		16		Do.
Nepheline pyroxenite, Kola Peninsula and Karelia, U.S.S.R.	202	18.7	10.8	Kukharenko and others (1965).
Pyroxenite, Kola Peninsula, U.S.S.R	5.4	.55	10	Gerasimovskii and Karpushina (1965).
Pyroxenite, Iron Hill, Colo	290			Temple and Grogan (1965).
Do	220			Do.
Kimberlite, U.S.S.R. (349)	94			Kudryavtsev (1964).
Yakutia, U.S.S.R. (57)	160			Burkov and Podporina (1965).
Basutoland (14)	240			Dawson (1962).

[1] Numbers in parentheses refer to number of analyses averaged.

stones and conglomerates. Such accumulations, which constitute placers and fossil placers, are not listed in the table.

ABUNDANCE IN METEORITES AND TEKTITES

Ten samples of meteorites, including both the stony and the iron types, were analyzed by Rankama (1944, 1948). Only two samples of the stony meteorites had detectable niobium (0.3 and 2.1 ppm). None of the iron meteorites had niobium and none of the 10 samples had tantalum detectable by Rankama's methods. Atkins and Smales (1960) and Ehmann (1965), using neutron activation, determined the tantalum content of several chondritic meteorites to average 0.023 and 0.021 ppm respectively. The tantalum content of iron meteorites is at least an order less than that for stony meteorites, ranging from 0.0008 to 0.005 ppm (Atkins and Smales, 1960). Unfortunately, the niobium contents of these samples have not been determined; therefore, the Nb:Ta ratio cannot be computed. Vinogradov (1962) estimated the niobium and tantalum contents of chondrites to be 0.3 ppm and 0.02 ppm respectively and the Nb:Ta ratio to be 15. (See table 14.)

Ehmann (1965) also analyzed several tektites for tantalum by neutron activation. (See table 14.) These tektites range from 0.56 to 3.3 ppm tantalum, roughly in the range of ordinary rocks. So far as is known, no data on their niobium contents are available.

TABLE 13.—*Niobium and tantalum in some sedimentary rocks and other rocks or deposits*[1]

Material	Number of samples	Nb (ppm)	Ta (ppm)	Nb:Ta	References
"Minerogenic sediments" [1]	17	12	1.4	8.6	Rankama (1944, 1948).
Chemical sediments [2]	8	.4	.2	2	Do.
Organogenic sediments [3]	18	.6	.2	3	Do.
Deep-sea sediments [4]	7	40	1	40	Do.
Clay and sand sediments		20			Goldschmidt (1937b).
Clays and shales	10	10	<.9		Rankama (1944, 1948).
Deep sea clays and oozes	5	16	<4		Do.
Arid-environment clays, Russian Platform	199	13.3	.9	14.8	Pachadzhanov (1963).
Humid-environment clays, Russian Platform	155	20.1	2.4	8.4	Do.
Clays, average for Russian Platform	354	18.3	2	9.1	Do.
Manganese nodule, outer shell, *Challenger*	1	35			Rankama (1944, 1948).
Manganese nodule, *Albatross*	1	147			Do.
Manganese nodule core, Indian Ocean	1	7.6	2.3	3.3	Pachadzhanov and others (1963).
Manganese nodule, outer shell, Indian Ocean	1	29	.17	170	Do.
Bauxites, Hungary	4	35.6	5.1	7	Pachadzhanov (1964).
Bauxites, U.S.S.R	25	27.7	4.4	6.3	Do.
Bauxites	2	38	5	7.6	Rankama (1944, 1948).
Bauxite, Arkansas	46	450			Gordon and Murata (1952); Fleischer and others (1952).

[1] Includes sandstones, clays, shales, bauxites, etc.
[2] Includes iron ores and calcareous sinters.
[3] Includes limestones, cherts, coals, lignites, etc.
[4] Includes clays, oozes and manganese nodules.

Table 14.—*Niobium and tantalum contents of meteorites and tektites*

	Nb (ppm)	Ta (ppm)	Reference
Silicate meteorites			
Rhodite, Mikkeli	0.3	----------	Rankama (1948).
Olivine enstatite chondrite, Lake Labyrinth. South Australia.	2.1	----------	Do.
Johnstown, Colo		0.008	Atkins and Smales (1960).
Ness County, Kans		.022	Do.
Long Island, Phillips County, Kans		.027	Do.
Forest City, Iowa		.023	Do.
Chateau Renard		.027	Do.
Holbrook, Ariz		.025	Do.
Chandakaphur		.020	Do.
Bjurböle		.021	Do.
Tabory (Ochansk)		.018	Do.
Average for preceding 8 chondrites		.023	Do.
Average for 10 chondrites		.021	Ehmann (1965).
Vinogradov's average [1]	.3	.02	Vinogradov (1962).
Iron meteorites			
Canyon Diablo		0.002	Atkins and Smales (1960).
Henbury		.005	Do.
San Martin		.0008	Do.
Tektites			
Philippinite, Isabella site		0.74	Ehmann (1965).
Pugad Babuy site		3.3	Do.
Thailand tektite, Kan Luang Dong (unstrained type).		.61	Do.
Kan Luang Dong (ordinary type).		.56	Do.

[1] Nb:Ta=15.

ISOMORPHOUS SUBSTITUTION

Isomorphous substitution of niobium for tantalum in most minerals of these elements is well illustrated by the minerals listed in the glossary of this paper. Substitution in a more limited degree by niobium and tantalum for elements such as titanium, tin, tungsten, zirconium, and others is also well known in a host of minerals. It therefore seems appropriate to delve more deeply into the principles involved in isomorphous substitution and the nature of substitution as applied to these elements.

Isomorphous substitution (diadochy) among trace elements and their behavior during crystallization has been discussed in detail by Ringwood (1955a, b), and some of Ringwood's ideas have been applied by Herz and Dutra (1964). This slightly different approach to the subject of isomorphism seems appropriate for discussion here. In prior work, Goldschmidt (1937a, 1954) proposed the following rules governing the substitution of ions which relate the size of ions and their charges:

1. For two ions to be able to replace one another in a crystal structure, the ionic radii must not differ by more than 15 percent.
2. When two ions that possess the same charge but different radii compete for a lattice site, the ion with the smaller radius is preferentially incorporated.
3. When two ions that possess similar radii but different charges compete for a lattice site, the ion with the higher charge is incorporated.

Ringwood noted that Goldschmidt's rules did not always apply, and suggested that these rules do not adequately consider the partial covalent bonding that coexists with ionic bonding in most lattices. To allow for the partial covalent bonding, Ringwood utilized the property of electronegativity (Pauling, 1940) and thus formulated the following rule (Ringwood, 1955a, p. 193):

> Whenever diadochy in a crystal is possible between two elements possessing appreciably different electronegativities, the element with the lower electronegativity will be preferentially incorporated because it forms a stronger and more ionic bond than the other.

Ringwood found that the Goldschmidt rules commonly applied where electronegativities were nearly the same, but the above rule was applicable where electronegativities differed by one-tenth or more.

Ionic potential is a property closely related to electronegativity and can be used to express the same general relations inasmuch as it is a relative measure of ionic or covalent character of the chemical bond also. Ionic potential is defined as the cation charge, z, divided by the ionic radius, r, or z/r and is a value more conveniently computed than electronegativity. Ionic radii, electronegativities, and ionic potentials of niobium, tantalum, and some related elements are given in table 15.

Table 15.—*Physical constants of some elements*

Element	Atomic number	Charge	Ionic radius (A)	Electronegativity [1]	Ionic potential
Aluminum	13	+3	0.51	1.5	5.88
Titanium	22	+4	.68	1.6	5.88
Vanadium	23	+3	.74	1.4	4.06
Do	23	+5	.59	1.9	8.48
Iron	26	+2	.74	1.7	2.71
Do	26	+3	.64	1.8	4.69
Zirconium	40	+4	.79	1.5	5.07
Niobium	41	+5	.69	1.7	7.25
Molybdenum	42	+4	.70	1.6	5.71
Tin	50	+4	.71	1.8	5.64
Hafnium	72	+4	.78	1.3	5.13
Tantalum	73	+5	.68	1.5	7.35
Tungsten	74	+4	.70	1.6	5.71
Do	74	+6	.62	2	9.68

[1] Gordy and Thomas (1956).

Most univalent, divalent, and some of the larger trivalent ions of trace elements during crystallization exist free in the magma; and their crystallization can be interpreted satisfactorily in terms of ionic radius, ionic charge, and electronegativity or ionic potential according to the rules of Goldschmidt and of Ringwood that were given above. Ions with charges greater than these and some of the smaller trivalent ions, however, form complexes with oxygen, hydroxyl, fluorine, chlorine, and other anions, and these complexes maintain their identity during the crystallization process. Complex-forming ions reflect properties of the individual complexes more than they reflect properties of the central cation during crystallization (Ringwood, 1955b).

Elements whose ionic potentials are greater than 4.80 tend to form complexes, and the higher the ionic potential the more stable are the complexes formed. Values of ionic potential in some complex-forming ions range from $Ga^{+3}=4.83$ to $Cr^{+3}=25$; Nb^{+5} and Ta^{+5} have intermediate values (7.25 and 7.35 respectively). Cations of highest ionic potential seldom dissociate in the magma; however, cations such as Si^{+4}, Nb^{+5}, and Ta^{+5}, have high enough values to form stable complexes but, on the other hand, are also in the range of values where partial dissociation under certain conditions is possible.

Elements whose ionic potentials are less than 2.70 occur as free ions in the magma and do not form complexes, whereas elements ranging between 4.80 and 2.70 are transitional, behaving either as free ions or as complex formers depending on the composition of the magma.

The structures of most minerals crystallizing from magmas are based upon SiO_4 tetrahedra linked in various ways. Therefore, trace element complexes in the magma may either replace SiO_4 tetrahedra in silicate minerals or precipitate as separate phases. Ringwood modified the Goldschmidt rules to apply to diadochy between trace-element complexes and SiO_4 tetrahedra as follows:

1. On geometric grounds only complexes of the tetrahedrally coordinated type can substitute for SiO_4.
2. The larger the change on the central cation the smaller will be the tendency for tetrahedrally coordinated complexes to replace SiO_4 tetrahedra.
3. The larger the size of the cation the smaller will be the tendency for tetrahedrally coordinated groups to replace SiO_4 tetrahedra.

Pentavalent niobium and tantalum probably can form both the tetrahedral complexes, NbO_4^{-3} and TaO_4^{-3}, and the octahedral complexes, NbO_6^{-7} and TaO_6^{-7}. Although both forms possibly exist in the magma, the octahedral form is the one found in most niobium-bearing minerals. For example, the structure of some oxide minerals such as perovskite and columbite are formed basically from linked octahedrally coordinated groups and contain no tetrahedral groups at all. These octahedra are composed of titanium, iron, niobium, tantalum, and other cations in sixfold coordination with oxygen ions. Another niobium-bearing mineral, sphene, is made up of both tetrahedral and octahedral groups linked together with calcium ions filling the interspaces. The tetrahedra are SiO_4 groups and the octahedra contain titanium, niobium, tantalum, and other elements as central cations.

Neither the tetrahedral nor the octahedral complexes of niobium and tantalum would be easily incorporated into silicate minerals in substitution for the SiO_4 tetrahedral complexes if Ringwood's rules apply. The octahedral complexes would be ruled out on the basis of geometry alone, although substitution in octahedral positions in some silicate minerals is possible (for example, niobium in muscovites, probably in the aluminum position). Tetrahedral complexes of niobium and tantalum would be difficultly incorporated also because of the higher charge and considerably larger size of the niobium and tantalum cations with respect to the silicon cation. Hence, niobium and tantalum complexes would tend to accumulate in some felsic magmas during crystallization until sufficiently concentrated to allow precipitation, most likely as multiple oxide minerals. In some other magmas, especially mafic ones, however, these elements probably would tend to be scavenged by crystallizing accessory minerals of titanium or titanium and iron and thus would be dispersed and not concentrated during crystallization.

Although niobium, tantalum, titanium, zirconium, tin, tungsten, and other similar elements possibly are present in magmas as complexes with oxygen, hydroxyl, fluorine, and other anions, and may enter or form minerals in part as complexes, these elements can be considered as individual ions for the purpose of examining schemes of isomorphism and the electrostatic balances involved.

There are two types of isomorphism—isovalent and heterovalent (Kuz'menko, 1959). Isovalent isomorphism means the substitution of ions of similar ionic radius and the same ionic charge; heterovalent isomorphism is the substitution of ions of similar size but differing ionic charges.

The common mutual substitution of niobium and tantalum in most minerals of these elements is the isovalent type of isomorphism. The ions of these two elements are so similar in their properties that one seldom occurs in nature to the complete exclusion of the other.

Heterovalent isomorphism is extensive between niobium-tantalum and titanium, as well as among other elements such as zirconium, tin, tungsten, and some others. Where such substitution occurs the overall electrostatic neutrality of the mineral is preserved by the simultaneous substitution of ions of greater or lesser charge in other parts of the crystal lattice or by the development of lattice deficiencies or vacancies in either oxygen or cation positions (Aleksandrov, 1963).

Schemes of heterovalent isomorphism in niobium-tantalum minerals have been pointed out by many authors, notably Rankama (1944, 1948), Kuz'menko (1959, 1961), Es'kova (1960), and Kukharenko, Skrizhinskaya, Vainshtein, and Kakhana (1961). Some schemes of substitution that apply in either a major or minor degree in niobium-tantalum-bearing minerals are listed in table 16.

TABLE 16.—*Schemes of isomorphous substitution in niobium-tantalum-bearing minerals*

Scheme	Example
Ti	
$(Nb, Ta)^{+5}+Na^{+1}\leftrightarrow Ti^{+4}+Ca^{+2}$	Loparite, perovskite.
$(Nb, Ta)^{+5}+2Na^{+1}+RE^{+3}\leftrightarrow Ti^{+4}+3Ca^{+2}$	Sphene, irinite.
$(Nb, Ta)^{+5}+(Fe, Al)^{+3}\leftrightarrow 2Ti^{+4}$	Biotite.
$2(Nb, Ta)^{+5}+Fe^{+2}\leftrightarrow 3Ti^{+4}$	Rutile, tapiolite.
Zr	
$(Nb, Ta)^{+5}+Na^{+1}\leftrightarrow Zr^{+4}+Ca^{+2}$	Wöhlerite, zircon.
$2(Nb, Ta)^{+5}+Fe^{+2}\leftrightarrow 3Zr^{+4}$	Polymignyte.
$2(Nb, Ta)^{+5}+Ca^{+2}\leftrightarrow 2(Ti, Zr)^{+4}+(Th, U)^{+4}$	Zirconium betafite.
$(Nb, Ta)^{+5}+RE^{+3}\leftrightarrow 2Zr^{+4}$	Zircon.
$(Nb, Ta)^{+5}+Fe^{+3}\leftrightarrow 2Zr^{+4}$	Zircon, baddeleyite.
W	
$(Nb, Ta)^{+5}+Sc^{+3}\leftrightarrow W^{+6}+Fe^{+2}$	Wolframite.
Sn	
$2(Nb, Ta)^{+5}+Fe^{+2}\leftrightarrow 3Sn^{+4}$	Cassiterite.
Al, Si, Fe	
$(Nb, Ta)^{+5}+2(Mn, Mg)^{+2}\leftrightarrow 3Fe^{+3}$	Iron oxides.
$(Nb, Ta)^{+5}+2Mg^{+2}\leftrightarrow Al^{+3}+2Fe^{+3}$	Pyroxenes, amphiboles.
$(Nb, Ta)^{+5}+Na^{+1}+Al^{+3}\leftrightarrow Ca^{+2}+Fe^{+3}+Si^{+4}$	Aegirine.
$(Nb, Ta)^{+5}+Be^{+2}\leftrightarrow Al^{+3}+Si^{+4}$	Muscovite.
$(Nb, Ta)^{+5}+Li^{+1}\leftrightarrow 2Al^{+3}$	Muscovite.
Others	
$(Nb, Ta)^{+5}+Li^{+1}\leftrightarrow Mg^{+2}+Ti^{+4}$	Biotite, lepidolite.
$(Nb, Ta)^{+5}+(Ce, La)^{+3}\leftrightarrow 2Th^{+4}$	Thorite.
$(Nb, Ta)^{+5}+Si^{+4}\leftrightarrow P^{+5}+Ce^{+4}$	Monazite(?).
$(Nb, Ta)^{+5}+2Si^{+4}\leftrightarrow 2P^{+5}+RE^{+3}$	Erikite.

