

Metasomatism and Ore Formation at Contacts of Dolerite with Saliferous Rocks in the Sedimentary Cover of the Southern Siberian Platform

M. P. Mazurov, S. N. Grishina, V. E. Istomin, and A. T. Titov

*Institute of Geology and Mineralogy, Siberian Branch, Russian Academy of Sciences,
pr. Akademika Koptuyuga 3, Novosibirsk, 630090 Russia*

Received March 22, 2007

Abstract—The data on the mineral composition and crystallization conditions of magnesian skarn and magnetite ore at contacts of dolerite with rock salt and dolomite in ore-bearing volcanic–tectonic structures of the Angara–Ilim type have been integrated and systematized. Optical microscopy, scanning and transmission electron microscopy, electron microprobe analysis, electron paramagnetic resonance, Raman and IR spectroscopy, and methods of mineralogical thermometry were used for studying minerals and inclusions contained therein. The most diverse products of metasomatic reactions are found in the vicinity of a shallow-seated magma chamber that was formed in Lower Cambrian carbonate and saliferous rocks under a screen of terrigenous sequences. Conformable lodes of spinel–forsterite skarn and calciphyre impregnated with magnesian magnetite replaced dolomite near the central magma conduit and apical portions of igneous bodies. At the postmagmatic stage, the following mineral assemblages were formed at contacts of dolerite with dolomite: (1) spinel + fassaite + forsterite + magnetite ($T = 820\text{--}740^\circ\text{C}$), (2) phlogopite + titanite + pargasite + magnetite ($T = 600\text{--}500^\circ\text{C}$), and (3) clinocllore + serpentine + pyrrhotite ($T = 450^\circ\text{C}$ and lower). Rock salt is transformed at the contact into halite as an analogue of calciphyre. The specific features of sedimentary, contact-metasomatic, and hydrothermal generations of halite have been established. The primary sedimentary halite contains solid inclusions of sylvite, carnallite, anhydrite, polyhalite, quartz, astrakhanite, and antarcticite; nitrogen, methane, and complex hydrocarbons have been detected in gas inclusions; and the liquid inclusions are largely aqueous, with local hydrocarbon films. The contact-metasomatic halite is distinguished by a fine-grained structure and the occurrence of anhydrous salt phases ($\text{CaCl}_2 \cdot \text{KCl}$, $\text{CaCl}_2 \cdot n\text{MgCl}_2 \cdot m\text{CaCl}_2$) and high-density gases (CO_2 , H_2S , N_2 , CH_4 , etc.) as inclusions. The low-temperature hydrothermal halite, which occurs in skarnified and unaltered silicate rocks and in ore, is characterized by a low salinity of aqueous inclusions and the absence of solid inclusions. The composition and aggregative state of inclusions in halite and forsterite indicate that salt melt-solution as a product of melting and dissolution of salt was the main agent of high-temperature metasomatism. Its total salinity was not lower than 60%. The composition and microstructure of magnetite systematically change in different mineral assemblages. Magnetite is formed as a result of extraction of iron together with silicon and phosphorus from dolerite. The first generation of magnetite is represented by mixed crystals, products of exsolution in the Fe–Mg–Al–Ti–Mn–O system. The Ti content is higher at the contact of dolerite with rock salt, whereas, at the contact with dolomite, magnetite is enriched in Mg. The second generation of magnetite does not contain structural admixtures. The distribution of boron minerals and complex crystal hydrates shows that connate water of sedimentary rocks could have participated in hydrothermal metasomatic processes.

DOI: 10.1134/S1075701507040022

INTRODUCTION

The Permian–Triassic traps of the Siberian Platform stand out among other large igneous provinces not only by their giant volumes of igneous rocks but also by their active interaction with the unmetamorphosed sedimentary cover. In paleorift domains in the south of the platform, which evolved in a geodynamic setting of dispersed spreading, this process is the most impressive at the contacts with Cambrian terrigenous–evaporite–carbonate and carbonate–saliferous sequences. Pore solutions and connate brines are regarded as among the most reactive agents in the interacting systems (Pavlov, 1975; Vinogradov et al., 2006). Crystallization of

tholeiitic basaltic magma in a chemically heterogeneous and active medium results in development of fluid ore-magmatic systems responsible for the formation of numerous deposits and occurrences of ferrous, nonferrous, and noble metals; boron; strontium; phosphorus; graphite; Iceland spar; and other solid minerals hosted in the sedimentary cover. Emplacement of traps induces redistribution of matter in saliferous and petroliferous formations.

