

Merwinite-Facies Magnesian Skarns in Xenoliths from Dunite of the Dovyren Layered Intrusion

N. N. Pertsev*, E. G. Konnikov**, E. V. Kislov***, D. A. Orsoev***, and A. N. Nekrasov**

**Institute of the Geology of Ore Deposits, Petrography, Mineralogy, and Geochemistry, Russian Academy of Sciences, Staromonetnyi per. 35, Moscow, 109017 Russia; e-mail: pertsev@igem.ru*

***Institute of Experimental Mineralogy, Russian Academy of Sciences, ul. Institutskaya 14, Chernogolovka, Moscow oblast, 142432 Russia*

****Geological Institute, Siberian Division, Russian Academy of Sciences, ul. Sakh'yanovoi 6a, Ulan-Ude, 670047 Russia*

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Abstract—The late Proterozoic Dovyren dunite–troctolite–gabbro layered massif in the northwestern Baikal area has the morphology of a sill and shows evidence of the replacement of a terrigenous–sedimentary rock sequence, including a 140-m carbonate layer. Relics of the latter are discernible throughout the whole massif in the form of numerous skarn and carbonate xenoliths. Xenoliths in the upper portion of the dunite unit include unique apodolomite spinel–periclase–merwinite skarns, apopericlase brucitites with interstitial spinel and forsterite, and spinel olivinite and spinel monticellitite skarns. The chemistry of the skarn minerals is close to the respective theoretical iron-free end members, which enabled us to apply experimental data to determining their genetic parameters. The merwinite skarns were produced at temperatures above 820°C, p_{CO_2} higher than 7 bar at 820°C and lower than ~100 bar at 1000°C, and assumed $p_{\text{H}_2\text{O}}$ of 500 bar (inferred from geologic reconstructions). The two hypotheses proposed to account for the genesis of the periclase xenoliths are as follows: contact metamorphism of the brucitites and the preferable extraction of Ca (as compared with Mg) from the primary dolomite in mafic–ultramafic magma.

INTRODUCTION

Magnesian skarns contained in the Dovyren dunite–troctolite–gabbro massif are interesting because they are hosted by ultramafic rocks. Widespread in nature and exhaustively studied are magmatic-stage skarns related only to silicic, mafic, and alkaline magmas (Zharikov *et al.*, 1998). It is usually thought that no intermediate (skarn) zones can develop at contacts between a dunite magma and magnesian carbonate rocks because the differences between the activities of major components (SiO_2 , Al_2O_3 , MgO , and CaO) in them are too low. Moreover, the mineral assemblages of these magnesian skarns belong to the rare spinel–merwinite facies, including the merwinite–periclase subfacies, which has not yet been described in skarns. These features impelled us to examine these rocks more closely. The results of this research are presented in this paper.

The very first information about skarns in xenoliths contained in this pluton was published by Gurulev (1965, 1983) and Gurulev *et al.* (1974), but detailed data on the mineralogy of these rocks were absent. The mineralogy and genetic conditions of these rocks were later studied in depth by Pertsev and Shabynin (1979), who described some rare skarn minerals, evaluated the T - p_{CO_2} parameters under which the skarns developed, and hypothesized that the periclase xenoliths could have been produced by contact metamorphism of the

brucitites. Some issues of the mineralogy of the Dovyren skarns and their genesis were touched upon by Efimov *et al.* (1986), Orsoev *et al.* (1993), and Kislov (1998). Wenzel *et al.* (2001, 2002) proposed another hypothesis for the genesis of periclase xenoliths, which involved the partial melting of dolomite with the development of periclase residues, the removal of the calcite melt, and its assimilation by the magma. This model stimulated discussion between the authors of this paper and also stimulated them to more thoroughly examine the magnesian skarns with periclase.

GEOLOGIC SETTING OF THE MASSIF AND THE INNER STRUCTURE OF THE SKARN XENOLITHS

The geology of the Dovyren Massif (which is also referred to as the Ioko-Dovyren Massif) was described in much detail by Gurulev (1965), Konnikov (1986), and Kislov (1998), because of which here we limit ourselves to the brief outline of information needed in the context of this paper.

