

# Magnesioneptunite, $\text{KNa}_2\text{Li}(\text{Mg}, \text{Fe})_2\text{Ti}_2\text{Si}_8\text{O}_{24}$ , a New Mineral Species of the Neptunite Group<sup>1</sup>

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**Abstract**—A new mineral of the neptunite group, magnesioneptunite  $\text{KNa}_2\text{Li}(\text{Mg}, \text{Fe})_2\text{Ti}_2\text{Si}_8\text{O}_{24}$ , a Mg-dominant analogue of neptunite and manganoneptunite, has been found in the Upper Chegem caldera near Mount Lakargi, Kabardino–Balkaria, the North Caucasus, Russia in a xenolith of altered sandstone located between skarnified carbonate xenoliths and ignimbrite. Magnesioneptunite occurs as nearly isometric grains and aggregates up to 0.1 mm in size in the cores of some grains of a Mg-rich variety of neptunite with  $\text{Mg}/(\text{Fe} + \text{Mn}) = 0.7\text{--}1.0$ . The chemical composition of magnesioneptunite with a maximum Mg content is as follows, wt %: 3.63  $\text{K}_2\text{O}$ , 8.21  $\text{Na}_2\text{O}$ , 1.73  $\text{Li}_2\text{O}$ , 6.47  $\text{MgO}$ , 0.04  $\text{MnO}$ , 5.87  $\text{FeO}$ , 0.07  $\text{Al}_2\text{O}_3$ , 18.73  $\text{TiO}_2$ , 56.88  $\text{SiO}_2$ , 99.62 in total. The empirical formula is  $(\text{K}_{0.67}\text{Na}_{0.32}\text{Ca}_{0.01})_{\Sigma 1.00}\text{Na}_{2.06}\text{Li}_{1.00} \cdot (\text{Mg}_{1.39}\text{Fe}_{0.71}^{2+})_{\Sigma 2.10}(\text{Si}_{7.90}\text{Al}_{0.01})_{\Sigma 7.91}\text{O}_{24}$ . Grains of magnesioneptunite are dark brown to red-brown, translucent, with vitreous luster.  $D_{\text{calc}} = 3.15 \text{ g/cm}^3$ , and the Mohs hardness is 5–6. Cleavage parallel to the (110) is perfect. The new mineral is optically biaxial, positive,  $\alpha = 1.697(2)$ ,  $\beta = 1.708(3)$ ,  $\gamma = 1.725(3)$ ,  $2V_{\text{meas}} = 45(15)^\circ$ . The mineral is associated with quartz, alkali feldspar, rutile, aegirine, and neptunite. Magnesioneptunite and the Mg-rich variety of neptunite were formed as products of ilmenite alteration. Magnesioneptunite is monoclinic,  $C2/c$ ; unit-cell parameters:  $a = 16.327(7)$ ,  $b = 12.4788(4)$ ,  $c = 9.9666(4) \text{ \AA}$ ,  $\beta = 115.6519(5)^\circ$ ,  $V = 1830.5(1) \text{ \AA}^3$ ,  $Z = 4$ . The type specimen is deposited at the Fersman Mineralogical Museum of the Russian Academy of Sciences, Moscow.

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## INTRODUCTION

A new mineral magnesioneptunite was discovered at the interfluvial of the Chegem and Kestanty rivers near Mount Lakargi in the Upper Chegem volcanic caldera located in the mountain part of Kabardino–Balkaria, the North Caucasus, Russia. The Upper Chegem caldera is about 110 km<sup>2</sup> in area with several volcanic centers of different ages. A sequence of rhyolitic and rhyodacitic ignimbrites and tuffs 1.5 km thick intruded by granodiorite porphyry stock occupy the lower part of the volcanic edifice. The volcanic rocks are covered by moraine of Mindel glaciation, in turn, overlapped by lava flows of two-pyroxene andes-

ite. The K/Ar age of ignimbrite is 2.8–3.0 Ma; the age of granodiorite porphyry is  $2.5 \pm 0.2 \text{ Ma}$  (Borsuk, 1979) or 2.7 Ma (Ar–Ar method) (Lipman et al., 1993; Gazis et al., 1995).