The investigation of dolerite interaction with rock salt is an important line of research related to trap magmatism. In the second half of the 20th century, many geologists attracted attention to the role of saliferous sequences in the genesis of iron deposits of the Angara–Ilim type in the southern Siberian Platform. Pavlov

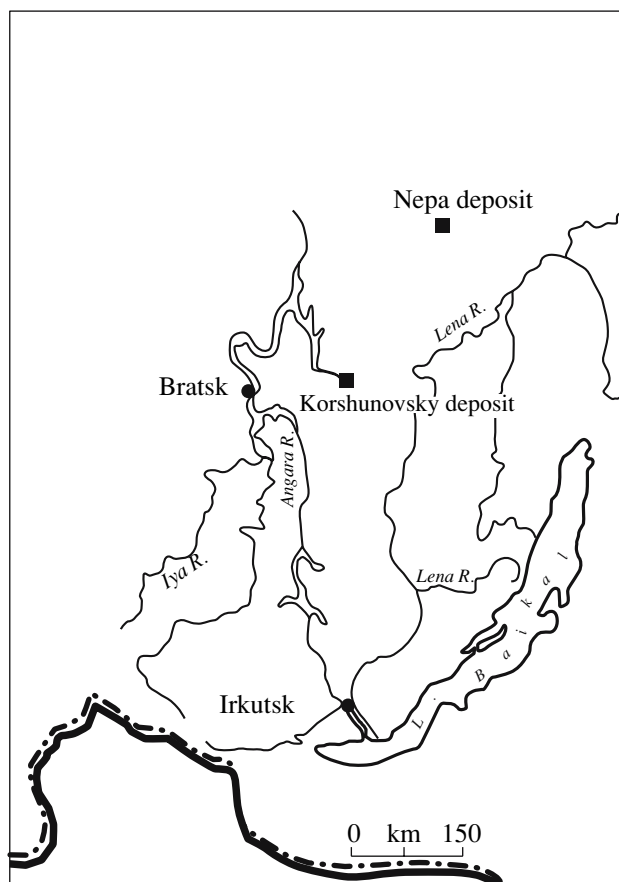


Fig. 1. Index map.

(1975), Pavlov and Ryabchikov (1968, 1970), Pavlov and Pek (1979), and Pukhnarevich (1986) considered the activity of brines mobilized from evaporites to be the main factor in ore formation. It should be noted that evidence for interaction of dolerite with saliferous