The Dovyren Massif (Fig. 1) 60 km north of the settlement of Nizhneangarsk in the Northern Baikal District of Buryat Republic, Russia, is spatially restricted to a Riphean pericraton structure and is coeval with riftogenic basaltic magmatism in this structure at 740–700 Ma. The morphology of the mas-

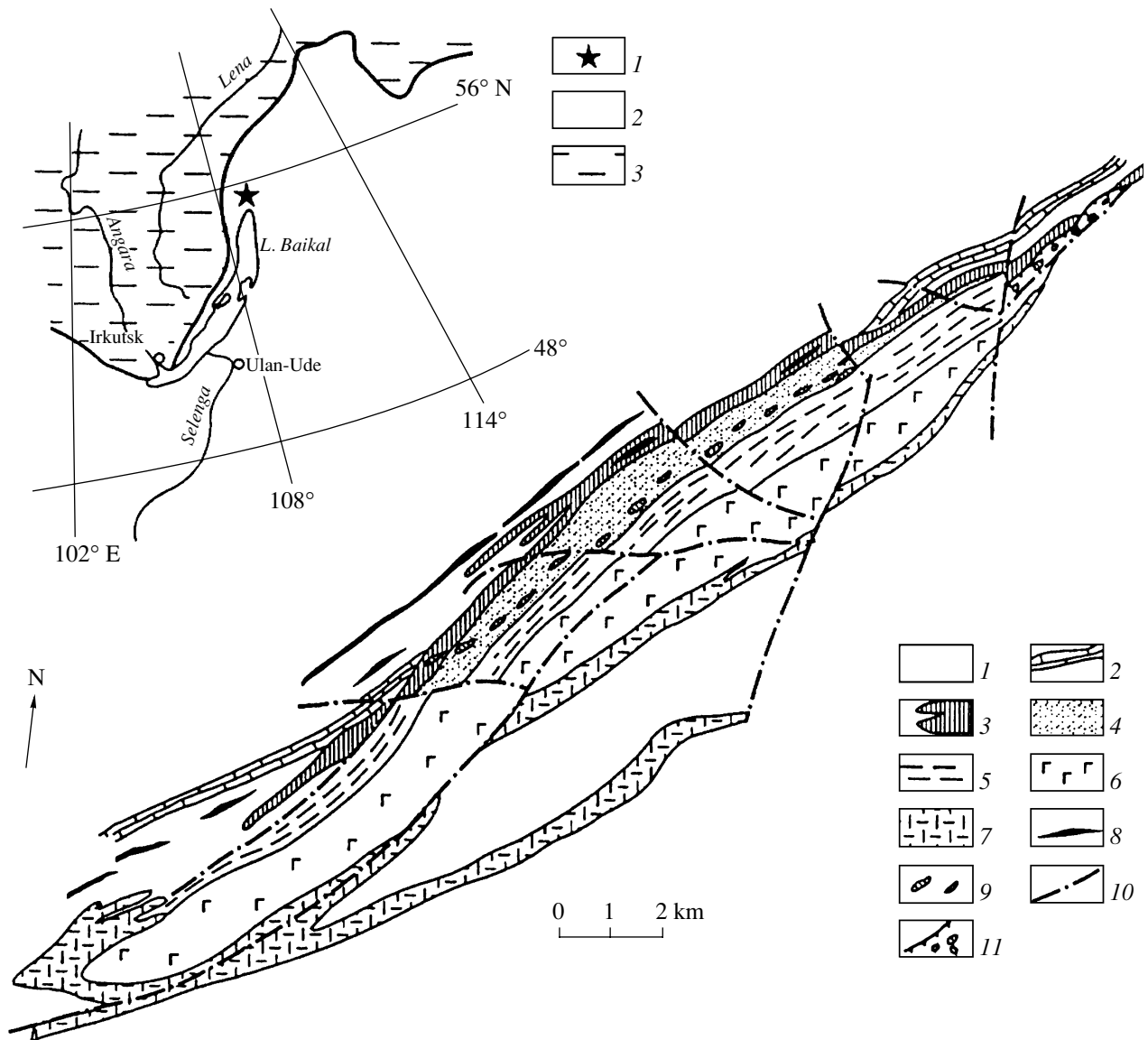


Fig. 1. Schematic map of the Dovyren Massif.

(1) Host terrigenous rocks; (2) host carbonate rocks; (3) plagioclase lherzolite of the lower contact zone; (4–6) units of the layered series of the massif: (4) dunite, (5) troctolite, (6) gabbro; (7, 8) granophyre olivine-free gabbro: (7) large sills, (8) smaller bodies (not to scale); (9) xenoliths of apodolomite magnesian skarns; (10) postintrusive faults; (11) Vendian–Cambrian conglomerates disconformably overlying the rocks of the massif.