[1] RE=rare-earth elements.

An example is given in the table for each scheme, though some schemes apply to a great number of minerals, and more than one scheme may apply to the same mineral.

The most prevalent substitution of niobium and tantalum is for titanium. The close association of these elements has been long recognized. Fleischer, Murata, Fletcher, and Narten (1952) pointed out that the content of niobium was greatest in titanium minerals from alkalic rocks and granitic pegmatites and least in those from ordinary gabbro and anorthosite. Examination of the formulas of niobium-tantalum minerals in the glossary section of this report shows that a large proportion of these minerals have titanium as an integral part, commonly in isomorphous substitution for niobium and tantalum. Titanium minerals in which niobium and tantalum proxy for titanium are sphene, rutile, ilmenite, perovskite, and many others listed in the glossary. Certain pyroxenes, amphiboles, and titaniferous micas have been shown to contain minor amounts of niobium and tantalum, presumably also present in the titanium position in the lattices of these minerals. The average atomic ratio of niobium to titanium in titanium minerals is about 1:3,000 and the ratio of tantalum to titanium is 1:7,000 (Hevesy and others, 1929).

The substitution of niobium and tantalum for zirconium in some minerals is also well known. Minerals known to contain small amounts of niobium and tantalum include zircon, eudialyte, catapleiite, lavenite, baddeleyite, and others. According to Goldschmidt (1954, p. 504) the average ratio of niobium to zirconium is about 1:10 in granites, liparites (rhyolites), syenites, trachytes, nepheline syenites, and phonolites.

Niobium and tantalum substitute also in certain tungsten and tin minerals, and minor amounts of tungsten and tin are found in many niobium-tantalum minerals. Wolframite is a common tungsten mineral and cassiterite is a common tin mineral containing these substituted elements. The presence of minor scandium in some wolframite apparently compensates for the electrostatic disequilibrium caused by minor niobium-tantalum incorporated in the structure. Some wolframites and cassiterites are known to be mixtures of these minerals and columbite-tantalite (Grigor'ev and Dolomanova, 1951).

Kuz'menko (1959) mentions minor substitution of niobium and tantalum as charge-compensating elements in the substitution of phosphorus for silica in such minerals as monazite, erikite, and rhabdophane. Substitution in minor amounts for thorium, cerium, and lanthanum in the minerals steenstrupine, hydrocerite, and thorite is also proposed, but the great difference in the ionic radii of these elements as well as the difference in charge suggests the difficulty of such substitution.

GEOCHEMICAL BEHAVIOR

MAGMATIC ROCKS

Niobium and tantalum are commonly dispersed in magmatic rocks as camouflaged elements in iron- and iron-titanium-bearing minerals and to a certain extent in zirconium minerals; rarely, under specific conditions, independent minerals of niobium and tantalum are formed. Many rock-forming minerals have been shown to contain small amounts of these elements (see Glossary), but as noted by several authors, pyroxenes, amphiboles, micas, sphenes, titanium-iron oxides, and zircons contain most of the niobium and tantalum that is sparsely disseminated throughout large igneous rock masses.

Niobium and tantalum generally tend to accumulate and increase in abundance in the later differentiates and crystallates during differentiation of magmas (Goldschmidt, 1954, p. 500; Kuz'menko, 1959; Butler and Smith, 1962; Podol'skii and Serykh, 1964). Characteristically in a series of comagmatic rocks, the contents of these elements increase from ultramafic and mafic to the more silicic and alkalic rocks, and in late magmatic and postmagmatic products such as pegmatites, aplites, greisens, and carbonatites these elements are concentrated in greatest amounts.

Niobium and tantalum tend to be concentrated in certain magma types. Alkalic rocks normally contain more niobium and tantalum than other rock types, and certain alkalic granites and metasomatized(?) biotite granites contain sufficient niobium-tantalum to have formed independent niobium-tantalum minerals such as pyrochlore, columbite-tantalite, fergusonite, and euxenite.

The abundance of niobium and tantalum varies also to a certain extent from one petrographic province to another. Similar classes of rocks in different provinces, as well as province averages, differ greatly in their abundance values, either exceeding or being less than clarke values.

The behavior of niobium and tantalum in granitic rocks, alkalic rocks, alkalic ultramafic rocks, pegmatites, greisens and veins, and carbonatites is discussed below.

GRANITIC ROCKS

The geochemical behavior of niobium and tantalum in granitic rocks depends to a certain extent on the paragenesis of the titanium minerals in which these elements are dispersed and on the types of granite involved. Znamenskii and coworkers, in discussing dispersion and concentration of niobium and tantalum, considered two major types of granitic rocks: (1) monazite-bearing granites commonly containing ilmenite and rutile, and (2) allanite-bearing granites containing sphene and magnetite. These authors, in a series of papers (Znamenskii and others, 1957; Znamenskii and others, 1962, Znamenskii and Popolutov, 1964), pointed out the contrasting geochemical distribution of niobium and tantalum in these two types of granite and interpreted some of the magmatic processes involved on the basis of these facts.

In monazite-bearing granites containing ilmenite and rutile, most of the niobium and tantalum is concentrated in accessory biotite. For example, in the Kalbinsk massif of eastern Kazakhstan 60–86 per ent of the niobium and 50–72 percent of the tantalum are concentrated in the biotite of the rocks, which incidentally also contains most of the titanium in the rocks. (See table 17.) It should be noted that the ilmenite in these rocks contains much higher percentages of niobium and tantalum than the biotite, but the latter is so much more abundant that it is the principal carrier of these elements.

In allanite-bearing granites containing sphene and magetite, however, most of the niobium and tantalum is concentrated in the sphene, with subordinate amounts concentrated in biotite. This suggests that the calcium content of the whole rock may be an important factor in determining the distribution of niobium and tantalum among the rock-forming minerals.

In granite of this type from the eastern Sayan Mountains only 16–60 percent of the niobium and up to 38 percent of the tantalum in the rock is in biotite, whereas 35–85 percent of the niobium and 60 percent or more of the tantalum is in sphene. Most of the titanium of the rock is contained in biotite. (See table 18.)

Gottfried and Dinnin (1965) showed that most of the tantalum in the southern California batholith occurs in the biotite and its coexisting hornblende. (See table 19.) The southern California rocks are not amenable to classification under Znamenskii's scheme because these rocks range in composition from gabbro to granite. In tonalite from the batholith, biotite contains the predominant percentage of tantalum, but in granodiorite from the batholith, hornblende and biotite share the tantalum almost equally. In the quartz monzonite, the hornblende contains more tantalum than the biotite, although both minerals are enriched in tantalum as compared to these minerals in the tonalites and in the granodiorite of the batholith. In all rocks from the batholith, sphene, magnetite, and ilmenite play a relatively insignificant role in the distribution of tantalum, principally because of their low abundance in the rocks compared with biotite and hornblende.

It should be emphasized that the granites and other rocks mentioned above do not contain high levels of niobium or tantalum; in fact, some have levels below the clarke values.

Certain rare varieties of granite contain independent minerals of niobium and tantalum as accessories, which in some granites are sufficiently abundant to be characteristic. Such granites are the source of some of the world's commercially important residual and placer deposits of niobium and tantalum. These granites may be classed as columbite granites, euxenite granites, fergusonite granites, or pyrochlore granites, and they all apparently are monazite-ilmenite-rutile-bearing types. According to Pavlenko, Chung-Yang, and Morozov (1960), columbite, euxenite, and fergusonite granites are all highly aluminous, having

TABLE 17.—*Distribution of niobium and tantalum in granitic rocks of the Kalbinsk massif, U.S.S.R.*

[After Znamenskii and others (1957)]

Mineral	Content of mineral in rock (wt percent)	Content of Nb and Ta in mineral phases			Amount of Nb and Ta in analyzed mineral fractions		Percent of total Nb and Ta from data on minerals		Total content of Nb and Ta in rock bulk		
		Nb (ppm)	Ta (ppm)	Nb:Ta	Nb (ppm)	Ta (ppm)	Nb	Ta	Nb (ppm)	Ta (ppm)	Nb:Ta
Porphyritic biotite granodiorite, Asu-Bulak											
Biotite	13.00	96.0	7.6	12.0	12.5	1.0	60.0	50.0			
Ilmenite	.30	860.0	130.0	6.6	2.6	.4	12.5	20.0			
Zircon	.26	70.0	110.0			.3		15.0			
Sum					15.1	1.7	72.5	85.0	21	2.0	10.5
Porphyritic biotite granite, Miroliubovsk Ridge											
Biotite	8.00	130.0	18.0	7.2	10.1	1.44	68.0	65.5			
Ilmenite	.17	1200.0	210.0	5.8	2.1	.36	14.0	16.5			
Sum					12.2	1.80	82.0	82.0	15	2.2	6.8
Coarse-grained biotite granite, Mount Baich											
Biotite	5.6	200.0	26.0	7.7	11.2	1.45	86.0	72.5			
Ilmenite	.05	3600.0	640.0	5.6	1.8	.32	14.0	16.0			
Sum					13.0	1.77	100.0	88.5	13	2.0	6.5
Coarse-grained biotite granite, Chur-Chut-Su											
Biotite	8.1	80.0	9.5	8.4	6.5	0.77	65.0	59.0			
Ilmenite	.1	1700.0	260.0	6.5	1.7	.26	17.0	20.0			
Sum					8.2	1.03	82.0	79.0	10	1.3	7.7

TABLE 18.—*Distribution of niobium and tantalum in granitic rocks from the eastern Sayan Mountains, U.S.S.R.*

[After Znamenskii and others (1962)]

Mineral	Content of mineral in rock (percent)	Nb and Ta contents in mineral		Amount of Nb and Ta(in γ) in given mineral per gram of rock		Percent of total Nb and Ta bound in a given mineral		Total Nb and Ta content in rock (ppm)	
		Nb (ppm)	Ta (ppm)	Nb	Ta	Nb [1]	Ta [2]	Nb	Ta
Coarse-grained biotite granite (no. 126)									
Biotite	4.5	145	3.9	6.53	0.18	59.6	38.4		
Sphene	.25	1550	115	3.88	.29	35.4	61.6		
Total				10.41	.47	95.0	100.0	11	<0.7
Coarse-grained biotite granite (no. 152)									
Biotite	8.2	37	<3.5	3.0	<0.28	21.4	<22.0		
Sphene	.5	2400	200	12.0	1.0	85.6	>78.0		
Total				15.0	<1.28	107.0	100.0	14	1
Medium-grained biotite granodiorite (no. 113)									
Biotite	15.0	29	<3.3	4.3	<0.50	56.5	<50.0		
Sphene	.3	1350	155	4.0	.46	52.5	≈50.0		
Total				8.3	<.96	109.0		7.6	<1
Medium-grained biotite hornblende granodiorite (no. 149)									
Biotite	8.0	12	<4	1.0	<0.32	16.1	<45.0		
Hornblende	7.4	1	(3)						
Sphene	.7	705	58	5.0	.40	80.7	>55.0		
Total				6.0	<.72	96.8		6.2	<1

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[1] Percentage of the total Nb content in the rock.

[2] As distributed between biotite and sphene.

[3] Not determined.

TABLE 19.—*Tantalum in hornblende and biotite from igneous rocks of the southern California batholith*

[After Gottfried and Dinnin (1965)]

Mineral	Parent rock	Tantalum (ppm)		Distribution coefficient [1] Ta in biotite/Ta in hornblende
		Chemical	Neutron activation	
Hornblende	San Marcos Gabbro (hornblende norite).		0.17	
Hornblende	Green Valley Tonalite	0.7		2.3
Biotite		1.6		
Hornblende	Lakeview Mountain Tonalite.	.8	.88	2.1
Biotite		1.7	1.64	
Hornblende	Bonsall Tonalite	.9		1.7
Biotite		1.5		
Hornblende	Woodson Mountain Granodiorite.	2		1
Biotite		2		
Biotite	Woodson Mountain Granodiorite.		1.62	
Hornblende	Quartz monzonite, coarse phase of Rubidoux Mountain.	18	8.8	.4
Biotite		6.6	6.4	
Hornblende	Quartz monzonite, coarse phase of Rubidoux Mountain.	10		.5
Biotite		4.8		
Hornblende	Quartz monzonite, fine phase of Rubidoux Mountain.	12		.5
Biotite		6		

[1] Calculated from chemical analyses.

Al>(K+Na+2Ca). On the other hand, pyrochlore granites are highly alkalic, or agpaitic, having (K+Na)>Al. Normal allanite-sphene-biotite granite has the relation (K+Na)<Al<(K+Na+2Ca), and such granite commonly does not contain independent niobium-tantalum accessory minerals.

The columbite granites may not result entirely from magmatic processes, because columbite and some other accessory minerals are interpreted as formed by autometasomatic processes akin to greisenization. In the process of alteration of the normal biotite granite to columbite granite, calcium is removed from the plagioclase and iron, manganese, titanium, niobium, and tantalum are removed from the biotite. These elements are recombined to form fluorite, magnetite, and columbite. The notable biotite granites of the Jos Bukuru complex in Nigeria are of this type. The Lunyo albite granite of Uganda (Knorring, 1960) and its associated aplites, pegmatites, and greisens have a characteristically high content of niobium, which is present in columbite. In addition, betafite is found in some of the pegmatites. The niobium content varies from 0.05 to 0.1 percent in the granite and from 0.1 to 0.2 percent in the greisens, and in aplites and pegmatites it reaches 0.5 percent locally. In some respects, this granite resembles the albite-riebeckite granite of Nigeria. Present also are fluorite and the lithium-fluorine mica, zinnwaldite.

Euxenite and fergusonite granites owe the formation of their niobium-tantalum accessory minerals to late magmatic crystallization. The hyperaluminous condition of these rocks is interpreted to have limited the entry of titanium, niobium, and tantalum into the biotite and hornblende during their crystallization and caused these elements to accumulate in the rest magma and then to crystallize in late paragenesis. Euxenite granite (quartz monzonite or quartz diorite) is known from the Idaho batholith, Bear Valley, Idaho (Mackin and Schmidt, 1956). Fergusonite granite occurs in the basin of the Gava Say River, U.S.S.R.

Pyrochlore granites are highly alkalic and are composed principally of microperthite, sodic plagioclase, quartz, sodic amphibole, and sodic pyroxene. Niobium and tantalum apparently do not enter the lattices of such amphiboles and pyroxenes in sufficient degree to prevent the accumulation and late crystallization of these elements in pyrochlore. Granites of this type are the pyrochlore-riebeckite granite of Nigeria (Beer, 1952; MacLeod, 1956) and the Mount Rosa Granite near Pikes Peak, Colo.