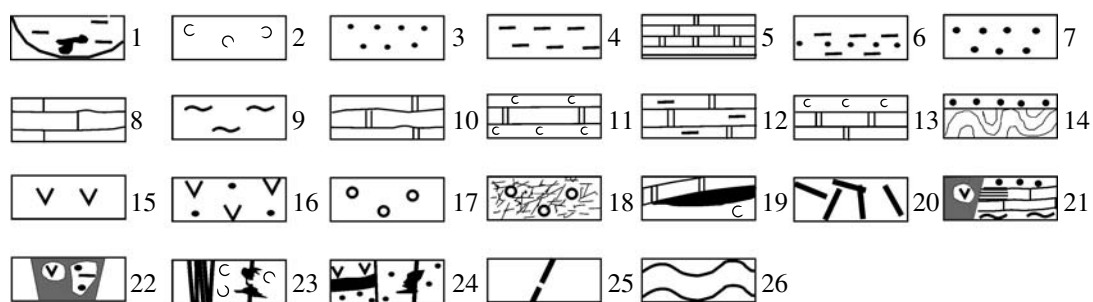
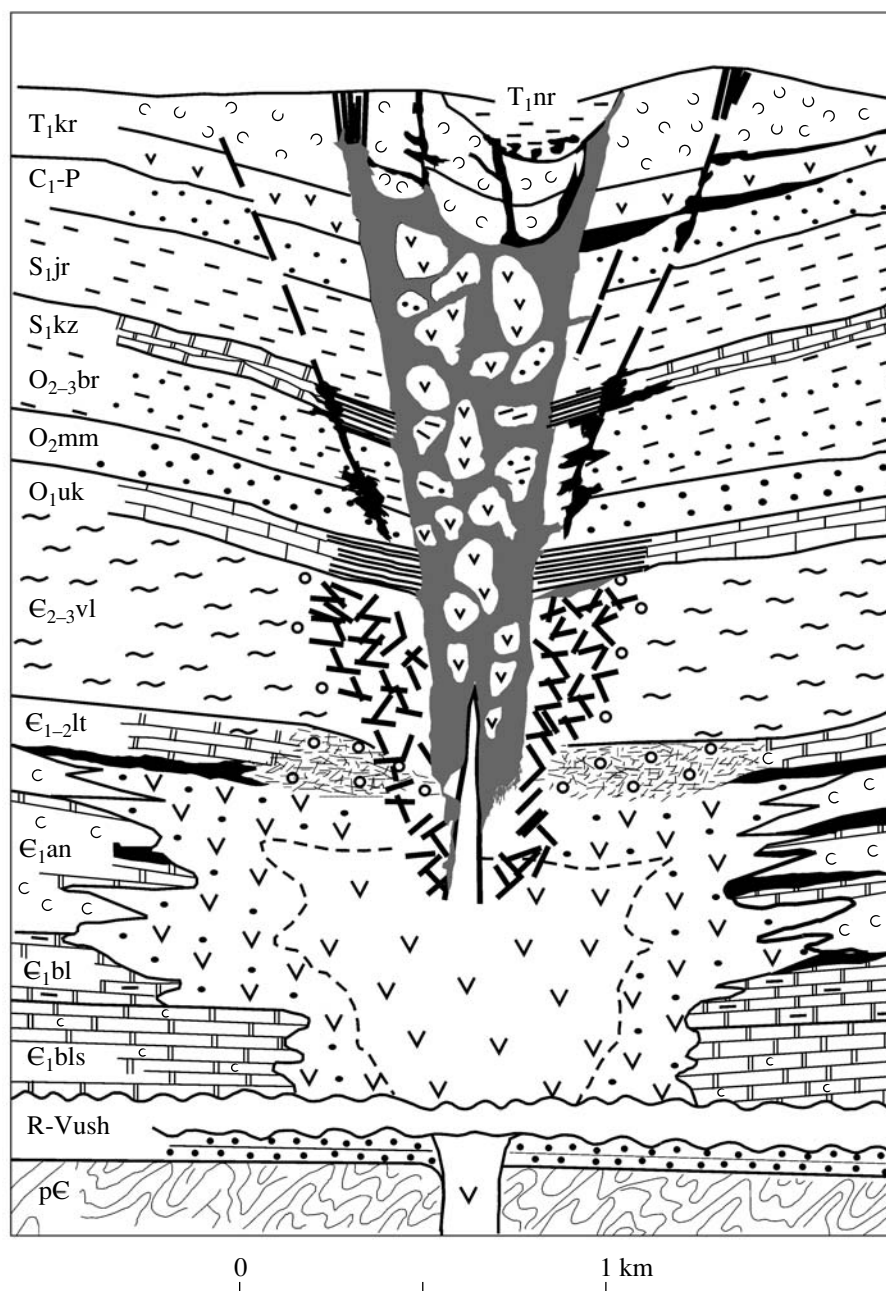
country rocks was first obtained from the examination of contacts of dolerite sills beyond the ore fields. New data on the structure and composition of reaction zones at the contacts of dolerite with dolomite and rock salt were obtained in recent decades from the deep levels and flanks of the Korshunovsky and Nepa deposits (Fig. 1).

The objective of this study is to use comprehensive information on the composition and structure of minerals to provide insights into the evolution of ore-forming and metasomatic processes at the immediate contacts of dolerite with rock salt and to estimate the role of fluids as products of this interaction in ore deposition.