The inset shows the position of (1) the Dovyren Massif in (2) the folded formations surrounding (3) the Siberian Platform.

sif resembles a sill-shaped lopolith 26×3 km in size, which sits synformally in a terrigenous–carbonate sequence underlying the Late Riphean volcanics and dipping at steep angles as a result of younger folding. Because of this, the exposed portion of the massif represents its whole cross section, in which the following petrographic units are conventionally distinguished (listed in order from bottom to top): (1) plagioclase lherzolite, (2) dunite and wehrlite, (3) cyclically alternating troctolite layers with diverse mafic indices,

(4) olivine gabbro, (5) olivine gabbro: (7) large sills, (8) smaller bodies (not to scale); (9) xenoliths of apodolomite magnesian skarns; (10) postintrusive faults; (11) Vendian–Cambrian conglomerates disconformably overlying the rocks of the massif.

Depth, m		Rocks and skarn mineral assemblages	Depth, m		Rocks and skarn mineral assemblages
466.4	ooooo	dunite	681	<x<x<	<i>Spl-Mer-Mtc</i> skarn
469.4	::::::::::	wehrlite with sulfides	<x<x<		
470	/ / /	<i>Di</i> veins in wehrlite	<x<x<		
472	<x<x<	alternating <i>Spl-Mtc-Fo</i> ,	694.7	жжжжж	<i>Spl-Fo-Per (Brc)</i> skarn
473	<x<x<	<i>Mer-Per, Spl-Mtc</i> skarn	жжжжж		
473	m m	<i>Mel</i> skarn	700.5	xxxxx	<i>Spl-Mtc-Per (Brc)</i> skarn
481	<x<x<				
481	<x<x<	alternating <i>Spl-Mtc-Fo</i> ,	705.5	xxxxx	alternating <i>Spl-Mtc</i> and
481.5	<x<x<	<i>Mer-Per, Spl-Mtc</i> skarn	714.5	<x<x<	
481.5	xxxxx	<i>Spl-Mtc-Per (Brc)</i> skarn	715	<x<x<	
	xxxxx		<i>Spl-Mtc</i> skarn	m m	<i>Mel</i> skarn
	xxxxx				
	xxxxx				
580	xxxxx				
	xxxxx				
	xxxxx				
616	xxxxx	<i>Spl-Mtc</i> skarn	724.3	L L L	calcic skarn (<i>Ves-Gar-Di-Cal</i>)
622	<<<<	<i>Spl-Mer</i> skarn	L L L		
644	<<<<		<i>Spl-Mer-Mtc</i> skarn	L L L	calcic skarn (<i>Ves-Gar-Di-Cal</i>)
644.3	<x<x<				
	<<<<	<i>Spl-Mer</i> skarn	826	ooooo	alternating wehrlite and pyroxenite
	<<<<				
	<<<<				
	<<<<		844.6	a a a	anorthosite vein
	<<<<		854	T T T T	troctolite with gabbro- pegmatite veins
	<<<<		T T T T		
	<<<<		890.7	T T T T	

Fig. 2. Schematic column of prospecting borehole 143 (borehole head corresponds to the stratigraphic bottom).

marble and calciphyre. More rare rocks here are apodolomite brucite marble, and vein brucitite.¹ The siltstone and sandstone are transformed into pyroxene-facies hornfels. The skarn xenoliths are subdivided into a number of compositional groups. One of them, sampled along Belyi Brook (Fig. 1), is spatially restricted to the troctolite unit. There, large (up to 100 m thick) carbonate xenoliths with lens- and pipe-shaped chert concretions contain diffusion skarns with *Di*, *Wo*, *Mtc*, and other skarn silicates developing around silicified chert nodules. Merwinite was never reliably identified in the rocks, which were described by Pertsev and Shabynin (1978) and are not considered in this publication.

Merwinite skarns (with spurrite and melilite) were first found at the Crestmore deposit in California (Burn-