Large xenoliths of marmorized and skarnified limestone, dolomite, mudstone, and siltstone were found on the eroded surface of the volcanic edifice close to the crest of a small ridge between the Lakargi and Vorlan peaks. The size of carbonate xenoliths ranges from a few meters to a few tens of meters; mudstone and siltstone xenoliths reach a few meters across (Gazeev et al., 2006). Carbonate xenoliths have been studied in more detail. Marble cores and skarn envelopes are distinguished. These xenoliths were repeatedly described in connection with new minerals found therein: calcioolivine  $\gamma\text{-Ca}_2\text{SiO}_4$  (Zadov et al., 2008), lakargiite  $\text{CaZrO}_3$  (Galuskin et al., 2008), chegemite  $\text{Ca}_7(\text{SiO}_4)_3(\text{OH})_2$  (Galuskin et al., 2009), kumtyubeite  $\text{Ca}_5(\text{SiO}_4)_2\text{F}_2$  (Galuskina et al., 2009), bitikleite-

<sup>1</sup> The new mineral magnesioneptunite and its name were recommended by the Commission on New Minerals and Mineral Names, Russian Mineralogical Society, and approved by the Commission on New Minerals, Nomenclature, and Mineral Classification, International Mineralogical Association (IMA no. 2009-009).

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(ZrFe), and bitikleite-(SnAl) (Galuskina et al., 2010). The location of the xenoliths and their numeration were published by Galuskin et al. (2009). In contrast to the aforementioned minerals, magnesioneptunite was found in the altered sandstone separating carbonate larnite–cuspidine skarn of xenolith no. 5 and host ignimbrite rather than in the skarn itself.

In the type locality of magnesioneptunite, fragments of skarn, hornfels after sandstone, and unaltered arkosic sandstone were found as a residual material. The contact of carbonate xenolith with rhyodacitic ignimbrite is stripped there. Fragments of sandstone up to 10–15 cm in size are traced along the contact between ignimbrite and skarn, and relics of reaction zones with both contacting rocks are observed in some fragments. The fine-grained, substantially quartz sandstone, occasionally with small quartz pebbles, is composed of angular and rounded quartz grains, minor potassic feldspar, and sodic plagioclase. Sandstone is enriched in Cs (up to 0.5 ppm), which concentrates in the micrograins of pollucite and Cs-bearing analcime. The texture of sandstone is inequigranular psammitic with basal and less frequent contact–porous cement containing segregations of silica and iron hydroxides.

Magnesioneptunite and visually indistinguishable Mg-rich variety of neptunite (Table 1) were identified in altered sandstone (hornfels) containing quartz, (fractured grains up to 1–2 mm in size), newly formed sanidine (minor), microcline, albite, aegirine, and isotropic matrix (glass) containing SiO<sub>2</sub>, CaO, and a little Na<sub>2</sub>O and K<sub>2</sub>O. The minerals of neptunite–magnesioneptunite series occur as brownish almost isometric grains and less frequent prismatic crystals up to 0.06 mm in size and aggregates of the crystals and grains up to 0.1 mm in size, which are always confined to rutile grains (Fig. 1). The content of the neptunite-group minerals in rock locally reaches 1 vol %.

Aegirine is more abundant in altered sandstone than the neptunite-group minerals. The compositions of rutile and aegirine are variable; ilmenite is enriched in Mg (Table 2). Micrograins of monazite-(Ce) are abundant; thin veinlets of calcite with andradite have been noted.

#### MAGNESIONEPTUNITE: COMPOSITION AND PROPERTIES

Until now, the neptunite group comprised three minerals (Table 1): neptunite (FeTi member), manganeseptunite (MnTi member), and its vanadium counterpart watatsumiite (Matsubara et al., 2003). A significant amount of Mg can be incorporated in these minerals (Table 1). The variety of neptunite enriched in Mg was reported from San Benito County, California, USA (Bradley, 1909). Recently, the Mg-richest neptunite was identified in the Dara-i-Pioz alkaline pluton, Alai Ridge, Tajikistan (Dusmatov and Kabanova,