GEOLOGICAL SETTING OF DOLERITE CONTACTS WITH CARBONATE AND SALIFEROUS FORMATIONS

The Permian–Triassic trap complex in the southern Siberian Platform comprises extended sills and complexly built volcanic–tectonic edifices. The sills intruded into the unmetamorphosed bedded sequences of the Paleozoic sedimentary cover at several levels (Feoktistov, 1978; Pukhnarevich, 1986), and only the Zayarsk and Usol’e levels reside in the Lower Cambrian salinas. The ore-bearing volcanic–tectonic edifices (Strakhov, 1978; Baryshev et al., 1980; Dunaev, 1992; Mazurov and Bondarenko, 1997; Von der Flaass and Nikulin, 2000) cut through the sedimentary cover from the Vendian to the Lower Triassic and are rooted in the crystalline basement. These edifices have a zonal structure (Fig. 2). Their upper portion is composed of lavas and pyroclastic rocks, including facies of crater lakes. The central portion is a near-vertical diatreme (explosion pipe, vent) filled with eruptive and explosion breccias and fragmented country carbonate–terrigenous rocks. The centrosymmetric structure typical of volcanoes is observed only in those segments that cut homogeneous terrigenous rocks. On intruding into intercalating rock members of different competence,

Fig. 2. Schematic section of an ore-magmatic system of the Angara–Ilim type, modified after Mazurov and Bondarenko (1997). (1) Volcanomictic rocks of crater lakes, the Lower Triassic Neryunda Formation (T_{1nr}); (2) explosion breccia, lava flows, and pyroclastic rocks, the Lower Triassic Korvunchan Formation (T_{1kr}); (3) Lower Carboniferous–Permian poorly lithified coal-bearing sequence (C_{1-P}); (4) red mudstone, siltstone, and marlstone with sporadic sandstone interlayers, the Lower Silurian Yarsk Formation (S_{1jr}); (5) sandstone with carbonate–clayey interlayers, the Lower Silurian Kezhem Formation (S_{1kz}); (6) red mudstone and marlstone with sporadic sandstone interlayers, the Middle–Upper Ordovician Bratsk Formation (O_{2-3br}); (7) quartz sandstone, the Middle Ordovician Mamyr Formation (O_{2mm}); (8) limestone, the Lower Ordovician Ust-Kut Formation (O_{1uk}); (9) marlstone with interlayers of fine-grained calcareous sandstone, siltstone, gypsum, and limestone, the Middle–Upper Cambrian Verkholsensk Formation (C_{2-3vl}); (10) dolomite of the Lower–Middle Cambrian Litvintsevo Formation (C_{1-2lt}); (11) dolomite and rock salt with mudstone and siltstone interlayers, the Lower Cambrian Angara Formation (C_{1an}); (12) massive dolomite, the Lower Cambrian Bulai Formation (C_{1bl}); (13) dolomite and anhydrite with salt interlayers, the Lower Cambrian Bel’sk Formation (C_{1bls}); (14) sandstone, siltstone, and mudstone at the bottom of the platform cover, the Riphean–Vendian Ushakovo Formation ($R-Vush$), and Precambrian crystalline schists of the basement (pC); (15) intrusive bodies of the trap complex: sills, laccoliths, dikes, and off-sets of dolerite bodies; (16) skarnified dolerite in the zone of mingling of dolerites and evaporites; (17) magnesian and calcic skarn, skarnoid, and calciphyre; (18–24) iron orebodies: (18) conformable orebodies in magnesian skarn and calciphyre, (19) halite–magnetite ore in the Angara Formation, (20) ore stockwork in the Verkholsensk Formation, (21) bedding plane calcite–magnetite ore in limestone of the Ust-Kut and Kezhem formations, (22) telescoping orebodies in diatremes, (23) near-vertical banded, oolitic, and brecciated ore hosted in volcanic and pyroclastic rocks, (24) ore veins localized beneath sills and fill of late fissures; (25) faults; (26) bottom of the platform cover remaining unexplored with respect to iron ore formation.



variable saturation with fluids, and contrasting composition, the magmatic melts form branching bodies of complex morphology. The multiple pulses of magmatic activity and sagging of rocks above the exhausted magma chambers created prerequisites for mingling of magma with country rocks and formation of breccias with magmatic or hydrothermal metasomatic cement.