The ratio Nb:Ta is useful in showing the relative concentration of niobium and tantalum in various stages of magmatic differentiation, even though some of the ratios are extremely variable due to insufficient accuracy of some of the analyses. General trends in the Nb:Ta ratio between granitic comagmatic rocks show that, in differentiation, rocks of the monazite-ilmenite-rutile type are enriched in tantalum with respect to niobium, but that significant enrichment does not occur in rocks of the sphene-allanite type. For example, in the Kalbinsk massif, composed of the monazite-ilmenite-rutile-type rocks, the Nb:Ta ratio decreases from 10.5 in the early rocks to one in genetically related pegmatites and shows a progressive decrease in the ratio through successively younger differentiates between these extreme members of the massif.

On the other hand, in sphene-allanite-bearing granites sphene is the principal carrier of niobium and tantalum. During magmatic stages of intrusion of this type rock, including the postmagmatic stage, apparently no significant enrichment in tantalum as compared with niobium occurs. Notable contents of niobium and tantalum do not appear in the pegmatites of this type of granite. From their study of the distribution of niobium and tantalum in granitic rocks, Znamenskii and Popolutov (1964) concluded that the presence of sphene in granitic rocks is not a favorable sign for widespread occurrence of niobium, and especially tantalum, mineralization in pegmatites derived from the same magma as such granites. Conversely, biotite granites without sphene are favorable for the formation of predominantly tantalum mineralization in genetic association with rare-metal pegmatites.

Such a generalization on lack of tantalum concentrations in pegmatites of sphene-bearing granites does not apply to the remarkable tantalum concentration at the

Harding pegmatite, New Mexico (Montgomery, 1950). This pegmatite is related to the Dixon Granite of Just (1937) that contains abundant sphene (as much as 4 percent) in areas 2 miles or more beyond the pegmatite; however, only traces of sphene are found in the granite surrounding the pegmatite. Tantalum that is dispersed in the granite is carried mostly in the sphene. The near absence of sphene in the granite surrounding the pegmatite is considered one of the principal factors in the concentration of tantalum in the pegmatite. Montgomery (1950, p. 865) stated,

> specific absence of abundant Ta-bearing sphene, present in the same granite elsewhere, from all pegmatite-adjacent granite, which during crystallization of that granite may have freed, or left free, sufficient Ta from this source alone to supply the entire Harding enrichment.

Other attributive factors mentioned are: a genetically related tantalum-rich granite; some indirect wallrock control during pegmatite replacement that made available calcium needed to combine with tantalum to form microlite; a lack of tantalum-receptive minerals in both parental crystallizing granite and pegmatite; and a long-continued process of deformation fracturing that kept the pegmatite open to successive invasions of solutions from the granitic magma below.

ALBITIZED AND GREISENIZED GRANITIC ROCKS

Granitic rocks of the Ognitsk complex in the eastern Sayan Mountains, U.S.S.R., are metasomatically albitized and have high concentrations of niobium and tantalum (Kovalenko and others, 1964). The Nb:Ta ratio is lowest in the most intensely albitized zones, showing enrichment in tantalum with respect to niobium as a result of albitization. A sharp increase in the content of niobium in albitized and greisenized rocks was noted also by Podol'skii and Serykh (1964) in the Kokchetav uplift, Kazakhstan; however, Voloshin and Miletskii (1966) noted a decrease in niobium to almost nothing in the most highly albitized Kazakhstan rocks such as albitites.

The relative distribution of niobium and tantalum is shown by Kudrin, Kudrina, and Shuriza (1965) to be complex in varieties of metasomatic rocks characterized by riebeckite, biotite, zinnwaldite, or cryophyllite. Niobium minerals in these rocks range in paragenetic sequence from euxenite and fergusonite to pyrochlore through three successive generations of columbite and show considerable variation in their relative niobium-tantalum contents. Early pyrochlore (data on fergusonite and euxenite not given), formed in the sodium stage of metasomatism, is characterized by a relatively high Ta_2O_5 content of about 6–7 percent and a Nb_2O_5:Ta_2O_5 ratio of about 7.5–9. In the later columbite stages columbite I, associated with cryophyllite, topaz, and cassiterite, is characterized by a lower Ta_2O_5 content of 2–3 percent and a high Nb_2O_5:Ta_2O_5 ratio of 20–30; columbite II, closely associated with zinnwaldite, is characterized by a sharp decrease in the Nb_2O_5:Ta_2O_5 ratio to about 7–8; and columbite III, formed in the stage of silicification, has a high ratio near 35. These authors attribute the variation in the niobium-tantalum contents to the variation in physicochemical conditions at the time of formation of the respective minerals, especially the variations in alkalinity and acidity of the effective solutions.

Beus and Sitnin (1960, 1961) and Sitnin and Bykova (1962) have described the occurrence of niobium and tantalum in greisens and greisenized granites and pegmatites. They have noted the occurrence of microlite in addition to columbite-tantalite in greisenized granites and remark on the separation of niobium from tantalum and the tantalum enrichment in the process of alteration, albitization, and greisenization. The maximum concentration of tantalum is associated with the most intensely greisenized rocks, and these authors attribute the enrichment in tantalum and its separation from niobium to fluorine-bearing solutions that were active during greisenization. In a fluorine-rich environment, niobium and tantalum could combine with fluorine to form ionic complexes, and a separation of these elements could result from tantalum-fluorine complexes being more mobile and stable than niobium-fluorine complexes.

According to Sitnin and Razina (1963), biotite is gradually changed to lithium-bearing micas in the process of metasomatic formation of some amazonite-albite granites from biotite granites. Niobium and tantalum are released from the biotite during this process to form independent niobium or tantalum minerals.

Greisenized rocks, high temperature quartz, and quartz-feldspar veins are often found beyond the boundaries of the parent intrusives. Such rocks commonly contain columbite, tantalum-bearing rutile, cassiterite, or wolframite (Beus and Sitnin, 1961).

GRANITE PEGMATITES

High concentrations of niobium and tantalum in granite pegmatites are well known. Granite pegmatites are also the only known commercial source of tantalum. As mentioned previously, niobium and tantalum tend to be concentrated in the later products of crystallization of certain types of granite, and the rocks tend to be enriched in tantalum with respect to niobium. In most granites, independent accessory minerals of niobium and tantalum are not found, but in pegmatite phases of such granites a wide variety of niobium-tantalum minerals is commonly formed. Niobium and tantalum enter also to a certain degree into the structure of other pegmatite minerals such as micas, garnets, tourmaline, ilmenite, and zircon. Certain types of pegmatites seem to be more intensely mineralized with niobium and tantalum than others. These are commonly complexly zoned pegmatites with strong development of albite or lithium minerals.

Granitic pegmatites range from homogeneous, relatively unzoned pegmatites to heterogeneous, very complexly zoned and replaced pegmatites. Such pegmatites have been classed as unzoned and zoned by Cameron, Jahns, McNair, and Page (1949). Niobium and tantalum minerals are found in both types, although these elements seem to be more prevalent in the zoned type, at least in pegmatites of the United States. Columbite-tantalite is the most common niobium-tantalum mineral in the relatively unzoned pegmatites, whereas the zoned pegmatites contain a wide variety of other minerals of these elements in addition to columbite-tantalite.

Niobium–tantalum enrichment is common in muscovites and other micas that were formed in the late stages of pegmatite crystallization. Odikadze (1958) and Heinrich (1962) demonstrated that muscovites in pegmatites with columbite and beryl contain appreciably greater amounts of niobium and beryllium than muscovites from pegmatites without these minerals. (See table 20.) Niobium-bearing pegmatites from the Petaca, New Mexico, and south-central Colorado districts contain muscovites averaging slightly over 400 ppm niobium, whereas the niobium-poor pegmatites of Franklin-Sylva, North Carolina, have muscovites that average only 94 ppm niobium. Niobium and tantalum are considered to be present in the lattice of the micas in isomorphous substitution for titanium and aluminum. In biotite, niobium and tantalum probably substitute for titanium with simultaneous substitutions of lithium for magnesium to preserve electrostatic equilibrium:

$$Mg^{+2}+Ti^{+4}\longleftrightarrow Li^{+1}+(Nb,Ta)^{+5}.$$

Muscovite contains only minor titanium so that substitution in the mineral probably occurs between aluminum (eight-fold coordination) and lithium, niobium, and tantalum:

$$2Al^{+3}\longleftrightarrow Li^{+1}+(Nb,Ta)^{+5}.$$

Kuz'menko (1961) suggests that niobium is preferentially taken into the mica structure leaving tantalum to accumulate and form independent minerals of its own such as microlite and tantalite. The presence of lithium-bearing micas in pegmatites has significance in the formation of separate tantalum deposits.

TABLE 20.—*Comparison of percentage of occurrence of niobium minerals in pegmatites with averages of niobium in accompanying muscovites*

[After Heinrich (1962)]

District	Pegmatites with columbite (percent)	Average Nb (percent)	Number of analyses
Petaca, N. Mex	87	0.0404	10
South-central Colorado	17	.0419	9
Black Hills, S. Dak	17	.0298	10
Franklin-Sylva, N.C	[1] 0.4	.0094	10

[1] Samarskite.

The enrichment of tantalum in successive later stages of crystallization of lithium-rich pegmatites is discussed by Beus and Sitnin (1961) from a different standpoint. In pegmatites showing evidence of strong lithium metasomatism in the late phases of pegmatite genesis, microlite or other high-tantalum-bearing minerals are formed, effecting in some deposits a nearly complete separation of niobium from tantalum. The high fluorine content of the lepidolite indicates the role played by that element in the alteration. Fluorine may be the primary factor in the enrichment and fractionation of niobium from tantalum because of the difference in mobility between tantalum-fluorine and niobium-fluorine complexes, the probable form in which these elements were present in the pegmatite-forming fluids. As noted before, a similar process involving fluorine is ascribed to the separation of these elements in the formation of greisens.

The content of tantalum with respect to niobium tends to increase from the earliest to the latest phases of pegmatite development. This is shown in a general way by the increase of tantalum in columbite-tantalite from the walls inward in various zones of pegmatites (Cameron and others, 1949, p. 64; Page and others, 1953, p. 58). Such an increase of tantalum from wall zones to cores of pegmatites as reflected by the progressive increase in specific gravity in columbite-tantalite of the Quartz Creek district, Colorado, is shown in the following table (Staatz and Trites, 1955, p. 40):

Pegmatite	Internal unit	Specific gravity
1234	Wall zone	5.0
1234	do	5.1
1574	Intermediate zone	6.0
452	Albite-quartz-biotite layer	5.8
205	Core	6.1
205	do	6.3
245	do	5.7
1557	do	6.7

Rudovskaya (1964) has shown that the youngest granitic pegmatites in the northwestern part of the White Sea region, U.S.S.R., are progressively enriched in tantalum with respect to niobium and both of these elements are concentrated in independent niobium-tantalum minerals. These elements are also contained in small amounts in micas and cyrtolite. (See table 21.) Niobium-tantalum minerals of the same paragenetic sequence in the pegmatites of the region show an enrichment of tantalum from early columbite to tapiolite, microlite, and djalmaite, then a sharp decrease in tantalum with respect to niobium in the fergusonites that followed. This reversal in trend has yet to be explained.

A dispersal of niobium and tantalum, rather than concentration, has been noted by Slepnev (1964) in the extensively greisenized pegmatites of the Sayan Mountains, U.S.S.R. In the greisenized pegmatites, niobium and tantalum are dispersed in muscovite and cassiterite, whereas in those pegmatites not greisenized, these elements are contained in columbite-tantalite and a manganese-niobotantalate mineral. Muscovite of the greisenized pegmatites contains as much as 0.02 percent niobium and 0.003 percent tantalum; the cassiterite contains 0.14–0.98 percent niobium and up to 0.68 percent tantalum. A reversal of the normal order of zoning is also suggested in some of the pegmatites in which tantalite, instead of columbite, is characteristic of the outer zones and a manganese-niobotantalate, poorer in tantalum, is found in the central zones.

TABLE 21.—*Niobium and tantalum contents (percent by weight) in micas from pegmatites of different ages and from the enclosing rocks in the northwestern White Sea region, U.S.S.R.*

[After Rudovskaya (1964)]

Locality	Nb_2O_5	Ta_2O_5	Rock
Biotite			
Paiv-Oiva	0.003	<0.001	Kyanite-garnet-biotite gneiss.
Do.	.003	<.001	Kyanite-garnet-biotite gneiss with cordierite.
Rikolatva	.003	<.001	Amphibolitized gabbro.
Rikolatva-179	.006	(1)	Early pegmatite.
Rikolatva	.0094	.004	Do.
Kuru-Vaara	.010	.001	Do.
Leivoiva	.007	(1)	Do.
Muscovite			
Rikolatva-179	0.006	<0.001	Early pegmatite.
Rikolatva-198	.002	(1)	Do.
Rikolatva	.008	≈.001	Do.
Leivoiva-4	.005	.001	Do.
Leivoiva-201	.006	.001	Do.
Kheta-Lambino.	.004	(1)	Do.
Paiv-Oiva	.006	<.001	Do.
Leivoiva-4	.013	.004	Early pegmatite near a later pegmatite dike.
Rikolatva-198	.012	.005	Do.
Leivoiva-4bis	.036	.007	Later pegmatite.
Rikolatva	.033	.010	Do.

[1] Not found.

NEPHELINE SYENITE

Nepheline syenites have been studied extensively by Russian geologists and Russian reports dominate the literature on these rocks. According to Es'kova (1960), nepheline syenite comprises about one percent of the igneous rocks of the U.S.S.R., and more than thirty massifs of this type of rock are known to occur there. In eight prominent nepheline syenite massifs the average niobium content ranges from 100 to 900 ppm and the average tantalum content ranges from 8 to 70 ppm. The Nb:Ta ratios vary from 12.0 to 20.5. (See table 22).

As in granitic rocks, niobium and tantalum of nepheline syenites are more highly concentrated in late phases of intrusives, that is, pegmatites, albitized zones, and carbonatites, and in late hydrothermal veins. Such enrichment is several to tens of times the niobium and tantalum contents of the parent rocks (Es'kova, 1960).

Russian geologists recognize two classes of nepheline syenites, agpaitic and miaskitic (Ussing, 1912; Gerasimovskii, 1956, 1960, 1963; Gerasimovskii and others, 1957; Es'kova, 1960). Chemically these can be separated, on the basis of their ratios of total alkalies to alumina. The ratio $(K_2O+Na_2O):Al_2O_3$ is called the agpaitic coefficient, which exceeds 1 for agpaitic syenites and is 1 or less for miaskitic syenites. Gradual transitions from one type of syenite to the other can occur even within a single massif.

Niobium occurs in a wide variety of minerals in nepheline syenites and the veins and other features connected with them. More than 40 minerals are known from agpaitic syenite but only about 20 have been found in miaskitic syenite (Es'kova, 1960).

The geochemistry of niobium and tantalum is different in massifs of agpaitic syenite than in those of

TABLE 22.—*Average contents of niobium and tantalum in some massifs of nepheline syenite, U.S.S.R.*

[After Es'kova (1960), except as noted]

Massif	Number of samples averaged for massif	Average content (ppm)		Ratio Nb:Ta
		Nb	Ta	
Lovozero	39	900	70	12.8
Do. [1]	123	696	60	11.6
Vishnevye Gory	2	240	20	12
Il'men Mountains	2	110	8	13.8
Borsuksai	2	410	20	20.5
Karasyrsk	1	160	<10	--------
Khibina	1	100	(2)	--------
Koisk	1	100	(2)	--------
Tatarsk	1	140	(2)	--------

[1] Gerasimovskii and others, 1966.

[2] Not determined.

miaskitic nepheline syenite. In the latter, niobium is concentrated not only in minerals of titanium and zirconium, but accumulates and forms independent minerals in late magmatic and postmagmatic derivatives. On the other hand, in agpaitic nepheline syenites, in spite of higher average contents of niobium and tantalum, these two elements are largely fixed in titanium and zirconium minerals (Gerasimovskii and Venkina, 1960; Gerasimovskii and others, 1959).