1967). This finding was unique, because a background content of MgO in the Dara-i-Pioz neptunite is <1 wt % (personal communication of L.A. Pautov and our data). Natural Mg-dominant neptunite was repeatedly predicted (Semenov, 1972; *Mineralogy ...*, 2003). The described new mineral was named after its chemical composition and its belonging to the neptunite group. The idealized formula of the end member is KNa<sub>2</sub>LiMg<sub>2</sub>Ti<sub>2</sub>Si<sub>8</sub>O<sub>24</sub>, but taking into account real chemical compositions of the Lakargi samples, the simplified formula of the new mineral, KNa<sub>2</sub>Li(Mg,Fe)<sub>2</sub>Ti<sub>2</sub>Si<sub>8</sub>O<sub>24</sub>, is more correct.

The Mg/(Fe + Mg) value of the neptunite-group minerals from Lakargi ranges from 0.68 (neptunite) to 1.39 (magnesioneptunite). These minerals are characterized by deficiency in K (K<sub>0.6–0.7</sub>) and a small excess of Na (Na<sub>2.1–2.3</sub>) relative to the idealized formula KNa<sub>2</sub>Li(Mg,Fe)<sub>2</sub>Ti<sub>2</sub>Si<sub>8</sub>O<sub>24</sub>. Characteristic admixtures reach, wt %: 0.4 MnO, 0.3 Al<sub>2</sub>O<sub>3</sub>, 0.4 CaO, 0.3 V<sub>2</sub>O<sub>5</sub>, 0.2 ZrO<sub>2</sub> and 0.2 Cr<sub>2</sub>O<sub>3</sub>. The representative compositions of magnesioneptunite, accompanying neptunite and other members of the group are given in Table 1.

The physical properties of all minerals of the neptunite group are similar (Table 3). The cleavage of magnesioneptunite is perfect parallel to the (110), and the color ranges from dark brown to red-brown.

The new mineral is biaxial, positive,  $n_p = 1.697(2)$ ,  $n_m = 1.708(3)$ ,  $n_g = 1.725(3)$ ,  $2V(\text{calc}) = 78^\circ$ ,  $2V(\text{meas}) = 78^\circ$ . The absorption of magnesioneptunite is similar to that of other titanium members of the group ( $N_g > N_m > N_p$ ), but pleochroic colors are lighter:  $N_p$ , from light greenish brown to very light brown;  $N_m$ , light brown; and  $N_g$ , brown. The refractive indices (Table 3) and pleochroism of magnesioneptunite are almost identical to those of Mg-rich neptunite from Dara-i-Pioz ( $n_g = 1.723$ ,  $n_p = 1.698$ ) reported by Dusmanov and Kabanova (1967), undoubtedly owing to close chemical compositions of the minerals from both localities.

#### X-RAY CRYSTALLOGRAPHY

The X-ray powder diffraction pattern (Table 4) of magnesioneptunite (camera RKD 57.3, FeK<sub>α</sub> radiation, Mn filter) is little different from the X-ray powder diffraction patterns of the other titanium members of the group.

The crystal structure of magnesioneptunite was studied on a single crystal 0.04 × 0.16 × 0.08 mm in size with an XCaliburS equipped with a CCD detector ( $\lambda\text{MoK}_\alpha = 0.7107 \text{ \AA}$ , graphite monochromator). Magnesioneptunite is monoclinic, space group  $C2/c$ ; the unit cell dimensions are  $a = 16.3271(7)$ ,  $b = 12.4788(4)$ ,  $c = 9.9666(4) \text{ \AA}$ ,  $\beta = 115.651(5)^\circ$ ,  $V = 1830.5(1) \text{ \AA}^3$ ,  $Z = 4$ ;  $R = 2.5\%$ .