The terrigenous rocks that host ore-bearing edifices are replaced with depth by Upper Cambrian red beds and evaporites (Anatol'eva, 1972) and then by Lower Cambrian gray-colored carbonate, saliferous-carbonate, and saliferous formations (Zharkova, 1976). The intrusive sheets residing in these rocks are complex in structure. At the deep levels of the best-explored Korshunovsky deposit, a large laccolith with bedding plane offsets has been contoured in saliferous sedimentary rocks of the Lower Cambrian Angara Formation. The thickness of the laccolith in its central portion is greater than 500 m, and particular offsets extend for 1500 m.

In contrast to the dolerites solidified in the overlying terrigenous rocks, the intrusive bodies crystallized more deeply are not delineated by sharp contacts. Their margins are composed of disintegrated rocks with caliche, halite, or magmatic cement. These rocks resemble automagmatic intrusive and eruptive breccias that accompany the branches of the Noril'sk and Talnakh intrusions (Zotov, 1979; *Prospecting...*, 1978). The number and thickness of sill-like offsets and the width of fragmentation, skarnification, and mineralization of zones in country rocks and dolerites are variable.

Borehole 17d at the Korshunovsky deposit penetrated six bedding plane intrusive bodies within the depth interval 804.4–1250 m. The correlation of the section of this borehole with those drilled beyond the ore field indicates that the igneous rocks largely occupy the place of salt members. Precisely this region of large-scale interaction of basic magma with carbonate and saliferous rocks of the sedimentary cover may be regarded as an intermediate magma chamber. The occurrence of an echelon arranged system of such chambers at a greater depth is inferred from geophysical data. The deepest salinas of the Lower Cambrian Usol'e Formation in the Angara-Ilim ore district, as well as dolerite sills residing therein, were not penetrated by exploration holes.

The multistage development of metasomatic reactions, especially with participation of mobilized brines, resulted in diversity of minerals and rocks. In the upper portion of the edifices, composed of lavas and pyroclastic rocks, the main metasomatic processes are expressed in propylitization and greenstone alteration. In the underlying zone of the diatreme and related pinnate fractures, marly rocks and sandstones with carbonate cement are replaced by calcic and magnesian skarnoids; infiltration and diffusion bimetasomatic calcic skarn replaces dolerite, limestone, and disintegrated rocks. Skarn composes cement of heterogeneous breccia and contains relics of the replaced rocks and thus

may be defined as a typical fragmentary metasomatic rock (Pospelov, 1973; Tsarev, 1984; *Metasomatism...*, 1998). Infiltration bodies of magnesian skarn up to 200 m in visible thickness are localized at the upper contacts of doleritic laccoliths with massive dolomite of the Lower–Middle Cambrian Litvintsevo Formation. Magnesian exoskarn of the magmatic stage replaces the country dolomite and occurs as xenoliths in the contact zone of dolerite sills. The mineral assemblages of the postmagmatic stages make up a single stockwork that involves dolerite previously unaffected by skarnification and magnesian skarn of the magmatic stage. The mineral assemblages, textural and structural appearance, and zoning of skarn bodies are similar to plutonogenic frontal skarn lodes in island-arc and marginal continental settings (Pertsev, 1977; Shabynin et al., 1984). The occurrences of magnesian skarn in the interlayers, marginal portions, and frontal zones of sheetlike bedding plane offsets of the laccolith hosted in the Lower Cambrian carbonate-saliferous rocks of the Angara Formation are quite distinct in appearance (Mazurov and Titov, 1999). The thickness of skarn bodies varies here from a few meters to a few tens of meters, and a negative correlation is commonly established between the thickness of skarn and that of unaltered dolerite. In visual appearance, the rock resembles a conglomerate with carbonate or anhydrite-halite-calcite cement. Banded, lenticular-banded, and spotty rocks are abundant. The amount of fragments ranges from 50 to 95%, and their size varies from fractions of a millimeter to a few centimeters. The color of rocks varies from black to light gray with green, brown, and yellow hues. The transition from unaltered dolerite to disintegrated areas may be either sharp or gradual via an increase in size and roundness of fragments. Spheroid or slightly flattened fragments are predominant; they are often gathered into dumbbells and aggregates more complex in morphology. The smaller a fragment, the closer its morphology approaches a sphere and the more strongly this sphere is altered. In the upper and lower exoskarn bodies adjoining dolerite offsets on both sides, fragments of skarn and metamorphosed country rocks occur in breccia. These fragments are cemented by late generations of anhydrite, halite, and calcite with sulfides and other postskarn minerals. The most intricate textural pattern and diverse composition of skarn and subsequent mineral assemblages are established in the areas characterized by multiple intrusions of magma.