ham, 1959). Later, monomineralic merwinite skarn was described at the Igljka deposit in Bulgaria (Ivanova-Panaiotova, 1962), Gavasai deposit in Kirgizia (Pertsev, 1973), in xenoliths of the Ozerskii Massif in the western Baikal area (Savel'eva *et al.*, 1990), and in the Dovyren Massif (this paper). In the latter massif, merwinite skarns were found in the core of recently drilled Hole 143, which intersected a suite of large (up to 30 m) xenoliths near the top of the dunite unit, and on the continuation of this layer in the upper reaches of Bol'shoi Brook. The stratigraphic column along the drillhole is shown in Fig. 2. The true thickness of the rocks in this column is much smaller, because the drillhole intersected the layers at a very acute angle (~25°) and yielded a reversed rock succession. The dunites of this unit have a mesocumulate texture with interstitial calcic plagioclase between subhedral olivine (14–16% *Fa*) grains. Farther down the drillhole, dunite gives way to wehrlite mesocumulates, consisting of rounded olivine grains and interstitial diopside oikocrysts (containing up to 5.65 wt % Al₂O₃) with disseminated sulfide inclusions. Rare spinel grains contained in this mineral are prone to be restricted to contacts of *Ol* and *Cpx* grains. Dunite (without *Pl*) appears again in contact with the first xenolith. This dunite has a cumulative texture and contains small (no more than 3–5 mm) xenoliths of *Spl-Fo-Mtc* skarn (thin section 143-470a). This skarn composes, together with *Spl-Fo-Brc* (developing after

¹ Here and below, the following conventional symbols of minerals are used: *Ab*—albite, *Adr*—andradite, *Ak*—akermanite, *An*—anorthite, *Ap*—apatite, *Brc*—brucite, *Cal*—calcite, *Di*—diopside, *Dol*—dolomite, *Fa*—fayalite, *Fo*—forsterite, *Fst*—fassaite, *Gar*—garnet, *Gh*—gehlenite, *Grs*—grossular, *Mag*—magnetite, *Mel*—melilite, *Mtc*—monticellite, *Ol*—olivine, *Per*—periclase, *Pl*—plagioclase, *Prv*—perovskite, *Qtz*—quartz, *Spl*—spinel, *Tnt*—titanite, *Ves*—vesuvianite, and *Wo*—wollastonite. Additionally introduced symbols are: *Del*—dellaite Ca₆Si₃O₁₁(OH)₂, *Djr*—djerfisherite K₆(Fe,Cu,Ni)₂₅S₂₆Cl, *Kil*—kilchoanite Ca₃Si₂O₇, *Lar*—larnite Ca₄Si₂O₈, *Mer*—merwinite Ca₃MgSi₂O₈, *Ran*—rankinite Ca₃Si₂O₇, *Spu*—spurrite Ca₅Si₂O₈(CO₃), and *Til*—tilleyite Ca₅Si₂O₇(CO₃)₂.

Per) skarn, the first xenolith. At greater depths, thin zones of *Mer* + *Brc* (*Per*), *Spl* + *Fo* + *Brc* (*Per*), *Spl* + *Mtc* + *Brc* (*Per*), *Spl* + *Mer* + *Brc* (*Per*), and *Spl* + *Mtc* skarn alternate. Among them, a contact between *Spl-Mtc* and *Mel-Mer* skarns was documented at a depth of 473 m. In places, *Mer* is replaced along fractures by white cryptocrystalline secondary products and veinlets of awillite $\text{Ca}_3\text{Si}_2\text{O}_4(\text{OH})_6$. *Mer* is sometimes replaced in margins by fine-grained aggregates of *Mtc* and *Spu* or Ca-hydrosilicates and calcite. The skarns usually have granoblastic textures or have graphic intergrowths of *Mel* and *Mer* (thin section 723). Merwinite-bearing skarn is absent only from the near-bottom part of the first xenolith. The second, largest xenolith (from the depth interval of 628.5–722 m) is dominated by alternating “layers” of *Spl-Mer*, *Spl-Mer-Mtc* ± *Per*, *Spl-Mtc-Fo*, and *Spl-Mtc-Per* skarn. Near its top contact with wehrlite, more calcic *Mel* ± *Mer* and *Mtc* varieties develop, which are overprinted by the retrograde *Ves-Gar-Di-Cal* assemblage. At a higher stratigraphic level (depth interval of 724.3–844.6 m), a thick wehrlite unit with veins of olivine and monomineralic diopsidites occurs, which is analogous to that observed near the roof of the first xenolith.

SKARN MINERALS

The chemistry of skarn minerals from the profile was examined by EPMA on a type-1 Camebax-MBX at the Institute of Experimental Mineralogy, Russian Academy of Sciences. The analyses were conducted on a EDA Link AN10/55S analytical set with a Si–Li glass detector. The current at the Co standard was 1.3 nA, the accelerating voltage was 15 kV, and the counting time was 70 s. Representative analyses of the minerals are listed in the table.