A detailed description of the crystal structure of magnesioneptunite will be published in a separate paper. Here, only major attributes of the crystal struc-

**Table 1.** Chemical composition of magnesioneptunite in comparison with other neptunite-group minerals

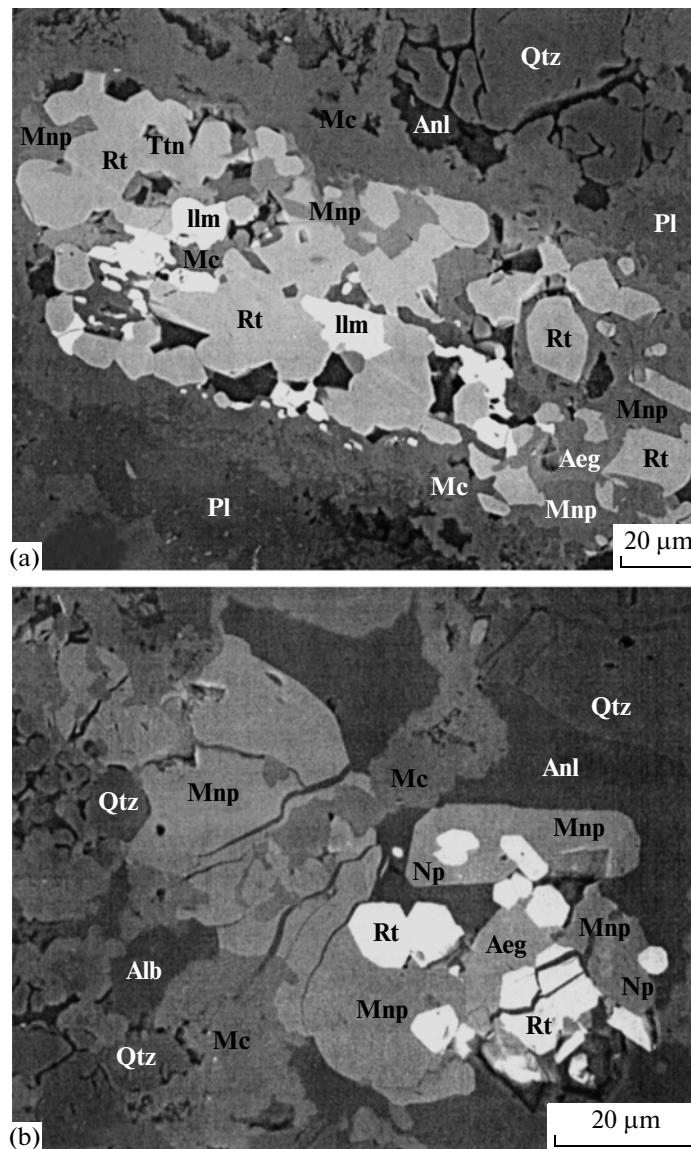
Component	1	2	3	4	5	6	7	8	9	
Wt %										
$\text{Li}_2\text{O}$	1.77	1.70	1.71 <sup>a</sup>	1.71 <sup>a</sup>	1.71 <sup>a</sup>	1.50	1.69 <sup>a</sup>	1.66 <sup>a</sup>	1.60	
$\text{Na}_2\text{O}$	7.33	7.07	8.08	8.21	8.10	7.44	9.56	7.11	7.12	
$\text{K}_2\text{O}$	5.57	5.37	3.61	3.63	3.56	4.46	5.08	5.01	4.89	
$\text{CaO}$			0.08	0.06	0.06	0.50	1.56	—		
$\text{BaO}$									0.85	
$\text{MgO}$	9.54	4.60	5.36	6.47	3.97	4.51	1.44	—	1.60	
$\text{MnO}$			0.07	0.04	0.06	0.60	0.85	15.35	12.31	
$\text{FeO}$		8.19	7.30	5.87	10.14	9.70	11.69	—	0.32	
$\text{Fe}_2\text{O}_3$						1.02	—	—		
$\text{Al}_2\text{O}_3$			0.12	0.07	0.21	0.58	—	—		
$\text{SiO}_2$	56.88	54.82	54.78	54.68	54.72	52.65	52.87	53.28	52.91	
$\text{TiO}_2$	18.91	18.23	18.38	18.73	17.51	16.00	17.83	17.68	3.18	
$\text{V}_2\text{O}_5$			0.07	—	0.26				16.68	
$\text{ZrO}_2$			0.05		0.05					
Total	100	99.98	99.61	99.62	100.41	98.96	102.57	100.09	101.46	
Formula coefficients calculated on the basis of 24 O atoms										
Li	1	1	1.00	1.00	1.00	0.90	1.00	1.00	0.97	
Na	2	2	2.27	2.30	2.29	2.16	2.73	2.07	2.08	
K	1	1	0.67	0.67	0.66	0.85	0.96	0.96	0.94	
Ca			0.01	0.01	0.01	0.08	0.25	—		
Ba								—	0.05	
Mg	2	1	1.16	1.39	0.86	1.01	0.32	—	0.36	
$\text{Mn}^{2+}$			0.01	0.00	0.01	0.08	0.11	1.95	1.57	
$\text{Fe}^{2+}$		1	0.88	0.71	1.24	1.21	1.44	—	0.04	
$\text{Fe}^{3+}$				—		0.11	—	—		
Ti	2	2	2.01	2.03	1.92	1.80	1.98	2.00	0.36	
$\text{V}^{5+}$			0.01		0.03				1.66	
Al			0.02	0.01	0.04	0.10	—	—		
Si	8	8	7.96	7.90	7.97	7.87	7.80	8.015	7.97	
	Technique		Electron microprobe			Chemical analysis		Electron microprobe		
	Source		This study			a	b	c	d	