According to Es'kova (1960) in summarizing the relations in Russian alkalic massifs, niobium and tantalum are concentrated in agpaitic nepheline syenites in the minerals loparite, murmanite, lomonosovite, belyankinite, ramsayite, lamprophyllite, fersmanite, rinkolite, lovchorrite, epistolite, nenadkevichite, shcherbakovite, gerasimovskite, sphene, eudialyte, lovozerite, catapleiite, and in other minerals of titanium and zirconium. The content of Nb_2O_5 in them ranges from 0.01 to 44.9 percent. The minerals have low contents of Nb_2O_5 (commonly 1–3 percent, but as much as 10–12 percent) in the nepheline syenite proper, in simple undifferentiated pegmatites, and in high temperature, fine-grained, equigranular zones of complexly replaced differentiated pegmatites. Highest contents of niobium are found in minerals of late stages of differentiated pegmatites that are genetically associated with late (?) phases of nepheline syenites. Some late zeolite veins and albitites contain minor pyrochlore, but the occurrence of such minerals is not characteristic. The contents of Ta_2O_5 in titanium and zirconium minerals of agpaitic nepheline syenite varies from 0.04 to 0.93 percent and the Nb:Ta ratio ranges from 5 to 95.

Niobium and tantalum are concentrated in rocks and veins of miaskitic nepheline syenites in minerals of the pyrochlore group and aeschynite, and in ilmenite, ilmenorutile, fersmite, sphene, zircon, biotite, and rarely columbite, chevkinite, or others. The contents of Nb_2O_5 and Ta_2O_5 in the minerals range from 0.003 to 71.5 and from 0.04 (where detected) to 8.65 percent respectively.

An increase in niobium and tantalum and a decrease in titanium can be demonstrated in minerals of miaskitic rocks representing magmatic and postmagmatic stages from nepheline syenite to pegmatites and to albitized and carbonatized rocks. For example, pyrochlore from miaskites and pegmatites contains 60–65 percent Nb_2O_5 and 5–10 percent TiO_2, whereas pyrochlore from carbonatite contains 71.5 percent Nb_2O_5 and 0.5 percent TiO_2. Pyrochlore from miaskites and early stages of pegmatites are characterized by small contents of tantalum (up to 1.5 percent Ta_2O_5); however, in the late stages of pegmatite formation, hydropyrochlore is formed with an increase in tantalum content (up to 4 percent Ta_2O_5). In postmagmatic albitites (formed by albitization of pegmatites) minerals of the pyrochlore group with Ta_2O_5 reaching almost 9 percent, are formed.

The independent niobium minerals crystallize later than the titanium and zirconium minerals in both the nepheline syenite and postmagmatic formations and are commonly associated with processes of albitization and more rarely carbonatization.

Commercial concentrations of niobium occur in magmatic, pegmatitic, pneumatolytic, hydrothermal, and exogenic formations of nepheline syenites. Magmatic deposits are typical of agpaitic nepheline syenites, and pegmatitic and metasomatic deposits are associated with miaskitic syenites.

ALKALIC ULTRAMAFIC ROCKS

The geochemistry of niobium and tantalum in the alkalic ultramafic rocks of the Kola Peninsula was discussed at length by Kukharenko and others (1961, 1965). Geological, petrological, and geochemical generalizations were made from data for at least nine alkalic ultramafic massifs of this region as studied by a number of Russian geologists. Represented are the Afrikanda, Kovdor, Vuori-Yarvi, Salmagorsk, Lesnaya Baraka, Lake Baraka, Tur'e Peninsula, Sallanlatvin, and Sebl'yavr massifs.

The most characteristic features of most of the massifs are the concentric arrangement of rock series and the constitution of individual intrusive bodies as multiple phases. Early phases of intrusions are injections of olivinites of different varieties including melilite- and perovskite-titanomagnetite-bearing types (Afrikanda).

A second intrusive phase in all the massifs is pyroxenite of different varieties. Some pyroxenites containing titanomagnetite and perovskite are coarse-grained and commonly constitute the core of the massifs. Fine-grained pyroxenites, enriched in apatite and sphene, and to a certain extent enriched in nepheline and melanite, are associated with the border zones of the massifs. In some massifs the nepheline pyroxenites grade into jacupirangites (Afrikanda, Vuori-Yarvi). Pegmatites of diverse composition are associated with the pyroxenites.

A third intrusive phase consists of a series of melteigite-ijolite-urtite rocks accompanied by veins of ijolite pegmatite. These rocks commonly lie in the circumferential zone of the massifs.

As a result of postmagmatic alteration, ultramafic rocks and others have been changed in part to biotite-phlogopite, apatite-forsterite-magnetite, and phlogopite-calcite-magnetite rocks, and carbonatites of diverse composition. Reaction between the alkalic ultramafic intrusives and the gneissic country rock has produced a contact aureole of fenites around the massifs.

The alkalic ultramafic rocks of the Kola Peninsula are anomalously high in both niobium and tantalum.

The niobium content ranges from 134 to 518 ppm, and the tantalum content ranges from 13.2 to 59.6 ppm. The Nb:Ta ratio ranges from 8.7 to 10.2.

The geochemical behavior of niobium and tantalum was given in some detail by Kukharenko and associates from consideration of a large number of analyzed minerals from the alkalic ultramafic rocks and from the geologic succession of rock types. The character of the distribution of niobium and tantalum differs for different stages of formation of the massifs. In rocks of magmatic stages proper, these elements enter into titanium-bearing iron-magnesium silicates such as monoclinic pyroxenes, hornblendes, magnesium-iron micas, and titanomagnetites and especially into complex titanium oxide minerals such as perovskite and sphene and also into titaniferous garnet. In products of residual crystallization—alkalic pegmatites—and in some high-temperature autometasomatic products—calcite-amphibole-diopside rocks (Afrikanda)—not only is there some dispersal of niobium and tantalum in silicate and oxide minerals but some concentration in titanium and zirconium minerals such as dysanalyte and baddeleyite and in the independent niobium-tantalum minerals, ilmenorutile and pyrochlore. Higher concentrations of niobium and tantalum are characteristic of rocks of postmagmatic stages such as apatite-forsterite-magnetite and calcite-phlogopite-magnetite rocks and carbonatites, and minerals containing these elements are chiefly pyrochlore, zirkelite, baddeleyite, dysanalyte, and lueshite. Niobium and tantalum are apparently in part mobilized and reconcentrated in the process of postmagmatic alteration of pyroxenes and other minerals.

Kukharenko, Skrizhinskaya, Vainshtein, and Kakhama (1961) gave analyses for niobium and tantalum for 138 minerals from the alkalic ultramafic rocks of the Kola Peninsula. These analyses are grouped and summarized in table 23. From these data, these authors have concluded that a progressive increase in content of niobium and tantalum and a relative concentration of niobium with respect to tantalum occurs with the transition from pyroxenites to more alkalic rock types to pegmatites, or within different magmatic or postmagmatic phases. Such a general progression in concentration is shown well by monoclinic pyroxene, perovskite, titanomagnetite, sphene, pyrochlore, and others when considered as mineral groups related to the geologic succession of rock types for the Kola Peninsula as a whole. A similar progression is shown within the individual massifs such as Afrikanda. For example, concentrations of $(Nb,Ta)_2O_5$ in the pyroxenes range from 0.005 percent in earlier formed rocks to 0.0152 percent in later formed rocks of the Peninsula, and the ratio Nb_2O_5:Ta_2O_5 ranges from 4 to 11. In the Afrikanda massif the Nb_2O_5:Ta_2O_5 ratios in pyroxenes range from 2 to 3 in the earlier coarse-grained pyroxenite in the inner parts of the massif to 2–5 in the fine-grained pyroxenite to 5–25 in the later nepheline pyroxenite in the peripheral zone.

TABLE 23.—*Average contents of Nb_2O_5 and Ta_2O_5 and their ratios in some minerals of alkalic-ultramafic rocks of the Kola Peninsula, U.S.S.R.*

[Kukharenko and others (1961, table 3, p. 184; 1965, table 172, p. 584–586)]

No.	Mineral	$(Nb, Ta)_2O_5$ Content (in percent)	$(Nb, Ta)_2O_5$ Number of samples	Nb_2O_5:Ta_2O_5 Ratio	Nb_2O_5:Ta_2O_5 Number of samples
1	Pyroxene from normal and ore pyroxenites	0.005	13	4.0	12
2	Pyroxene from nepheline pyroxenites and ijolite-melteigites	.011	7	11	7
3	Pyroxene from alkalic pegmatites	.015	2	9	2
4	Pyroxene from fenites	.004	1	20	1
5	Hornblende from metasomatic calcite-amphibole-diopside rocks	.014	1	35	1
6	Hornblende from alkalic pegmatites	.008	2	15	2
7	Biotite from alkalic pegmatites and ijolites	.0006	2	≈4–5	2
8	Phlogopite from alkalic pegmatites and ijolites	.0005	2	≈4–5	2
9	Melanite from ijolite-melteigites and their pegmatites	.020	3	7	3
10	Schorlomites from ore- and alkalic-pegmatites	.049	4	13	4
11	Sphene from pyroxenites	.24	3	16.5	2
12	Sphene from metasomatic calcite-amphibole-diopside rock	.946	5	13	2
13	Sphene from alkalic pegmatites	.61	6	25	3
14	Titanomagnetites from olivinites	.0013	3	5	3
15	Titanomagnetites from alkalic pegmatites	.0015	2	8	2
16	Perovskites from fine-grained olivinites	.55	17	9	14
17	Perovskites from pegmatitic olivinites	.56	5	13	5
18	Perovskites from ore pyroxenites	.72	10	10	7
19	Perovskites from nepheline pyroxenites, melteigites, and ijolites	1.05	4	14	4
20	Perovskites from metasomatic calcite-amphibole-diopside rocks	1.37	5	16	4
	Of these, perovskite of first generation	1.29	1	9	1
	Of these, perovskite of last generation	1.45	1	28	1
21	Perovskite of alkalic pegmatites	1.17	18	17	10
22	Baddeleyites from rocks of "ore complex" and carbonatites	1.25	8	3	8
23	Zirkelites	18.46	8	12.3	7
24	Pyrochlores of Vuori-Yarvi massif; brown pyrochlores of first generation from rock of "ore complex"	42.61	1	8	1
25	Pyrochlores of Vuori-Yarvi massif; yellow pyrochlores from rocks of "ore complex" (second generation)	56.15	4	39	4
26	Pyrochlores of Vuori-Yarvi massif; pyrochlore from carbonatized ore	58.13	1	30	1
27	Pyrochlores of Vuori-Yarvi massif; pyrochlore from carbonatites	58.54	2	51	2
28	Pyrochlores of Vuori-Yarvi massif; hatchettolite from fenites	51.64	1	4.8	2
29	Pyrochlores of Kovdorsk massif; brown pyrochlores from rock of "ore complex"	48.0	1	7	1
30	Pyrochlore from carbonatite, early generation	53.18	1	6.7	1
31	Pyrochlore from carbonatite, late generation	64.23	1	28	4
32	Pyrochlore of Sebl'yavr massif; from calcite carbonatite (early generation)	62.69	1	10.7	1
33	Pyrochlore of Sebl'yavr massif; pyrochlore from dolomitic carbonatite (later generation)	66.16	1	38	3
34	Lueshite	65.75	1	≈115	2
35	Natroniobite	74.89	1	90	2

Pyrochlore in the alkalic ultramafic rocks is characterized by the greatest variation in the ratio Nb_2O_5:Ta_2O_5. Early generations of pyrochlore commonly are enriched in tantalum and uranium, approximating hatchettolite in composition and having ratios in the range 7–11. Second-generation pyrochlore from the same rocks have ratios 30–51. Maximum ratios reaching 53 are found in pyrochlore from the youngest dolomite carbonatite.

The same trend, niobium concentrating progressively with respect to tantalum, is shown clearly by paragenetic mineral series, both in different rock types and different massifs. Ratios of $Nb_2O_5:Ta_2O_5$ in paragenetically related minerals are given in table 24. In all the series given (with a single exception that Kukharenko suspects is an analytical error) representing olivinites, ore pegmatites, carbonatites, and ore complexes of several massifs a progressive increase in the ratio is shown.

In summary, in the beginning stages of massif formation of alkalic ultramafic rocks, niobium and tantalum do not form independent minerals but are camouflaged principally by titanium in rock-forming pyroxenes and titanium oxide minerals. The first fractions of crystallizing rock are relatively deficient in niobium or relatively enriched in tantalum. Later precipitates in each series of rocks are enriched in niobium. In differentiated intrusives, the relative concentration of niobium increases in the late alkali-enriched outer zones of the massifs. In products of residual crystallization, niobium and tantalum form independent minerals such as pyrochlore, or they enter into complex titanium or zirconium minerals. Generally, rock-forming silicates and oxides of residual origin are enriched in both niobium and tantalum but more highly enriched in niobium. In postmagmatic phases of alkalic ultramafic rocks such as carbonatites, local increases of niobium and tantalum in independent minerals and complex oxides of titanium and zirconium are also characteristic, niobium being relatively enriched as compared with tantalum. Niobium and tantalum are reconcentrated, in part at least, as a result of alteration of earlier formed primary rock-forming silicates.

TABLE 24.—*Ratios of $Nb_2O_5:Ta_2O_5$ in minerals grouped according to their paragenetic association, Kola Peninsula, U.S.S.R.*

[Kukharenko and others (1961, table 4; 1965, table 173, p. 590)]

Mineral	Locality and rock	$Nb_2O_5:Ta_2O_5$	Number of samples averaged
Titanomagnetite	Afrikanda; olivinites	5.0	3
Perovskite	do	12	19
Titanomagnetite	Afrikanda; ore pegmatite.	8	2
Perovskite	do	17	10
Baddeleyite	Vuori-Yarvi; rocks of ore complex.	3	2
Zirkelite	do	16.5	3
Pyrochlore	do	26.5	2
Zirkelite	Sebl'yavr; carbonatites.	7.6	2
Pyrochlore	do	24	2
Baddeleyite	Lake Varaka; carbonatites	4.6	--------
Pyrochlore	do	8.2	--------
Baddeleyite	Kovdor massif; rocks of ore complex.	3	5
Zirkelite	do	10.5	2
Pyrochlore	do	[1] 7	--------

[1] Suggested correct value (Kukharenko and others, 1961) =25.

VOLCANIC ROCK SERIES

David Gottfried (written commun., 1965), in studying the niobium content in suites of volcanic rocks, distinguished three fairly distinct trends of variation of niobium during magmatic differentiation. Niobium increases throughout differentiation as shown in the alkalic and alkali-calcic volcanic suites from Augusta County, Va., and the Big Bend area, Texas. Niobium decreases throughout differentiation as shown by series members in the high calcic suites from Saipan; Mount Garibaldi, British Columbia; and Strawberry Mountains, Oreg. Niobium increases slightly or remains nearly constant in calc-alkalic rocks from Medicine Lake Highland, Calif. The study of these suites suggests that the variation during magmatic differentiation of niobium, and probably tantalum, is more complex than generally assumed when examined on the basis of more detailed petrographic classification. Most of the literature treats the subject on the basis of very generalized classification, and, as a result, some complex variations are concealed by more dominant trends.