Merwinite is a characteristic mineral of the inner portions of the xenoliths, in which it often composes nearly monomineralic zones in association with *Per*, *Spl*, and *Mtc*. Assemblages of *Mer* with *Mel* are more rare, with the melilite more often having an akermanite-dominated composition or containing much more gehlenite in other instances. Some segments of the merwinite zone contain no brucite pseudomorphs after periclase, whereas other “layers” contain variable amounts (gradually increasing to ~20–25 vol %) of these pseudomorphs. The merwinite composes aggregates of equant or euhedral grains, which are polysynthetically twinned along two directions. The mineral has a high optic relief, moderate birefringence (~0.018), and +2V ~70°C. It contains practically no Fe, and its composition is close to the theoretical one. The mineral pervasively contains 0.3–0.8 wt % P_2O_5 .

When periclase inclusions are replaced by brucite, merwinite remains almost unaltered and occurs as a metastable phase together with *Brc*. Contacts between *Mer* and *Brc* are sometimes marked by thin *Mtc* rims. *Mer* is also sometimes replaced in margins by aggregates of *Mtc* + *Spu* (*Til*) in a *Per*-bearing skarn.

Forsterite is typical of the near-contact zones between the magnesian skarn and ultramafic rock. It composes interstitial rims and oikocrysts (with abundant small spinel inclusions) between pseudomorphs after periclase (Fig. 3a). If the rock contains *Mtc*, forsterite–spinel rims usually separate this mineral from *Per* (*Brc*) (Fig. 3b). The skarn forsterite is low in Fe (1–3% *Fa*), which makes it different from magmatic olivine (8–16% *Fa*) (Kislov, 1998). The *Fo* also contains Ca (~2% *Mtc*). Forsterite can occur in equilibrium with brucite over a fairly broad temperature interval, up to the onset of serpentinization.

Monticellite is a widespread mineral in the Dovyren skarns and occurs in a number of mineral assemblages: *Per* + *Spl* + *Mer* + *Mtc*, *Mel* + *Mer* + *Mtc*, and *Spl* + *Fo* + *Mtc* (highest temperature prograde-stage assemblages) and retrograde assemblages with secondary *Mtc* overprinted on *Mer*, *Mel*, and *Per*: *Spu* (*Til*) + *Mtc*₂, *Cal* + *Mtc*₂, *Ves* (and/or hydrogarnet) + *Mtc*₂, *Brc* + *Mtc*₂, and cuspidine + *Mtc*₂. *Mtc* and *Mtc*₂ are practically identical in composition and are low in Fe (2–4% kirschsteinite). In contrast to the metastable association with *Mer*, brucite forms a stable assemblage with *Mtc*. Associations of *Mtc* and *Mtc*₂ with pseudomorphs of platy *Brc* that supposedly developed after *Fo* grains are characteristic of the rocks and show no evidence of equilibrium disturbance. Thin rims of *Mtc*₂ developed at contacts between *Mer* and *Brc* (after *Per*). The *Mtc-Brc* assemblage is also unique in skarn deposits. As the temperature further decreased, the *Mtc-Brc* assemblage became unstable and was replaced by *Fo-Brc* ± *Cal*.

Melilite occurs in skarns in assemblage with *Mtc* and *Mer* in the form of ingrowths and inclusions in merwinite and as large individual grains. Sometimes it composes nearly monomineralic zones of large (2–3 mm) tabular crystals or granular masses. Large crystals sometimes bear merwinite inclusions. In Al-poor skarns, melilite is high in akermanite (80–83% *Ak*, ~10% $\text{NaCaAlSi}_2\text{O}_7$ end member, and ~8% *Gh*), whereas this mineral in high-Al zones is rich in gehlenite. Melilite in the skarns is separated from spinel and occurs in more calcic or less magnesian associations. Additionally, assemblages with melilite can locally overprint *Spl-Mer* and *Spl-Mtc* magnesian skarns during the postmagmatic stage, composing irregularly shaped veinlets in which spinel and adjacent monticellite are replaced (Fig. 3c). These are postmagmatic calc-skarn overprints on the magnesian skarns. As the temperature further decreased, aluminous melilite was replaced by *Mtc* + *Ves* symplectitic pseudomorphs and by isotropic aggregates of hydromelilite and hydrogarnet. Akermanite is decomposed to *Mtc-Wo* symplectites.