Note: (1) Theoretical composition of magnesioneptunite (end member); (2) theoretical composition of intermediate member of the neptunite–magnesioneptunite series; (3–5) minerals of the neptunite–magnesioneptunite series from Lakargi; (3) magnesioneptunite (average of 29 analyses), (4) magnesioneptunite with maximum content of Mg, (5) neptunite with maximum content of Fe; (6) Mg-rich neptunite from Dara-i-Pioz, Alai Ridge, Tajikistan; (7) Mg-bearing neptunite from Benitoite Gem Mine, San Benito Co., California, USA; (8) Fe- and Mg-free manganoneptunite from the Kirovsky Mine, Khibiny, Kola Peninsula, Russia; (9) watatsumiite from the Tanohata Mine, Iwate Prefecture, Japan. Dash, the content of element is below the detection limit. Empty column denotes no data. <sup>a</sup>Calculated from stoichiometry for  $\text{Li}_{1.00}$ ; <sup>b</sup>Dusmatov and Kabanova (1967); <sup>c</sup>Mineralogy [...] (2003); <sup>d</sup>Pekov (2005); <sup>e</sup>Matsubara et al. (2003).

ture of magnesioneptunite (Fig. 2) emphasizing its individual features are described.

Magnesioneptunite belongs to “silicates with interrupted frameworks,” where part of the oxygen apices of  $[\text{SiO}_4]$  tetrahedra linking Si atoms in a continuous 3D framework remain unshared. In the anion Si, O

framework of the mineral, zigzag pyroxene-type chains extend along the  $[110]$  and  $[1\bar{1}0]$  and intersect one another at 80 and 100°. Chains of different levels are connected by bridge oxygen atoms to form almost straightened chains parallel to the  $[001]$ . As a result, a tracery framework (more precisely, a quasi-frame-



**Fig. 1.** Ilmenite replaced by magnesian neptunite. Polished section, SEM image in reflected electrons: (a) pseudomorph with relicts of ilmenite, (b) zonal crystal of magnesian neptunite–neptunite in microcavity. Mnp, magnesian neptunite; Np, neptunite; Aeg, aegirine; Rt, rutile; Ilm, ilmenite; Mc, microcline; Qtz, quartz; Ttn, titanite; Pl, plagioclase; Anl, analcime; Alb, albite.

work)  $(\text{Si}_4\text{O}_{11})_{\infty\infty}$  arises, where each tetrahedron has only two or three bridge O atoms. In the structure, there are two independent tetrahedral frameworks held by an inversion center, penetrating each other but not intersecting. They are linked by the columns of Ti- and Fe(Mg) octahedra also extending along the  $[110]$  and  $[1\bar{1}0]$ . The columns are crossed at the same angles of 80 and 100°. At the crossing points, they are share apices and are additionally fastened by a couple of nearly regular Li octahedra to form an octahedral cation quasi-framework. Na and K atoms fill cavities (Fig. 2).