SEDIMENTARY ROCKS

Data on the niobium and tantalum content of sedimentary rocks are summarized in table 13. They indicate that niobium and tantalum dissolved during the weathering cycle tend to be concentrated in the hydrolyzates—clays, laterites, and bauxites. An appreciable amount of niobium, however, evidently escapes precipitation and reaches the ocean where it precipitates with the clays and especially with the manganese oxide nodules. Two such nodules analyzed by Rankama (1944, 1948) contain 147 and 35 ppm niobium and less than 1.6 and less than 0.7 ppm tantalum. A nodule from the Indian Ocean analyzed by Pachadzhanov, Bandurkin, Migdisov, and Girin (1963) contains 7.6 ppm niobium and 2.3 ppm tantalum (Nb:Ta=3.3) in its core and 29 ppm niobium and 0.17 ppm tantalum (Nb:Ta=170) in its outer shell. The core in such nodules is considered to represent altered submarine volcanic material, whereas the outer shell is a product of deep-sea deposition. A strong relative enrichment in niobium with respect to tantalum is shown between core and shell, and the decrease in the tantalum content of the shell reflects the low abundance of tantalum in the deep-sea environment and is an indication of the geochemical separation of tantalum and niobium in this environment.

Pachadzhanov (1963) recently investigated the distribution of niobium and tantalum in clays of the

Russian Platform and has pointed out some interesting facts bearing on the geochemical behavior of these elements in sedimentary processes. In that report, clays formed in humid environments are distinguished from those formed in arid environments. The average niobium and tantalum contents for the humid clays are 20.1 and 2.4 ppm respectively, and the Nb:Ta ratio is 8.4. The same averages for arid clays are 13.3 and 0.9 ppm respectively, and the Nb:Ta ratio is 14.8. The averages of all clays investigated are 18.3 and 2, close to the clarkes of these elements. Higher concentrations of both niobium and tantalum occur in the humid environment clays and are ascribed to residual concentration resulting from the removal by leaching of ions—potassium, sodium, calcium, magnesium, silicon, and others. The Nb:Ta ratio is higher in the arid-environment clays because niobium appears to be more mobile and somewhat more easily removed than tantalum in the humid environment. The greater mobility of niobium and partial fractionation of niobium from tantalum are shown by a progressive decrease in the Nb:Ta ratio from the provenance area to the basin of marine deposition. Possible explanations offered for the fractionation are differences in solubility and stability of organic niobium and organic tantalum compounds that may be formed in weathering, or differences in the behavior of niobium and tantalum in solution with such elements as titanium, zirconium, and thorium, which may have chemical influence on them.

The content of niobium and tantalum in sediments evidently reflects to a considerable degree their content in the source rocks. A kaolinite formed from Nigerian columbite-bearing granites contained 478 ppm niobium and 82 ppm tantalum. This was not included in the samples averaged in table 13. The data on bauxites also illustrate the important nature of the source rock—bauxites from alkalic rocks containing twelve times as much niobium as those derived from other types of rocks. This is further verified by Fleischer, Murata, Fletcher, and Narten (1952) who found less than 100 ppm in each of 37 bauxitic rocks derived from sources other than alkalic rocks. The figures given by Pearson (1955) on Gold Coast bauxite (20 ppm niobium) derived from gneisses and on bauxite from Nyasaland (500 ppm niobium) derived from alkalic rocks agree with this.

Bauxites are commonly enriched in niobium and tantalum, however, as compared with their source rocks, and most bauxites contain concentrations of these elements that exceed their clarkes. Gordon and Murata (1952) showed that Arkansas bauxite derived from nepheline syenite is characterized by a 3.8-fold enrichment of niobium.

According to Pachadzhanov (1964) niobium and tantalum are present in the bauxite chiefly in the aluminum minerals, gibbsite, boehmite, and diaspore, and, to a lesser extent, in titanium and zirconium minerals. Fleischer, Murata, Fletcher, and Narten (1952), however, found that the niobium in the Arkansas bauxite is concentrated in ilmenite.

DEPOSITS OF NIOBIUM AND TANTALUM

Concentration or enrichment of niobium and tantalum is characteristic in several magmatic and postmagmatic stages involved in the emplacement and consolidation of various types of igneous rocks; additionally, some concentration, independent of the origin of the rocks, can be produced as a result of exogenic processes. Most examples of such concentration are of small magnitude and are of geochemical interest only; however, some concentration is of a magnitude large enough to be considered in the realm of commercial deposits.

Deposits of these elements are grouped in table 25 both according to the type of rocks or magma series in which they occur or to which they are genetically related and according to the geologic process by which they were formed. This scheme of classification was used by Kuz'menko (1959, 1960), but it is somewhat modified here to include more examples of North American deposits. It is beyond the scope of this paper to describe the individual niobium and tantalum deposits and their geology. Some of them have been mentioned in other parts of this text in connection with geochemical subjects. The classification table of Kuz'menko will serve to place the different deposits and examples in the proper genetic perspective. Most occurrences of niobium and tantalum can be conveniently classed using this scheme.

The commercial recovery of niobium is made at present from columbite-tantalite, pyrochlore, and euxenite ores and possibly from rocks containing loparite and murmanite. The recovery of tantalum is (or has been) chiefly from columbite-tantalite, microlite, and euxenite ores. Large commercial deposits of columbite-tantalite occur in biotite granites (magmatic type) of Nigeria, as well as in placers (exogenic type) derived from such rocks and pegmatites. Columbite-tantalite with high tenor of tantalum from pegmatites (pegmatitic type) of the Congo region, Africa, and Brazil is the world's principal source of tantalum. Deposits of microlite from lithium-rich pegmatites (pegmatitic type) constitute small but significant sources of tantalum in the Taos region, New Mexico. Placers (exogenic type) containing euxenite and other minor pegmatite minerals have been a commercial source of both niobium and tantalum at Bear Valley,

TABLE 25.—*Classification of deposits of niobium and tantalum*

[After Kuz'menko (1959)]

Process	Granites	Alkalic granites	Nepheline and alkalic syenites	Alkalic ultramafic rocks
Magmatic	Biotite granites with columbite (Jos Plateau, Nigeria).	Alkalic granites with riebeckite and pyrochlore (Nigeria; Mount Rosa, Colo.).	Agpaites-urtites, lujavrite, juvites with loparite (Lovozero massif, U.S.S.R.).	Pyroxenites and olivinites with perovskite (Afrikanda massif, U.S.S.R.).
	Granites with euxenite, fergusonite (Idaho batholith, Idaho).	----	Miaskites with pyrochlore (Vishnevye Mountains, U.S.S.R.).	
Pegmatitic	Simple pegmatites with columbite tantalite.	Pegmatites with columbite-tantalite, pyrochlore, astrophyllite, etc. (Mount Rosa, Colo.)	Nepheline syenite pegmatites (Urals and Kola Peninsula).	Rutile-brookite pegmatites (Magnet Cove, Ark.).
	Complexly zoned and replaced pegmatites with lithium minerals, tantalite, microlite, etc. (Harding pegmatite, New Mexico).	----	----	
Pneumatolytic-hydrothermal.	Feldspar-quartz veins	Feldspar-quartz veins	Albitites with pyrochlore	Feldspar-calcite veins (Magnet Cove, Ark.)
	Greisen veins	----	Biotite-calcite veins with pyrochlore.	Carbonatites with knopite (Magnet Cove, Ark.).
	----	Albitized zones	----	Carbonatites with pyrochlore and hatchettolite (Sukulu, Uganda).
	Albitized zones	----	Albitized zones with pyrochlore	Natrolite-biotite zones in ijolite with knopite (Oka, Quebec).
	Greisen zones	----	Carbonatized zones with pyrochlore	Carbonatized zones with pyrochlore.
Contact-metasomatic.	----	----	Albitized, nephelinized zones with perovskite, pyrochlore at contact of alkalic rocks and carbonatites (Oka, Quebec).	
Magmatic(?)-metasomatic(?).	----	----	Large stocklike carbonatite masses with pyrochlore (Iron Hill, Colo.).	
Exogenic	Cassiterite, columbite-tantalite placers (Nigeria)	----	Zircon, pyrochlore placers (Sukulu, Uganda).	
	Samarskite placers (Altai, U.S.S.R.)	----	Ilmenite-rutile placers (Urals).	
	Ilmenite placers (Ukraine)	----	Bauxites (Arkansas).	
	Euxenite placers (Bear Valley, Idaho)	----		

Idaho. Large, low-grade deposits of pyrochlore, probably the chief future source of niobium, occur in carbonatites and related alkalic rocks (classed variously from magmatic to pneumatolytic types) from complexes in Brazil, southeastern Canada, Norway, Germany, central Africa, Russia, and the United States (Pecora, 1956). Deposits of loparite and murmanite apparently have been mined in the agpaitic nepheline syenites and other alkalic rocks (magmatic types) of the Lovozero massif, Kola Peninsula, U.S.S.R. Although extraction has never been feasible economically, because of the low tenor of niobium, large quantities of the element are present in the bauxite deposits (exogenic type) of Arkansas and remain an untapped source. Similarly, certain riebeckite granites of Nigeria (magmatic type) contain sufficient disseminated pyrochlore to be considered another large potential source.

SUGGESTIONS FOR FUTURE WORK

Significant future advances in the field of niobium-tantalum geochemistry will depend largely on the availability of a large number of additional accurate chemical analyses of different types of rocks and minerals so that the abundances of these elements and their ratios can be more accurately established. Such data are fundamental to any understanding of geochemical processes and are necessary to deciphering the geochemical characteristics of these elements in different geologic environments.

Special attention should be given to the classification of rocks and to the selection of representative samples of rocks to be analyzed. If possible, rocks selected for niobium-tantalum analyses should also be analyzed chemically for major constituents, allowing more precise classification or allowing comparison on the basis of differentiation index or other groupings.

Representative sampling at the outcrop will remain the responsibility of the collector; however, the selection of sufficient samples to represent the worldwide occurrences reasonably and practically should be the goal. At the present time certain types of rocks are more abundantly represented than others, and certain regions are more extensively represented, so that considerable regional bias and petrologic bias exist.

The study of the distribution of these elements in comagmatic series or their distribution in related rocks of individual complexes or massifis can lead to a clearer understanding of the behavior of these elements in magmatic processes as well as demonstrate variations and peculiarities in concentration of these elements from complex to complex and region to region. Some studies of this type have been made in both the U.S.S.R. and the United States, but few have been made in which accurate analysis of both niobium and tantalum were available.

The available data on niobium and tantalum contents of sedimentary rocks are very scanty and do not permit evaluation of the fate of these elements in the weathering cycle. Study of the contents of these elements in series of samples from fresh rocks of various types of soils is badly needed.

Also highly desirable are additional detailed studies of the distribution of these elements among the major rock-forming minerals of various rock types. The available data have been discussed above, but there is evidence that there are large gaps in our knowledge.

More investigation is needed on the chemical behavior of these elements in compounds and minerals and on their mobility and solubility in ionic complexes in different media.

Increased knowledge of the geochemistry of niobium and tantalum can lead to a better understanding of the origin of these elements in rocks, minerals, and ores. Questions on niobium and tantalum remaining to be answered are:

1. Are some of the rocks anomalously high in niobium and tantalum derived from the mantle?
2. Has there been fractionation of these elements, relatively or absolutely, by magmatic processes during emplacement of rocks possibly originating in the mantle?
3. Are these elements present at clarke values in most crustal magmas, and are they concentrated or fractionated only in late magmatic and certain postmagmatic plutonic stages?
4. Are certain concentrations of these elements characteristic of certain magma types?
5. Are there relations between concentration of these elements in rocks and in ore deposits of these elements, and are there any proximal relations between ore deposits and the distribution of niobium and tantalum in the host rocks?

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GLOSSARY OF NIOBIUM AND TANTALUM MINERALS

A glossary of niobium and tantalum minerals is presented on the following pages as well as lists of minerals of other elements that contain niobium and tantalum in minor amounts. The chief purpose of these data is to show the relationships among the various series of minerals and to give the most recent information on synonomy among the minerals. Some of the names included in the glossary have been disapproved or discredited by the Commission on New Minerals and Mineral Names of the International Mineralogical Association. Although no indication has been made as to the present validity of these names as considered by the Commission, their presentation here is not meant to endorse their usage, but only to show the synonomy and to give reference to the original usage of the name, where possible.

Minerals that contain niobium and tantalum are chiefly oxides and multiple oxides, hydroxides, and silicates; one borate is known. About 90 species and varieties of these minerals contain niobium and tantalum as major constituents and can be considered niobium-tantalum minerals proper. A considerable number of minerals of other elements contain minor or trace amounts of niobium and tantalum. Complex ionic substitution in the various multiple-oxide minerals makes it difficult to represent them by simple chemical formulas. By convention, the minerals are represented by general formulas expressed in terms of three basic components, *A*, *B*, and *X*. (Palache and others, 1944; Bokii, 1956; Kuz' menko, 1959; Veen, 1963). Elements with ionic radii greater than 0.80 A and which normally occur in minerals in eight-fold (rarely six-fold) coordination or higher are designated by *A*. Elements having ionic radii in the range 0.57–0.80 A (such as niobium, tantalum, and titanium) and occurring in six-fold coordination are represented by *B*. Nonmetallic elements, oxygen, fluorine, chlorine, and hydroxyl ion are designated *X*. Silicates and phosphate-bearing minerals are expressed using the *A*, *B*, and *X* designations in conjunction with appropriate silicon-oxygen and phosphorus-oxygen combinations.

The glossary consists of four parts: I, a classification of the niobium-tantalum mineral series according to chemical types designated in terms of *A*, *B*, and *X*; II, an alphabetical listing of niobium-tantalum minerals giving their formulas and brief notations on their crystal system, composition, mode of occurrence, synonomy where appropriate, and pertinent references; III, an alphabetical listing of minerals and their chemical formulas in which 1–5 percent niobium-tantalum have been reported; and IV, an alphabetical listing of minerals and their chemical formulas in which less than one percent niobium-tantalum have been detected. The latter, list IV, is not meant to be complete, inasmuch as a systematic search of the literature for trace amounts of niobium-tantalum in minerals has not been made.

It is beyond the scope of this report to describe these minerals or to include determinative tables. The reader can obtain more detailed mineralogic data by consulting the references cited in the glossary. Supplemental information may be obtained from Dana's System of Mineralogy, 6th and 7th editions, and the "Chemical Index of Minerals" (Hey 1955, 1963). In the glossary Palache, Berman, and Frondel (1944) is entitled "Dana VII."