The lithology of saliferous members is rather variable, and immediate contacts of dolerite with homogeneous rock salt are not numerous. Such contacts are best expressed near vertical or steeply dipping dikes having chilled margins and broken by contraction cracks. At the Korshunovsky deposit, such dikes were revealed at deep levels of the Vtoraya Gora (Second Mountain) area and were crossed by boreholes drilled nearby in a search for sites for disposal of industrial sewage. A series of steeply dipping dikes was pene-

trated by boreholes at a depth greater than 800 m at the Nepa potash deposit. Hole 13 penetrated a dike of porphyritic dolerite within the depth interval 812.0–853.4 m. The transformed rock salt (halitite) that occurs at its upper contact is replaced by calciphyre with halitite spots and then by unmetamorphosed salt with halopelitic interlayers far from the contact. Halite veinlets and pockets are observed in the dike along its entire extent. Relatively light skarnified selvages stand out against the almost black background of slightly fragmented igneous rock at the immediate contact (Fig. 3). The width of such selvages varies from a few millimeters to a few centimeters. The width of metasomatic alteration increases at fracture intersections, where fragments acquire rounded outlines. Away from the contact, only small halite grains are contained at surfaces of dry joints in dolerite.

Thus, extended dolerite sills, as well as laccoliths and related offsets and dikes, come into contact with Cambrian saliferous rocks at deep levels of deposits of the Angara–Ilim type.

COMPOSITION AND STRUCTURE OF MINERALS IN CONTACT ZONES

The products of reaction of dolerite with carbonate and saliferous rocks are the most diverse at deep levels of the Korshunovsky deposit and nearby. Mineral assemblages of rock salt from the Lower Cambrian Angara Formation; contact-metasomatic rocks and ores; and hydrothermal veins that crosscut dolerite sills, skarn, ore, and postskarn Ca–Mg–Fe metasomatic rocks are recognized. All the above rocks contain halite, and, first of all, we had to determine the specific features of different generations of this mineral. In addition to optical microscopy, scanning electron microscopy (SEM), electron microprobe analysis (EPMA), electron paramagnetic resonance (EPR), and Raman and IR spectroscopy were applied for this purpose.

The unmetamorphosed saliferous members consist of all varieties of halite, dolomite–halite, and anhydrite–dolomite–halite rocks known in the Angara Formation from type localities of the Cambrian saliferous sequence of the Siberian Platform (Zharkova, 1976). The rock salts are classified according to color (red, gray, and colorless), texture (equi- and inequigranular, fine- to giant-grained (spathic) varieties), and composition (from monomineralic halite to rock salts containing no less than 10% pelitomorphic and phaneritic silicates, carbonates, chlorides, borates, oxychlorides, and other minerals). The most abundant rock salts are brownish gray to pink, from fine- to coarse-grained in texture, with inclusions of pelitomorphic mineral particles and dispersed organic matter, gases, and fluids both within halite grains and at intergranular boundaries. Pinkish gray fine-grained pale salts contain larger grains of light gray halite. In all these halite varieties, fluid and solid inclusions are arranged making up rhythmic zoning, and this arrangement is thought to be