The major distinctive feature of the magnesian neptunite structure having an inversion center is the distri-

bution of titanium atoms and divalent cations (Mg, Fe) in the octahedral columns: similar octahedra alternate in pairs [...Ti–Ti–(Mg, Fe)–(Mg, Fe)–Ti–Ti–(Mg, Fe)–(Mg, Fe)...] rather than next nearest [...Ti(Fe, Mn)–Ti–(Fe, Mn)–...] like in the acentric structure of neptunite (Kunz et al., 1991) or manganoneptunite (Zolotarev, Krivovichev, and Yakovenchuk, 2007). Note that in-pair alternation of octahedra had once been established in neptunite (Borisov et al., 1965).

According to the X-ray structural data, the formula of the Lakargi sample is  $(\text{K}_{0.8}\text{Na}_{0.1}\square_{0.1})_1\text{Na}_2\text{Li}(\text{Fe}_{0.53}\text{Mg}_{0.47})_2(\text{Ti}_{0.91}\text{Mg}_{0.09})_2[\text{Si}_4\text{O}_{11}]_2(\text{O, OH})_2$ .

The refined occupancy of octahedral sites of the two types has shown that Mg mostly occurs together

**Table 2.** Chemical composition (wt %) of aegirine, rutile, and ilmenite associated with magnesioneptunite

Component	Aegirine			Rutile		Ilmenite
Na <sub>2</sub> O	12.82	12.86	11.92			
CaO	0.59	0.04	1.88			
MgO	2.31	1.85	2.12			3.76
MnO	0.05	0.10				0.49
FeO	4.09	5.66	24.16*	0.54	0.05	43.04
Fe <sub>2</sub> O <sub>3</sub>	21.24	19.01				
Cr <sub>2</sub> O <sub>3</sub>	0.07	0.03		0.12		0.01
TiO <sub>2</sub>	4.64	6.81	4.14	98.76	99.96	48.93
V <sub>2</sub> O <sub>5</sub>	0.03					
Nb <sub>2</sub> O <sub>5</sub>				0.22		
ZnO			0.29			
Al <sub>2</sub> O <sub>3</sub>	0.21	0.12				0.07
SiO <sub>2</sub>	53.72	52.38	53.96	0.06		
Total	99.72	98.86	98.47	99.70	100.01	96.30

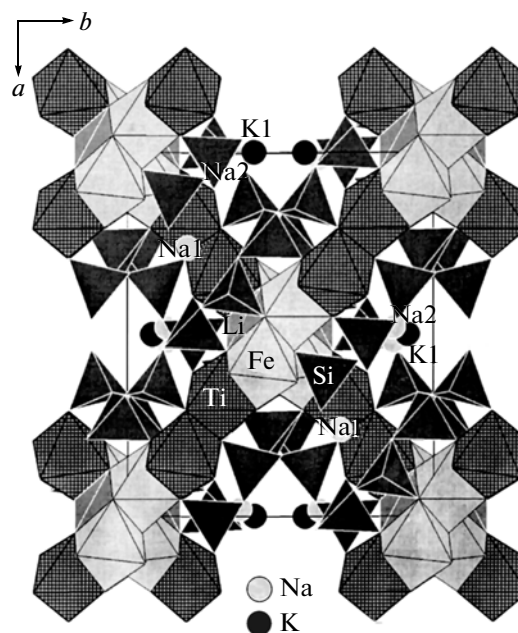
\* Total Fe as FeO

with Fe and a small part of it resides in Ti octahedra. It is evident that a small amount of Ti must enter into (Fe,Mg) octahedra, because the content of Ti is 2.0 apfu (electron microprobe data). The sample studied is also characterized by depletion in K (0.8 instead of 1 apfu) and enrichment in Na (2.1 instead of 2.0 apfu). An additional site of sodium Na2 localized at a distance of 0.65 Å from the site of potassium K1 (Fig. 2) was established in the structure. The K1 and Na2 sites are statistically occupied by atoms with occupancy factors of 0.8 and 0.1, respectively. The balance of valence forces is achieved by partial substitution of O atoms for hydroxyl groups at site O9 (pendant apices of Si tetrahedra).