PART I.—CLASSIFICATION OF MINERALS OF NIOBIUM AND TANTALUM ACCORDING TO CHEMICAL TYPES

OXIDES, HYDROXIDES, AND MULTIPLE OXIDES

- Ilmenorutile-strüverite series, BX_2, B_2X_4
    - Ilmenorutile $(Ti,Nb,Ta,Fe)_2O_4$
    - Strüverite $(Ti,Ta,Nb,Fe)_2O_4$
- Tapiolite-mossite series, BB_2X_6
    - Tapiolite $(Fe,Mn)(Ta,Nb)_2O_6$
    - Mossite $(Fe,Mn)(Nb,Ta)_2O_6$
- Perovskite series ABX_3
    - Dysanalyte $(Ca,Ce,Na)(Ti,Nb,Ta)O_3$
    - Latrappite $(Ca,Na)(Nb,Ti,Fe)O_3$
    - Loparite $(Na,Ce,Ca)(Ti,Nb)O_3$
        - Metaloparite=hydrated loparite
        - Nioboloparite=niobian loparite
        - Irinite=thorian loparite
    - Lueshite $NaNbO_3$
    - Natroniobite $NaNbO_3$ or $NaNb_2O_5OH$
- Fergusonite-formanite series ABX_4
    - Fergusonite $(Y,Er,Ce,Fe)(Nb,Ta,Ti)O_4$
        - Risörite $(Y,Er,Ce,Fe)(Nb,Ti,Ta)O_4$
    - Beta-fergusonite=polymorph of fergusonite
    - Formanite $(Y,Er,U,Th,Ca)(Ta,Nb,Ti)O_4$
- Stibiotantalite-stibiocolumbite series, ABX_4
    - Stibiotantalite $Sb(Ta,Nb)O_4$
        - Stibiobismutotantalite=bismuthian stibiotantalite
    - Stibiocolumbite $Sb(Nb,Ta)O_4$
    - Bismutotantalite $Bi(Ta,Nb)O_4$
- Columbite-tantalite series, AB_2X_6
    - Columbite $(Fe,Mn)(Nb,Ta)_2O_6$
        - Ferrocolumbite $(Fe,Mn)(Nb,Ta)_2O_6$
        - Manganocolumbite $(Mn,Fe)(Nb,Ta)_2O_6$
    - Magnocolumbite $(Mg,Fe)(Nb,Ta)_2O_6$
    - Tantalite $(Fe,Mn)(Ta,Nb)_2O_6$
        - Ferrotantalite $(Fe,Mn)(Ta,Nb)_2O_6$
        - Manganotantalite $(Mn,Fe)(Ta,Nb)_2O_6$
    - Ixiolite $(Ta,Fe,Sn,Nb,Mn)_4O_8$
    - Wodginite $(Ta,Sn,Mn,Nb,Fe,Ti)_{16}O_{32}$
        - Olovotantalite=Sn-Mn tantalate=wodginite?
- Euxenite-polycrase series, AB_2X_6
    - Euxenite $(Y,Ca,Ce,U,Th)(Nb,Ti,Ta)_2O_6$
    - Tanteuxenite $(Y,Ca,Ce,U,Th)(Ta,Ti,Nb)_2O_6$
    - Polycrase $(Y,Ca,Ce,U,Th)(Ti,Nb,Ta)_2O_6$
    - Tantpolycrase $(Y,Ca,Ce,U,Th)(Ti,Ta,Nb)_2O_6$
    - Kobeite $(Y,Fe,U)(Ti,Nb,Ta)_2(O,OH)_6$
    - Fersmite $(Ca,Ce)(Nb,Ti)_2(O,F)_6$
- Aeschynite-priorite series AB_2X_6
    - Aeschynite $(Ce,Ca,Fe,Th)(Ti,Nb)_2O_6$
        - Sinicite $(Ce,Nd,Th,U)(Ti,Nb)_2O_6$
        - Niobo-aeschynite $(Ce,Ca,Th)(Nb,Ti)_2O_6$
        - Lyndochite=niobian-thorian aeschynite(?)
    - Polymignyte $(Ca,Fe,Ce)(Zr,Ti,Nb,Ta)_2O_6$
    - Priorite $(Y,Er,Ca,U,Th)(Ti,Nb)_2O_6$
- Pyrochlore-betafite-microlite series $A_{2-x}B_2X_7$
    - Pyrochlore $(Na,Ca,Ce)_2(Nb,Ti,Ta)_2(O,OH,F)_7$
        - Koppite=cerian-ferrian pyrochlore
        - Marignacite $(Ce,Ca,Na)_2(Nb,Ti,Ta)_2(O,OH,F)_7$
    - Niobozirconolite $CaZr(Ti,Nb)_2O_7$
    - Obruchevite $(Y,U,Ca)_2(Nb,Ti,Ta)_2(O,OH,F)_7$
    - Pandaite $(Ba,Sr)_2(Nb,Ti,Ta)_2(O,OH,F)_7$
        - Priazovite=uranian-yttrian pyrochlore
    - Scheteligite=Mn, Y,Sb,Ti-pyrochlore
    - Yttrobetafite=intermediate between obruchevite and pyrochlore
    - Yttrohatchettolite $(Ca,Y,U)_2(Nb,Ta,Ti)_2(O,OH.F)_7$
    - Betafite $(U,Ca)_2(Nb,Ti,Ta)_2(O,OH,F)_7$
        - Hatchettolite $(Ca,U)_2(Nb,Ti,Ta)_2(O,OH,F)_7$
        - Rare-earth betafite $(RE,U,Ca)_2(Nb,Ti,Ta)_2(O,OH.F)_7$
        - Samiresite $(U,Pb)_2(Nb,Ti,Ta)_2(O,OH,F)_7$
        - Titanobetafite $(U,Ca)_2(Ti,Nb,Ta)_2(O,OH,F)_7$
        - Zirconium betafite $(U,Ca)_2(Ti,Nb,Zr)_2(O,OH,F)_7$
    - Microlite $(Ca,Na)_2(Ta,Nb,Ti)_2(O,OH,F)_7$
        - Bismutomicrolite=bismuthian microlite
        - Djalmaite=microlite
    - Plumbomicrolite $(Pb,Ca)(Ta,Nb)_2(O,OH,F)_7$
    - Rijkeboerite $(Ba,Fe,Pb,U)(Ta,Nb,Ti,Sn)_2(O,OH,H_2O)_7$
    - Westgrenite $(Bi,Ca)(Ta,Nb)_2O_6(OH)$
- Samarskite series AB_2X_6
    - Samarskite $(Y,Fe,U)(Nb,Ti,Ta)_2(O,OH)_6$
        - Calciosamarskite=calcian samarskite
        - Vietinghofite $(Fe,U,Y)(Nb,Ti,Ta)_2O_6$
    - Khlopinite $(Fe,Y,U)_2(Ti,Nb,Ta)_2O_6$
    - Ishikawaite $(U,Fe,Y)(Nb,Ta,Ti)_2O_6$
        - Plumboniobite $(Ca,Pb,Fe,Y,U)Nb_2O_6$
    - Yttrotantalite $(Y,Fe)(Nb,Ta)O_4$ (approximately)
    - Hjelmite=doubtful Mn-Ca yttrotantalite
- Other tantaloniobates
    - Thoreaulite $Sn(Ta,Nb)_2O_7$
    - Pisekite=complex multiple oxide
    - Belyankinite $Ca(Ti,Zr,Si,Nb)_6O_{13}\cdot 14H_2O$
    - Gerasimovskite $(MnCa)_2(Nb,Ti)_5O_{12}\cdot 9H_2O$
    - Simpsonite $Al_4(Ta,Nb)_3(O,OH,F)_{14}$

SILICATES

- Type $A_mB_n(Si_2O_7)_pX_{0-1}$
    - Nenadkevichite $(Na,Ca)(Nb,Ti)(Si_2O_7)\cdot 2H_2O$
    - Niobolabuntsovite $(Ca,Ba)(Ti,Nb)(Si_2O_7)\cdot 2H_2O$
    - Shcherbakovite $(K,Na,Ba)_3(Ti,Nb)_2(Si_2O_7)_2$
    - Wöhlerite $NaCa_2(Zr,Nb)(Si_2O_7)(O,F)$
    - Karnasurtite$(Ce,La,Th)(Ti,Nb)(Al,Fe)(SiP)_2O_7(OH)_4\cdot 3H_2O$
- Type A_4B $Si_2O_{10}X$
    - Niocalite $Ca_4NbSi_2O_{10}(OH,F)$

- Type $nA_2B_2Si_2O_9(n\text{-}x)Na_3PO_4 \cdot xH_2O$
  - Lomonosovite $Na_2(Ti,Nb)_2Si_2O_9 \cdot Na_3PO_4$
    - Beta-lomonosovite=hydrous variety of lomonosovite
  - Murmanite $Na_2(Ti,Nb)_2Si_2O_9 \cdot nH_2O$
    - Betamurmanite=weathered betalomonosovite
  - Epistolite $(Na,Ca)_{2-x}(Nb,Ti)_2Si_2O_{9-x}(OH)_x \cdot n(H_2O,Na_3PO_4)$
- Type $A_2B\ SiO_5X$
  - Fersmanite $(Ca,Na)_2(Ti,Nb)(SiO_5)(F,OH)$
- Type $A_4B_8(Si_4O_{12})X_{17}$
  - Baotite $Ba_4(Ti,Nb)_8(Si_4O_{12})ClO_{16}$
- Others
  - Niobophyllite $(K,Na)_3(FeMn)_6(Nb,Ti)_2(Si,Al)_8(O,OH,F)_{31}$
  - Ilimaussite $Na_4Ba_2CeFeNb_2Si_8O_{28} \cdot 5H_2O$

BORATE

Behierite $(Ta,Nb)BO_4$

PART II—NIOBIUM AND TANTALUM MINERALS

AESCHYNITE (also eschynite)
- $(Ce,Ca,Fe,Th)(Ti,Nb)_2O_6$
- Orthorhombic, naturally metamict.
- Cerium-dominant part of the aeschynite-priorite series.
- $(Nb,Ta)_2O_5$=30–33 percent.
- From granite pegmatites and nepheline syenites.
- Dana VII, v. 1, p. 793–796.
- Lyndochite
  - A niobian-thorian variety of aeschynite(?)
  - Butler (1957); Fleischer (1966); Dana VII, v. 1, p. 787, 789–791.
- Sinicite
  - A variety of aeschynite enriched in U.
  - Chang (1963).
- *Compare* Priorite, Niobo-aeschynite.

BAOTITE
- $Ba_4(TiNb)_8(Si_4O_{12})ClO_{16}$
- Tetragonal.
- A rare silicate of Ba, Ti, and Nb with Cl.
- Nb_2O_5=10.8, 11.5 percent.
- From carbonatic veins and from quartz veins associated with alkalic rocks.
- Vlasov (1964); Heinrich and others (1962); Semenov and others (1961).
- Pao-t'ou-k'uang
  - Synonym of baotite.
  - Heinrich and others (1962).

BEHIERITE
- $(Ta,Nb)BO_4$
- Tetragonal (zircon type, but with smaller unit cell).
- A borate of Ta and Nb.
- From granite pegmatite.
- Mrose and Rose (1961).

BELYANKINITE
- $Ca(Ti,Zr,Si,Nb)_6O_{13} \cdot 14H_2O$
- Orthorhombic or monoclinic (from optical data), poorly crystalline or amorphous?
- $(Nb,Ta)_2O_5$=7.2–7.5 percent (type material).
- From nepheline syenite pegmatite.
- Gerasimovskii and Kazakova (1950).
- Manganbelyankinite (Mn-belyankinite, manganobelyankinite)
  - A manganese-rich variety of belyankinite.
  - Nb_2O_5=7.4 percent.
  - Semenov (1957).
- *See also* Gerasimovskite.

BETAFITE
- $(U,Ca)_2(Nb,Ti,Ta)_2(O,OH,F)_7$
- Cubic, commonly metamict.
- A uranium-titanium-bearing pyrochlore; as redefined by Hogarth contains 15 percent or more U. Part of pyrochlore-betafite series.
- Nb_2O_5=10–50 percent; Ta_2O_5 up to 20 percent.
- Found in granite pegmatites and in alkalic rocks and carbonatites.
- Hogarth (1961 p. 610–633); Veen (1963, p. 35–36); Dana VII, v. 1, p. 803–805.
- Blomstrandite
  - Synonym of betafite.
  - Dana VII, v. 1, p. 803–805.
- Ellsworthite
  - Synonym of betafite; allied to hatchettolite.
  - Veen (1963, p. 36); Hogarth (1961, p. 631); Dana VII, v. 1, p. 751, 755.
- Hatchettolite
  - An uranian-tantalian-titanian variety of pyrochlore similar to betafite, probably in part synonymous with betafite and in part intermediate between betafite and pyrochlore.
  - Veen (1963, p. 36); Hogarth (1961, p. 631); Dana VII, v. 1, p. 751, 754.
- Mendeleyevite
  - Synonym of betafite.
  - Dana VII, v. 1, p. 803–805.
- Rare-earth betafite
  - Near obruchevite and yttrohatchettolite in composition.
  - Vlasov (1964, p. 499, 501).
- Samiresite
  - Plumboan variety of betafite.
  - Dana VII, 1, p. 803–805.
- Tantalobetafite (tantalohatchettolite?)
  - Tantalian betafite, synonym of betafite.
  - Veen (1963, p. 35).
- Titanobetafite
  - Betafite with high Ti content.
  - Veen (1963, p. 26).
- Zirconium betafite
  - Zirconium-bearing betafite, ZrO_2 up to 9.8 percent.
  - Vlasov (1964, p. 507).

BISMUTOTANTALITE
- $Bi(Ta,Nb)O_4$
- Orthorhombic.
- Probably isostructural with stibiotantalite.
- Ta_2O_5=48.7 percent (theoretical).
- From granitic pegmatites.
- Dana VII, v. 1, p. 769–770.
- Ugandite
  - Synonym of bismutotantalite.
  - Hey (1962, p. 221).

COLUMBITE
- $(Fe,Mn)(Nb,Ta)_2O_6$
- Orthorhombic.
- Part of the columbite-tantalite isomorphous series, Nb>Ta; includes ferrocolumbite with Fe>Mn and manganocolumbite with Mn >Fe.
- Nb_2O_5=78.9 percent (theoretical end member).
- Occurs widely in granites and granitic pegmatites.
- Dana VII, v. 1, p. 780–787.

COLUMBITE—Continued
Baierine (baierite)
Synonym of columbite.
Dana VII, v. 1, p. 780.
Dianite
Synonym of columbite.
Dana VII, v. 1, p. 780.
Ferro-ilmenite
Synonym of columbite.
Dana VII, v. 1, p. 780, 785.
Greenlandite
Synonym of columbite.
Dana VII, v. 1, p. 780, 784.
Hermannolite
Synonym of columbite.
Dana VII, v. 1, p. 780, 785.
See also Magnocolumbite, Tantalite.

DYSANALYTE (niobian perovskite)
$(Ca,Ce,Na)(Ti,Nb,Ta)O_3$
Pseudocubic, possibly orthorhombic or monoclinic.
A niobotantalian perovskite in which Nb normally exceeds Ta but not Ti, and Ce and Na may be absent.
Found in alkalic rocks and carbonatites.
Dana VII, v. 1, p. 730, 732–734; Hey (1962); Nickel and McAdam (1963).
Compare Latrappite.

EPISTOLITE
$(Na,Ca)_{2-x}(Nb,Ti)_2Si_2O_{9-x}(OH)_x \cdot n(H_2O,Na_3PO_4)$
Monoclinic.
The niobium analog of murmanite.
$(Nb,Ta)_2O_5$=33.6,32.3 percent.
From alkalic pegmatite.
Semenov and others (1961); Vlasov (1964, p. 547).

EUXENITE $(Y,Ca,Ce,U,Th)(Nb,Ti,Ta)_2O_6$ Orthorhombic, naturally metamict. Part of euxenite-polycrase series; ratios, Ti:(Nb+Ta) lie between 2:3 and 1:1 Nb_2O_5=about 21–34 percent; Ta_2O_5=about 1–22 percent.
From granitic rocks and pegmatites and placers derived from them.
Dana VII, v. 1, p. 787–792; Vlasov (1964, p. 458–470)
Eschwegeite
Tantalian variety of euxenite; synonym of tanteuxenite.
Tavora (1951); Dana VII, v. 1. p. 792–793.
Nuolaite
Variable mixtures of euxenite and obruchevite.
Oliveiraite
Alteration product of euxenite.
Dana, VII, v. 1, p. 774, 791
Tanteuxenite
Variety of euxenite with Ta substituting for Nb.
Dana VII, v. 1, p. 787, 789–791; Arnott (1950).
Wiikite
Variable mixtures of euxenite and obrachevite.

FERGUSONITE
$(Y,Er,Ce,Fe)(Nb,Ta,Ti)O_4$ Tetragonal, naturally metamict.
Part of fergusonite-formanite series; Nb>Ta and Y>Er.
Contains up to 8 percent U and Th in substitution for Y and Er.
Nb_2O_5=54.1 percent (theoretical end member).
Fairly common accessory mineral in granitic pegmatites.
Dana VII, v. 1, p. 757–762.