Periclase and brucite. *Per* occurs in the skarns as relics in characteristic brucite pseudomorphs, which look like concentric structures of crumpled flakes resembling a cabbage head. *Per* forms stable assemblages with *Fo*, *Mtc*, and *Mer* or composes the nearly

Representative microprobe analyses of skarn minerals from the Dovyren Massif

Component	1	2	3	4	5	6	7	8	9	10	11	12
	<i>Mer</i>	<i>Mtc</i>	<i>Fo</i>	<i>Spu</i>	<i>Til</i>	<i>Ak</i>	<i>Wo</i>	<i>Adr</i>	<i>Spl</i>	<i>Mag</i>	<i>Per</i>	<i>Djr</i>
SiO ₂	37.729	38.573	41.753	26.723	24.539	41.833	51.224	34.708	0.134	0.062	0.072	0.541
TiO ₂	0	0.042	0	0.094	0.107	0	0.223	0	0.437	0.947	0	0
Al ₂ O ₃	0.407	0	0.191	0	0.038	3.937	0.191	0.598	52.881	0.578	0	0.093
Cr ₂ O ₃	0.046	0	0	0.131	0.069	0	0.061		1.357	0	0.037	0
FeO(total)	0.654	1.373	1.659	0.048	0.058	0.643	0.137	28.752	16.831	86.874	5.147	53.056
MnO	0	0.197	0.06	0	0	0.08	0.021		0.227	0.916	0.14	
MgO	11.951	23.701	55.65	0.16	0.191	12.224	0.083	0.118	26.532	2.303	90.801	0.2
CaO	48.382	36.459	0.659	60.071	56.33	39.884	47.563	33.206	0.026	0	0.25	0.455
Na ₂ O	0.204	0.242	0.35	0.385	0.138	0.419	0.083	0.162	0.499	0.074	0.119	0
K ₂ O	0.363	0.03	0	0.011	0.07	0.152	0.039		0.038	0.032	0.03	8.406
P ₂ O ₅	0.427	0.088	0			0.054	0.037	0.037			0.006	0.061
S	0.099	0.091	0.025	0.012	0.173	0.094	0.005				0.175	33.222
Cl	0	0.025	0	0.051	0.042	0.042	0.046	0.051			0.006	1.368
[CO ₂]				9.808	17.999							
Cu							0.045					0.897
Co							0.038					0.01
Ni										0.091	0.157	
Total	98.262	100.821	100.346	87.886	81.755	99.411	99.796	97.632	98.962	91.892	97.284	98.308
Calculated total				97.694	99.754			100.824		98.762		
Si	1.985	1.021	0.986	2.057	2.009	1.915	0.994	2.939	0.003	0.002		0.472
Ti		0.002		0.005			0.003		0.003	0.027		
Al	0.027		0.005			0.212	0.004	0.059	1.658	0.025		0.094
Cr	0.002			0.008					0.029			
Fe ³⁺								1.968	0.342	1.935		
Fe ²⁺	0.03	0.03	0.033	0.003		0.024	0.002		0.032	0.802	0.033	23.268
Mn		0.005	0.01			0.003	0.002		0.005	0.029	0.001	
Mg	0.989	0.92	1.96	0.018	0.023	0.833	0.002	0.015	1.052	0.129	0.957	0.201
Ca	2.881	1.018	0.017	4.947	4.941	1.954	0.988	3.006			0.002	0.278
Na	0.022	0.012	0.016	0.057	0.022	0.037	0.001	0.027	0.026	0.005	0.005	
K	0.026	0.026		0.008	0.011	0.03	0.001			0.002		5.265
P	0.02	0.002				0.002		0.003				0.049
S	0.004	0.002		0.012		0.003	0.002			0.002	0.001	25.319
Cl		0.001		0.006		0.003	0.002	0.007				0.945
Cu												0.345
Co												0.005
Ni										0.011	0.001	
C				1	2							
O	8	4	4	11	13	7	3	12	4	4	1	0

Note: Oxides, S, Cl, Cu, Co, and Ni are in wt %, elements are recalculated to formula units. (1, 2) Merwinite and monticellite from an association with akermanite, melilite, and djerfisherite, sample 471-1; (3) forsterite with spinel (analysis 9) and periclase, sample 470V2; (4, 5) secondary spurrite and tilleyite developing after merwinite, sample 723-3; (6) akermanite-rich melilite, inclusions in merwinite, sample 723-1; (7) secondary wollastonite after akermanite, sample 723-3; (8) andradite from association with brucite (secondary, after olivine), sample 261ID; (9) spinel from association with olivine and periclase, sample 470V2; (10) magnetite from an association with forsterite and spinel, sample K35a; (11) periclase inclusion in merwinite, sample 30-2-2; (12) djerfisherite from association with merwinite, monticellite, and spinel, sample 723-3. Analysis is given in wt % of elements.