#### FORMATION CONDITIONS OF MAGNESIONEPTUNITE

The neptunite-group members are formed at high alkalinity (more precisely, peralkalinity) of the medium and associated with other alkaline minerals (*Mineralogy* ..., 2003). In the zone of altered sandstone, alkalinity is markedly elevated (up to common of granitoids). The effect of contact alkalization (Korzhinsky, 1993; Pertsev, 1998) develops when the fluids transfer substance from a medium enriched in acid constituents (primarily SiO<sub>2</sub>) to a basic medium (carbonates, ultramafic rocks, or skarn). In this case, the activity coefficients of bases (mostly alkalis) in the boundary zone increase, and alkaline minerals crystallize in the inner contact zone. The composition of minerals and their relationships show that the neptunite-group members replaced ilmenite, which was a source of titanium, rutile, and aegirine. Figure 1a shows a rutile–magnesioneptunite–aegirine pseudo-

morph that has retained the tabular shape of the primary mineral with relics of ilmenite. Sporadic inclusions of titanite and aegirine are also found within the pseudomorph. The pseudomorph is rimmed by newly formed potassic feldspar separating quartz and plagioclase grains of sandstone from neptunite-group minerals. Less frequently, magnesioneptunite crystallizes in the cavities near the pseudomorph (Fig. 1b). Here, in microcavities, Cs-free analcime is in immediate contact with microcline and quartz. Such a combination

**Fig. 2.** Crystal structure of magnesioneptunite.

**Table 3.** Comparison of titanium minerals of the neptunite group

Property	Magnesioneptunite KNa <sub>2</sub> Li(Mg,Fe) <sub>2</sub> Ti <sub>2</sub> Si <sub>8</sub> O <sub>24</sub>	Neptunite KNa <sub>2</sub> LiFe <sub>2</sub> Ti <sub>2</sub> Si <sub>8</sub> O <sub>24</sub>	Manganoneptunite KNa <sub>2</sub> LiMn <sub>2</sub> Ti <sub>2</sub> Si <sub>8</sub> O <sub>24</sub>
Symmetry	Monoclinic	Monoclinic	Monoclinic
Space group	<i>C2/c</i>	<i>Cc</i> or <i>C2/c</i>	<i>Cc</i> or <i>C2/c</i>
Unit cell dimensions			
<i>a</i> , Å	16.33	16.43–16.48	16.41–16.48
<i>b</i> , Å	12.48	12.48–12.50	12.52–12.55
<i>c</i> , Å	9.96	9.975–10.01	10.03
β, °	115.65	115.4–115.6	115.5
<i>Z</i>	4	4	4
Strong reflections in the X-ray powder diffraction pattern ( <i>d</i> , Å– <i>I</i> )	9.7–80 4.55–40 3.56–100 3.20–90 2.90–40 2.81–40 2.48–80 2.16–60 1.50–70 1.47–40	9.6–60 3.517–45 3.308–35 3.186–100 2.942–32  2.899–30 2.837–32 2.480–32 2.166–30	9.58–50 3.83–40 3.53–80 3.32–40 3.20–100 2.92–40 2.83–40 2.72–60 2.46–90 2.17–60 1.511–90 1.486–80
Density, g/cm <sup>3</sup>	3.15 (calc)	3.19–3.23 (meas)	3.17–3.20 (meas)
Optical parameters			
α	1.697	1.690–1.711	1.689–1.697
β	1.708	1.700–1.721	1.691–1.700
γ	1.725	1.723–1.744	1.713–1.728
optical sign, 2 <i>V</i>	(+) 45° (meas), 78° (calc)	(+) 40–62° (meas)	(+) 31–36° (meas)
Source	This study	Cannillo et al., 1966; Anthony et al., 1995;  <i>Mineralogy</i> [...], 2003	Borisov et al., 1965; Anthony et al., 1995; <i>Mineralogy</i> [...], 2003 Zolotarev, Krivovichev, and Yakovenchuk, 2007