FERGUSONITE—Continued
Adelpholite
Synonym of fergusonite?
A poorly defined substance, possibly an altered mossite.
Dana VII, v. 1, p. 762, 778–779.
Alpha-fergusonite
Synonym of fergusonite.
A naturally occurring nonmetamict tetragonal fergusonite. Gorzhevskaya and others (1961).
Arrhenite
An altered fergusonite.
Dana VII, v. 1, p. 762.
Beta-fergusonite
A naturally occurring nonmetamict monoclinic polymorph of fergusonite.
Gorzhevskaya and others (1961).
Bragite
Synonym of fergusonite.
Dana VII, v. 1, p. 757, 759, 761.
Kochelite
Synonym of fergusonite.
Dana VII, v. 1, p. 757, 761.
Risörite
A naturally metamict titanian variety of fergusonite.
Dana VII, v. 1, p. 757–758, 760–762.
Rutherfordite
An altered fergusonite.
Dana VII, v. 1, p. 757, 761, 762.
Sipylite
Synonym of fergusonite.
Dana VII, v. 1, p. 757, 759–762.
Tyrite
Synonym of fergusonite.
Dana VII, v. 1, p. 757, 760–761.

FERSMANITE
$(Ca,Na)_2(Ti,Nb)(SiO_5)(F,OH)$
Monoclinic.
A titano-niobosilicate of Ca and Na with F (some without Nb).
$(Nb,Ta)_2O_5$=15.4, 17.95 percent.
From alkalic pegmatite.
Vlasov (1964, p. 549); Hey (1962).

FERSMITE
$(Ca,Ce)(Nb,Ti)_2(O,F)_6$
Orthorhombic.
Isostructural with euxenite.
Nb_2O_5=70.1, 71.5 percent in type material.
Found in syenite pegmatites and in carbonatites.
Bonshtedt-Kupletskaya and Burova (1946); Wambeke (1965).

FORMANITE
$(Y,Er,U,Th,Ca)(Ta,Nb,Ti)O_4$
Tetragonal, naturally metamict.
Part of fergusonite-formanite series, Ta>Nb.
Ta_2O_5=66.2 percent (theoretical end member).
From placers.
Dana VII, v. 1, p. 757–762.

GERASIMOVSKITE (niobobelyankinite)
$(Mn,Ca)_2(Nb,Ti)_5O_{12} \cdot 9H_2O$(?)
Related to belyankinite.
Nb_2O_5=44.9 percent in type material.
Semenov (1957).

- ILIMAUSSITE
  - $Na_4Ba_2CeFeNb_2Si_8O_{28}\cdot 5H_2O$
  - Partly metamict.
  - $Nb_2O_5 = 13.2$ percent.
  - Found in nepheline-sodalite syenite.
  - E. I. Semenov, M. E. Kazakova, and R. A. Alexandrova (written commun., 1967).
- ILMENORUTILE
  - $(Ti,Nb,Ta,Fe)_2O_4$
  - Tetragonal.
  - Part of isomorphous series ilmenorutile-strüverite with $Nb > Ta$.
  - Nb_2O_5 as much as 33 percent; Ta_2O_5 as much as 14 percent—but most analyses are made on inhomogeneous samples.
  - Occurs mostly in alkalic rocks and pegmatites.
  - Cerny and others (1964); Dana VII, v. 1, p. 554, 557–560.
  - Niobo-rutile, rumongite
    - Synonyms of ilmenorutile.
    - Hey (1962, p. 221).
- IXIOLITE
  - $(Ta,Fe,Sn,Nb,Mn)_4O_8$
  - Orthorhombic.
  - A disordered form of tantalite, commonly high in Sn.
  - From granite pegmatites.
  - Nickel and others (1963a); Dana VII, v. 1, p. 778.
- KARNASURTITE
  - $(Ce,La,Th)(Ti,Nb)(Al,Fe)(Si,P)_2O_7(OH)_4\cdot 3H_2O$
  - Hexagonal, metamict.
  - A hydrous silicate of rare earth elements, Th, Al, Ti, and Nb containing P; presumably related to huttonite, cheralite, and monazite.
  - $Nb_2O_5 = 2.2\text{–}8.2$ percent.
  - From zoned aegirine-microcline-natrolite-hackmanite pegmatites.
  - Kuz'menko and Kozhanov (1959); Vlasov and others (1959, p. 423–425).
- KOBEITE
  - $(Y,Fe,U)(Ti,Nb,Ta)_2(O,OH)_6$
  - Metamict.
  - Near euxenite-polycrase or aeschynite-priorite series in composition, but with low $(Nb,Ta)_2O_5$ content.
  - $(Nb,Ta)_2O_5 =$ about 5 percent.
  - From granitic pegmatites, placers.
  - Takubo and others (1950); Hutton (1957)
- LATRAPPITE
  - $(Ca,Na)(Nb,Ti,Fe)O_3$
  - Orthorhombic.
  - A newly defined member of the perovskite group containing dominant Ca and Nb.
  - $Nb_2O_5 = 43.9$; $TiO_2 = 10.1$.
  - Occurs in carbonatites.
  - Nickel (1964).
- LOMONOSOVITE
  - $(Na,Ca,Ba,K)_9(Ti,Fe,Nb,etc.)_4\ (Si,Al)_4P_2(O,F)_{25}$ or $Na_2(Ti,Nb)_2Si_2O_9\cdot Na_3PO_4$
  - Triclinic.
  - Part of lomonosovite-murmanite series.
  - $(Nb,Ta)_2O_5$ reaches about 6 percent in some varieties.
  - From alkalic pegmatities.
  - Gerasimovskii (1950).
  - Beta-lomonosovite
    - Hydrous variety of lomonosovite.
    - Gerasimovskii and Kazakova (1962).

- LOMONOSOVITE—Continued
  - Metalomonosovite
    - Synonym of beta-lomonosovite.
    - Semenov and others (1961).
  - Ortholomonosovite
    - Synonym of lomonosovite.
    - Semenov and others (1961).
- LOPARITE
  - $(Na,Ce,Ca)(Ti,Nb)O_3$
  - Cubic.
  - A cerian-niobian perovskite with cerium-earth content near 30 percent.
  - $(Nb,Ta)_2O_5 =$ about 10 percent; Nb predominant.
  - Occurs in alkalic pegmatites.
  - Vlasov and others (1959, p. 332–339); Dana VII, v. 1, p. 730, 732–734.
  - Irinite
    - A metamict thorian variety of loparite.
    - Borodin and Kazakova (1954).
  - Metaloparite
    - A hydrated alteration product of loparite.
    - Gerasimovskii (1941).
  - Niobolopatite
    - A niobian variety of loparite with Nb_2O_5 content as much as 26 percent, but $Ti > Nb$.
    - Tikhonenkov and Kazakova (1957).
- LUESHITE
  - $NaNbO_3$
  - Orthorhombic (pseudocubic).
  - The sodium-niobium analog of perovskite.
  - $(Nb,Ta)_2O_5$ reaches 80 percent; Nb predominant.
  - Occurs in alkalic rocks and carbonatites.
  - Safiannikoff (1959); Bargasarov and others (1962); Parker and others (1962).
  - Igdloite
    - Synonym of lueshite.
    - Danø and Sørensen (1959).
  - Natroniobite
    - $NaNbO_3$ or $NaNb_2O_5OH$
    - Monoclinic; dimorph of lueshite? Structural affinities unknown.
    - Occurs in carbonatites.
    - Bulakh and others (1960); Kukharenko and others (1965).
- MAGNOCOLUMBITE
  - $(Mg, Fe, Mn)\ (Nb, Ta)_2O_6$
  - Magnesium analog of columbite.
  - $Nb_2O_5 = 70.6$ percent; $Ta_2O_5 = 10.45$ percent.
  - Occurs in pegmatite that has assimilated dolomite.
  - Matias and others (1963).
- MICROLITE
  - $(Ca,Na)_2(Ta,Nb,Ti)_2(O,OH,F)_7$
  - Cubic.
  - Part of pyrochlore-microlite series.
  - $Ta_2O_5 = 82.1$ percent (theoretical end member).
  - From albitized granitic pegmatites.
  - Dana VII, v. 1, p. 748–757; Veen (1963, p. 26); Bonshtedt-Kupletskaya (1966).
  - Bismutomicrolite
    - Bismuthian variety of microlite; ($Bi_2O_3 = 3.25$ percent).
    - Vlasov (1964), p. 507).
  - Djalmaite
    - Uranoan microlite or tantalian betafite?
    - Tavora (1950); Dana VII, v. 1, p. 805; Veen (1963, p. 36).

MICROLITE—Continued

Haddamite
Synonym of microlite.
Dana VII, v. 1, p. 748.

Metasimpsonite
Synonym of microlite.
Dana VII, v. 1, p. 748, 755.

Neotantalite
Synonym of microlite.
Dana VII, v. 1, p. 748, 755.

Uranmicrolite
Synonym of djalmaite.
Vlasov (1964, p. 507).

MURMANITE
$Na_2(Ti,Nb)_2Si_2O_9\cdot nH_2O$
Monoclinic.
Part of murmanite-lomonosovite series.
$(Nb,Ta)_2O_5$ reaches about 10 percent in some analyses.
From alkalic rocks, Kola peninsula, USSR.
Es'kova (1959); Vlasov (1964, p. 544–547).

Beta-murmanite
Of dubious validity; considered a weathering product of beta-lomonosovite.
Vlasov (1964, p. 546); Fleischer (1963).

Metamurmanite
Synonym of beta-murmanite.
Vlasov (1964, p. 544).

NENADKEVICHITE
$(Na,Ca)(Nb,Ti)Si_2O_7\cdot 2H_2O$
Orthorhombic (by optical methods).
Part of nenadkevichite-labuntsovite series; Nb_2O_5: $TiO_2=2$ or more.
$Nb_2O_5=24.05$–24.6 percent (original analyses).
From natrolite-albite pegmatite in aegirine lujavrite.
Kuz'menko and Kazakova (1955); Semenov (1959); Vlasov (1964, p. 533).

Niobolabuntsovite
Member of nenadkevichite-labuntsovite series; Nb_2O_5: $TiO_2=1:3$–$1:2$.
Semenov (1959); Vlasov (1964, p. 533–535).

NIOBO-AESCHYNITE
$(Ce,Ca,Th)(Nb,Ti)_2O_6$
Niobium analog of aeschynite.
$Nb_2O_5=41.4$ percent.
Zhabin and others (1960).

NIOBOPHYLLITE
$(K,Na)_{2.95}(Fe,Mn)_{6.35}(Nb,Ti)_{2.02}(Si,Al)_{7.70}(O,OH,F)_{31}$
Triclinic.
The niobium analog of astrophyllite.
$Nb_2O_5=14.8$ percent; $Ta_2O_5=0.5$ percent.
Found in paragneiss with albite, arfvedsonite, aegirine-augite, and pyrochlore.
Nickel and others (1964).

NIOBOZIRCONOLITE
$CaZr(Ti,Nb)_2O_7$
Pseudocubic, metamict.
A niobian variety of zirconolite.
$Nb_2O_5=24.8$ percent; $Ta_2O_5=2.0$ percent.
From apatite-magnetite rocks of the Vuori-Yarvi massif, U.S.S.R.
Borodin and others (1960).

NIOCALITE
$Ca_4NbSi_2O_{10}(OH,F)$
Monoclinic.
A silicate of Ca and Nb closely related to wöhlerite, hiortdahlite, and låvenite.
$Nb_2O_5=16.6$, 18.9 (type locality).
From carbonatite, Oka district, Quebec.
Nickel and others (1958).

OBRUCHEVITE
$(Y,Ca,U)_2(Nb,Ti,Ta)_2(O,OH,F)_7$
Yttrium analog of pyrochlore.
Veen (1963, p. 37).
Nuolaite and wiikite are variable mixtures of euxenite and obruchevite.

PANDAITE
$(Ba,Sr)_2(Nb,Ti,Ta)_2(O,OH,F)_7$
Barium analog of pyrochlore.
$Nb_2O_5=65$–67 percent; $Ta_2O_5=0.2$–0.5 percent.
From carbonatites.
Veen (1963, p. 37).

PISEKITE
A niobate-tantalate-titanate of U and rare earths with Th and Sn; no analysis.
Tetragonal or monoclinic(?), metamict.
From pegmatite with strüverite, beryl, tourmaline, monazite, and garnet.
Dana VII, v. 1, p. 807–808; Seidl (1960); Bouška (1960).

PLUMBOMICROLITE
$(Pb,Ca)(Ta,Nb)_2(O,OH,F)_7$
Lead analog of microlite.
$Ta_2O_5=50.4$ percent; $Nb_2O_5=11.1$ percent.
Safiannikoff and Wambeke (1961).

POLYCRASE
$(Y,Ca,Ce,U,Th)(Ti,Nb,Ta)_2O_6$
Orthorhombic, naturally metamict.
Part of euxenite-polycrase series; ratios $Ti:(Nb+Ta)$ lie between $1:1$ and $3:1$.
$Nb_2O_5=$ about 4–20 percent; $Ta_2O_5=$ up to 23 percent.
Found in granitic pegmatites.
Dana VII, v. 1, p. 787–792.

Tantalopolycrase
Variety of polycrase in which Ta replaces Nb.
Dana VII, v. 1, p. 790, 791; Simpson (1938, p. 112).

POLYMIGNYTE
Possibly $(Ca,Fe,Ce)(Zr,Ti,Nb,Ta)_2O_6$
Orthorhombic, metamict.
A zirconium-titanium-niobium mineral of uncertain affinities, possibly related to aeschynite or zirconolite.
$Nb_2O_5=11.99$, 6.37 percent and $Ta_2O_5=1.35$, 42.17 percent in two analyses from Fredricksvärn, Norway.
From alkalic rocks and pegmatites and granite pegmatite.
Dana VII, v. 1, p. 764–766; Lima-de-Faria (1964, p. 45–46); Vlasov (1964).

PRIORITE
$(Y,Er,Ca,U,Th)(Ti,Nb)_2O_6$
Orthorhombic, naturally metamic.
Part of aeschynite-priorite series (yttrian).
$(Nb,Ta)_2O_5=16$–37 percent.
From granite pegmatites and nepheline syenites.
Dana VII, v. 1, p. 793–797.

Blomstrandine
Also blomstrandinite.
Synonym of priorite.
Dana VII, v. 1, p. 793, 796.

PYROCHLORE
$(Na,Ca,Ce)_2(Nb,Ti,Ta)_2(O,OH,F)_7$
Cubic.
Part of the pyrochlore-microlite series.
Nb_2O_5=73.05 percent (theoretical end member).
From alkalic rocks and pegmatites, carbonatites, and albite-riebeckite granites.
Dana VII, v. 1, p. 747–757; Veen (1963); Bonshtedt-Kupletskaya (1966).

Azor-pyrrhite
Synonym of pyrochlore.
Dana VII, v. 1, p. 748, 754.

Chalcolamprite
Variety of pyrochlore(?) containing Si and Zr; possibly mixture of minerals.
Dana VII, v. 1, p. 748, 754.

Columbomicrolite
Synonym of pyrochlore.
Veen (1963, p. 26).

Endeiolite
Probably altered pyrochlore.
Dana VII, v. 1, p. 748, 754.

Fluochlore
Synonym of pyrochlore.
Dana VII, v. 1, p. 748.

Hydrochlore
Synonym of pyrochlore.
Dana VII, v. 1, p. 748.

Koppite
Cerian-ferrian variety of pyrochlore.
Veen (1963, p. 37); Dana VII, v. 1, p. 748, 750, 752, 754, 755.

Marignacite
A cerian pyrochlore, probably altered.
Dana VII, v. 1, p. 748, 751, 752, 755; Veen (1963, p. 37).

Niobpyrochlore
Synonym of pyrochlore.
Dana VII, v. 1, p. 748.

Priazovite
Uranian pyrochlore rich in Y, synonymous with obruchevite ?
Veen (1963, p. 37).

Pyrrhite
Synonym of pyrochlore.
Dana VII, v. 1, p. 748, 752, 754.

Scheteligite
Titanian pyrochlore rich in Mn, Y, and Sb.
Veen (1963, p. 36); Dana VII, v. 1, p. 757.

Uranpyrochlore
Uranium-bearing pyrochlore near hatchettolite in composition.
Vlasov (1964, p. 487–488); Dana VII, v. 1, p. 751, 754.

Yttrobetafite
A variety of pyrochlore intermediate between pyrochlore and obruchevite.
Kalita and others (1962).

Yttrohatchettolite
Yttrium-uranium-bearing pyrochlore with Nb and Ta nearly equal.
Vlasov (1964, p. 487–489).
Compare Obruchevite.

RIJKEBOERITE
$(Ba,Fe,Pb,U)(Ta,Nb,Ti,Sn)_2(O,OH,H_2O)_7$
Barium analog of microlite.
Ta_2O_5=71.6 percent; Nb_2O_5=5.9 percent.
Veen (1963, p. 135–137)

SAMARSKITE
$(Y,Fe,U)(Nb,Ti,Ta)_2(O,OH)_6$
Orthorhombic; normally metamict.
A titano-tantalo-niobate of Fe, Y, and U.
Nb_2O_5 = 27.8–46.4 percent; Ta_2O_5 = 1.8–27.0 percent.
From granite pegmatites.
Dana VII, v. 1, p. 797–800; Gorzhevskaya and Sidorenko (1963).

Ampangabeite
Synonym of Samarskite.
Dana VII, v. 1, p. 806–807; Wambeke (1960).

Ånnerödite
Synonym of Samarskite.
Dana VII, v. 1, p. 797, 799.

Calciosamarskite
A supposed calcian samarskite, but X-ray pattern after ignition differs from that of samarakite and is similar to that of obruchevite.
Dana VII, v. 1, p. 772; Gorzhevskaya and Sidorenko (1963).

Eytlandite
Synonym of samarskite.
Dana VII, v. 1, p. 797.

Hydrosamarskite
An altered samarskite.
Dana VII, v. 1, p. 800.

Ishikawaite
A variety of samarskite with high U and Fe content.
Gorzhevskaya and Sidorenko (1963); Dana VII, v. 1, p. 766.

Khlopinite
Also chlopinite, hlopinite.
A titanian variety of samarskite (?)
Dana VII, v. 1, p. 792.

Nohlite
Probably a mixture, part of which is samarskite.
Dana VII, v. 1, p. 772–773.

Nuevite
Synonym of samarskite.
Murdoch (1951).

Plumboniobite
Probably a plumbian variety of samarskite.
Dana VII, v. 1, p. 800–801.

Rogersite
An altered samarskite.
Dana VII, v. 1, p. 800; Heinrich and Quon (1963).

Uranniobite
Synonym of samarskite.
Dana VII, v. 1, p. 797.

Uranotantal
Synonym of samarskite.
Dana VII, v. 1, p. 797.

Vietinghofite
A ferroan variety of samarskite.
Dana VII, v. l, p. 800–801.

Yttroilmenite
Synonym of samarskite.
Dana VII, v. 1, p. 763, 797.

SHCHERBAKOVITE
$(K,Na,Ba)_3(Ti,Nb)_2(Si_2O_7)_2$
Monoclinic(?) or orthorhombic.

SHCHERBAKOVITE—Continued
Part of shcherbakovite-batisite series.
$(Nb,Ta)_2O_5$ = about 10 percent.
From pectolite-natrolite pegmatites associated with alkalic rocks.
Es'kova and Kazakova (1954);
Yakovlevskaya and Efimov (1963).

SIMPSONITE
$Al_4(Ta,Nb)_3(O,OH,F)_{14}$
Hexagonal.
Principally an oxide of Al and Ta.
Ta_2O_5 = 81.25 percent (theoretical).
From granite pegmatites.
Dana VII, v. 1, p. 771; Knorring and Hornung (1963).
Calogerasite
Synonym of simpsonite.
Guimarães (1944).

STIBIOCOLUMBITE
$Sb(Nb,Ta)O_4$
Orthorhombic.
Part of the stibiotantalite-stibiocolumbite series.
$Nb_2O_5=47.7$ percent (theoretical end member).
From granitic pegmatites.
Dana VII, v. 1, p. 767–769.

STIBIOTANTALITE
$Sb(Ta,Nb)O_4$
Orthorhombic.
Part of the stibiotantalite-stibiocolumbite series.
$Ta_2O_5=60.2$ (theoretical end member).
From granitic pegmatites.
Dana VII, v. 1, p. 767–769.
Stibiobismutotantalite
A bismuthian variety of stibiotantalite.
Bandy (1901).

STRÜVERITE
$(Ti,Ta,Nb,Fe)_2O_4$
Tetragonal.
Part of isomorphous series ilmenorutile-stüverite and partial series (?) rutile-tapiolite.
Nb_2O_5 as much as 9.3 percent; Ta_2O_5 as much as 38.2 percent, but some analyses possibly are made on inhomogeneous samples.
Found largely in granitic rocks and pegmatites.
Cerny and others (1964); Dana VII, v. 1, p. 554, 557, 558, 560.
Tantalorutile
Synonym of strüverite.
Hey (1962, p. 221).

TANTALITE
$(Fe,Mn)(Ta,Nb)_2O_6$
Orthorhombic.
Part of columbite-tantalite isomorphous series, Ta>Nb; includes ferrotantalite with Fe>Mn and manganotantalite with Mn>Fe.
$Ta_2O_5=86.1$ (theoretical end member). Found in granitic pegmatites, especially late-stage albitic pegmatites containing Li and Be.
Dana VII, v. 1, p. 780–787.
Alvarolite
Synonym of tantalite (manganoan).
Tavora (1955).
Calciotantalite
Synonym of tantalite ?
Perhaps a mixture of tantalite and microlite.
Dana VII, v. 1, p 787.

TANTALITE—Continued
Harttantalerz
Synonym of tantalite.
Dana VII, v. 1, p. 780.
Ildefonsite
Synonym of tantalite.
Dana VII, v. 1, p. 780.
Siderotantalite
Synonym of tantalite.
Dana VII, v. 1, p. 780.

TAPIOLITE
$(Fe,Mn)(Ta,Nb)_2O_6$
Tetragonal, dimorph of tantalite.
Part of isomorphous series rutile-tapiolite; Ta > Nb.
Nb_2O_5 = 0–35 percent, rarely exceeding 11 percent; Ta_2O_5 up to 86 percent.
Occurs in granitic pegmatites.
Cerny and others (1964); Dana VII, v. 1, p. 775–778.
Mossite
Doubtful apecies.
Niobian analog of tapiolite.
Original analysis in doubt; possibly does not occur in nature.
Cerny and others (1964); Wambeke and others (1964, p. 75); Dana VII, v. 1, p. 775–777.
Niobotapiolite
Niobian variety of tapiolite.
Synonymous with mossite.
Vlasov (1964, p. 438).
Skogbölite
Synonym of tapiolite.
Dana VII, v. 1, p. 775–778.
Compare Ixiolite, Wodginite.

THOREAULITE
$Sn(Ta,Nb)_2O_7$
Monoclinic.
An oxide of Sn, Ta, and Nb.
Ta_2O_5 = 27.8–72.8 percent; Nb_2O_5 up to 40.6 percent.
From tin-bearing pegmatite.
Dana VII, v. 1, p. 802; Thoreau and others (1950).

WESTGRENITE
$(Bi,Ca)(Ta,Nb)_2O_6(OH)$
Bismuth analog of microlite.
Ta_2O_5 = 45.5 percent; Nb_2O_5 = 5.65 percent.
From lithium-bearing pegmatite.
Knorring and Mrose (1962).

WODGINITE
$(Ta,Sn,Mn,Nb,Fe,Ti)_{16}O_{32}$
Monoclinic.
A "polymorph" of tantalite, commonly with high Sr content.
$Ta_2O_5=67.5–70.1$; $Nb_2O_5=7.1–1.35$ percent.
Occurs in granitic pegmatites.
Nickel and others (1963b).
Olovotantalite
Synonym of wodginite ?
Tin-manganese with X-ray pattern similar to that of wodginite
$Ta_2O_5=62.5$; $Nb_2O_5=12.5$ percent.
Matias (1961); Nickel and others (1963b, p. 401).

WÖHLERITE (woehlerite)
$NaCa_2(Zr,Nb)(Si_2O_7)O,F$
$(Nb,Ta)_2O_5=12.8–14.6$ percent.
From alkalic pegmatite and nepheline syenite.
Gossner and Kraus (1934); Nickel and others (1958).

YTTROTANTALITE

$(Y,Fe)(Nb,Ta)O_4$ (approximately).

Orthorhombic, metamict.

A niobate-tantalate of Y (and other rare earths), Ca, Fe, U, Th, Mn, and other elements with minor substitution of W, Zr, and Sn for Nb and Ta.

$Nb_2O_5 = 12–20$ percent; $Ta_2O_5 = 39–46$ percent.

From granite pegmatites.

Dana VII, v. 1, p. 763–764; Vlasov (1964, p. 521–524).

Hjelmite (hielmite)

A doubtful variety of yttrotantalite.

Some hjelmite from Norway proved to be a mixture of pyrochlore and tapiolite; however, this was not the type material from Sweden.

Dana VII, v. 1, p. 779–780; Matias (1961).

PART III.—MINERALS REPORTED TO CONTAIN 1–5 PERCENT NIOBIUM AND TANTALUM

Astrophyllite	$(K,Na)_2(Fe,Mn)_4(Ti,Zr)Si_4O_{14}(OH)_2$
Baddeleyite	ZrO_2
Brookite	TiO_2
Cassiterite	SnO_2
Catapleiite	$(Na_2,Ca)ZrSi_3O_9\cdot 2H_2O$
Chevkinite	$(Fe,Ca)(Ce,La,Y)_2(Si,Ti)_3O_{10}$
Chlorite	$(Mg,Fe)_5Al(Al,Si)_3O_{10}(OH)_8$
Elpidite	$Na_2ZrSi_6O_{12}(OH)_6$
Eudialyte	$(Ca,Na,Ce)_5(Zr,Fe)_2Si_6(O,OH,Cl)_{20}$
Freudenbergite	$Na_2Fe_2Ti_7O_{18}$
Hematite	Fe_2O_3
Hiortdahlite	$(Ca,Na)_{13}Zr_3Si_9(O,OH,F)_{38}$
Ilmenite	$FeTiO_3$
Keilhauite	Yttrian Sphene.
Kimzeyite	$Ca_3(Zr,Ti)_2(Al,Fe,Si)_3O_{12}$
Kupletskite	$(K,Na)_2(Mn,Fe)_4TiSi_4O_{14}(OH)_2$
Labuntsovite	$(K,Na,Ba)TiSi_2(O,OH)_7\cdot \tfrac{1}{2}H_2O$
Låvenite	A complex silicate of Zr, Na, and Ca, also containing Ti, Nb, Fe, Mn, and F.
Lorenzenite	$Na_2(Ti,Zr)_2Si_2O_9$
Lovchorrite	Mosandrite.
Manganosteenstrupine	$(La,Th,Ca)MnSiO_3(OH)_3\cdot 2H_2O$
Melanocerite	Silicate, borate, tantalate, fluoride, etc. of Ca and rare earths.
Mosandrite	$(Na,Ca,Ce)_3TiSi_2O_7(O,F)$
Perovskite	$CaTiO_3$
Ramsayite	Lorenzenite.
Rinkite	Mosandrite.
Rinkolite	Mosandrite.
Rutile	TiO_2
Sphene	$CaTiSiO_5$
Thortveitite	$(Sc,Y)_2Si_2O_7$
Titanolåvenite	$(Na,Mn,Ca)(Zr,Ti)(SiO_4)_2F$
Titanorhabdophane	Tundrite.
Triplite	$(Mn,Fe)_2(PO_4)F$
Tritomite	A silicate, borate, and fluoride of Ca, rare earths, and Th.
Tundrite	$(Ce,La,Nd)_2Ti(Si,P)(O,OH)_7\cdot 4H_2O$
Vernadite	$MnO_2\cdot nH_2O$(?)
Vinogradovite	$Na_5Ti_4AlSi_6O_{24}\cdot 3H_2O$
Vudyavrite	Altered Mosandrite(?)
Wolframite	$(Mn,Fe)WO_4$
Yttrotitanite	Yttrian Sphene.
Yuksporite	A silicate and fluoride of Ca, Sr, Ba, and alkalis(?)
Zircon	$ZrSiO_4$
Zirconolite	$CaZrTi_2O_7$
Zirfesite	$(ZrO_2,Fe_2O_3)SiO_2\cdot nH_2O$

PART IV.—MINERALS IN WHICH NIOBIUM AND TANTALUM HAVE BEEN DETECTED IN QUANTITIES LESS THAN 1 PERCENT

Aegirine	$NaFe^{+3}Si_2O_6$
Allanite	$(Ca,Ce)_2(Al,Fe)_3Si_3O_{12}(OH)$
Amblygonite	$(Li,Na)AlPO_4(F,OH)$
Anatase	TiO_2
Arfvedsonite	$Na_3Fe^{+2}_4Fe^{+3}Si_8O_{22}(OH)_2$
Biotite	$K_2(Mg,Fe^{+2},Al,Fe^{+3})_{4-6}(Si,Al)_8O_{20}(OH)_4$
Erikite	A doubtful phosphate and silicate of rare earths.
Garnet (almandine)	$Fe_3Al_2(SiO_4)_3$
Hisingerite	$Fe_2Si_2O_5(OH)_4\cdot 2H_2O$ (?)
Kaolinite	$Al_2Si_2O_5(OH)_4$
Lamprobolite	$(Ca,Na,K)_{2-3}(Mg,Fe^{+3},Al)_5(Si,Al)_8O_{22}(O,OH)_2$
Lamprophyllite	$Na_2SrTiSi_2O_8$
Lepidolite	$K(Li,Al)_3(Si,Al)_4O_{10}(F,OH)_2$
Leucosphenite	$Na_3CaBaBTi_3Si_9O_{29}$
Magnetite	Fe_3O_4
Muscovite	$KAl_3Si_3O_{10}(OH)_2$
Nontronite	$(Fe,Al)_2(Si,Al)_4O_{10}(OH)_2\cdot nH_2O$
Phlogopite	$KMg_3AlSi_3O_{10}(OH)_2$
Polylithionite	$K_2Li_4Al_2Si_8O_{20}(O,OH,F)_4$
Riebeckite	$Na_2(Fe^{+2},Mg)_3Fe^{+3}_2Si_8O_{22}(OH)_2$
Scheelite	$CaWO_4$
Seidozerite	$Na_8Zr_3Ti_3Mn_2Si_8O_{32}F_4$
Thorianite	ThO_2
Thorite	$ThSiO_4$
Titanomagnetite	$(Fe,Ti)_3O_4$
Tourmaline	$(Na,Ca)(Li,Mg,Fe^{+2},Al)_3(Al,Fe^{+3})_6B_3Si_6O_{27}(O,OH,F)_4$
Tungstite	H_2WO_4
Vlasovite	$Na_2ZrSi_4O_{11}$

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