of different mineral assemblage appears to have been caused by abrupt change of mineral-forming conditions, owing to interaction between contacting ignimbrite, sandstone, and skarn. The earliest and high-temperature event was partial or complete decomposition of magnesium ilmenite from sandstone, owing to the oxidation of iron (accessory hematite was found in ignimbrite). The oxidation was caused by high  $f_{O_2}$  in hot volcanic gas at the contact with air when ignimbrite formed. Contemporaneously with decomposition of ilmenite (or close to that in time and conditions), the alkalinity of volcanic fluid increases to form neptunite-group minerals, aegirine, rutile, potassic feldspar, and titanite. In fact, this is the initial stage of

finitization. Thus, Lakargi neptunite and magnesioneptunite are related to weakly finitized sandstone.

The sharp prevalence of Fe<sup>3+</sup> over Fe<sup>2+</sup> along with a low bulk Fe content in the system facilitated incorporation of Mg into the neptunite-group mineral and the formation of aegirine. In the zonal crystals, magnesioneptunite occurs in the core that formed before neptunite. The composition of crystals changes gradually, but in some cases (Fig. 1b), the boundary between magnesioneptunite and neptunite is sharp probably due to abruptly decreasing  $f_{O_2}$  in fluid. The source of Mg to form the neptunite-group minerals was ilmenite, skarn Mg-silicates, and dolomite. The temperature of this process was sufficiently high. We estimated it as no lower than 800°C, because these miner-

**Table 4.** X-ray powder-diffraction data on magnesioneptunite

$I_{\text{meas}}$	$d_{\text{meas}}, \text{\AA}$	$I_{\text{calc}}$	$d_{\text{calc}}, \text{\AA}$	$hkl$
80	9.7	100	9.52	110
20	4.78	18,11	4,798,4.759	$22\bar{1}$ , $220$
40	4.55	39	4.588,4.492	$11\bar{2}$ , $002$
10	3.82	11	3.828	$13\bar{1}$
100	3.56	47	3.506	131
90	3.20	43,24	3.180,3.173	$13\bar{2}$ , $330$
10	3.10	20	3.073	$51\bar{2}$
40	2.90	42,22,20,19	2.932,2.888,2.881,2.865	$22\bar{3}$ , $222$ , $24\bar{1}$ , $510$
40	2.81	51	2.828	132
30	2.74	6,25, 8	2.759,2.721,2.704	$331$ , $51\bar{3}$ , $312$
30	2.57	2,15	2.566,2.546	$33\bar{3}$ , $13\bar{3}$
80	2.48	17,22	2.478,2.462	$62\bar{2}$ , $62\bar{1}$
10	2.41	6	2.399	$44\bar{2}$
20	2.29	10	2.291	$71\bar{2}$
60	2.16	24	2.160	043
20	2.08	3, 8,3,6	2.073,2.072,2.065,2.061	$710$ , $62\bar{4}$ , $13\bar{4}$ , $114$
10	1.92	14	1.914	$26\bar{2}$
10	1.90	8	1.907	261
5	1.59	6,3,2,4	1.608,1.605,1.590,1.576	$750$ , $371$ , $26\bar{4}$ , $75\bar{4}$
5	1.53	5	1.547,1.536,1.518	$11\bar{6}$ , $10.2\bar{4}$ , $10.2\bar{1}$
70	1.50	7, 8,18	1.499,1.497,1.497	$751$ , $006$ , $84\bar{5}$
40	1.47	21,2	1.470,1.463	$841$ , $75\bar{5}$
20	1.38	4,4,3,11,3	1.388,1.382,1.382,1.380,1.379	$71\bar{7}$ , $481$ , $62\bar{7}$ , $190$ , $55\bar{6}$
30	1.35	3, 8,2, 8,2	1.356,1.352,1.351,1.349,1.337	$191$ , $624$ , $912$ , $95\bar{5}$ , $22\bar{7}$

als occur in the most altered part of sandstone xenoliths containing sanidine and Si-rich glass at the contact with ignimbrite. No lower temperature has been suggested at the opposite contact of the sandstone xenolith with the cuspidine–larnite skarn.

The type material of magnesioneptunite has been deposited at the Fersman Mineralogical Museum, Russian Academy of Sciences, Moscow, registration no. 3747/1.

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