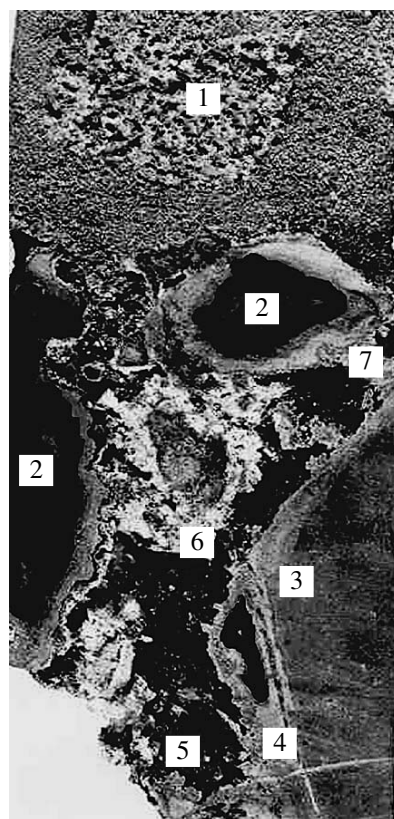


Fig. 3. Contact of dolerite with rock salt. The sample is 6 cm wide. (1) Halitite (gray salt), (2) dolerite, (3) zonal anhydrous magnesian skarn, (4) hydrated pargasite–phlogopite–chlorite magnesian skarn, (5) magnetite impregnation, (6) serpentine selvage, (7) hydrothermal halite. See text for explanations.

an indicator of sedimentary origin (Grishina et al., 1992). Halite saturated with orange-red pigment is localized near marlstone and siltstone interlayers and lenses. Films of iron hydroxides at intergranular boundaries are discernible under an optical microscope. A colored halo as wide as 0.5 mm surrounds some films. The intensity of the red coloration varies widely; coarse-grained varieties are commonly lighter. Light gray rock salts contain large spathic aggregates, pockets of transparent halite grains up to a few centimeters across, which break easily along cleavage planes and are firmly joined by induction boundaries. The admixtures are concentrated only at intergranular boundaries, indicating that the spathic salts are products of aggradation recrystallization.

According to EPR data (Istomin et al., 2000), the following features are characteristic of sedimentary halite: (1) a low concentration of Mn^{2+} ions stabilized as an isomorphic admixture in the regular lattice of the mineral; (2) diversity in Fe^{3+} ions, which make up initial groups, clusters, segregations of nuclei, and hydrogoethite films; and (3) the occurrence of dispersed organic matter. Gas, gas–liquid, solid, and multiphase

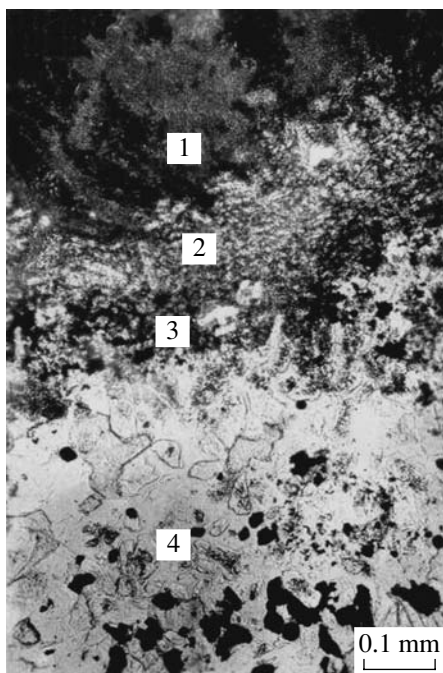


Fig. 4. Metasomatic column of magnesian skarn. (1) Fragmented dolerite, (2) pyroxene–feldspathic zone, (3) spinel–fassaite zone, (4) forsterite–spinel–magnetite zone. Plane line.

inclusions are established in halite crystals of sedimentary and diagenetic origin (Grishina et al., 1998). The solid inclusions consist of sylvite, carnallite, anhydrite, polyhalite, quartz, astrakhanite, and antarcticite. Nitrogen and methane and more complex hydrocarbons are detected in the gas phase. The liquid phase is largely aqueous. Hydrocarbon films are also observable in inclusions. In the primary rock salt, halite is associated with sylvite, carnallite, anhydrite, dolomite, magnesite, quartz, and borosilicate minerals: boracite, pandermite, sakhaite, sulfoborite, metaborite, and pinnoite (Semeikina and Kozlova, 1985).

Calcite and dolomite are the major minerals of the saliferous formation together with halite. As has been established by Zharkova (1976) and other researchers, calcite may be a product of chemical, biochemical, and biological processes, whereas dolomite is formed by direct precipitation or replacement of calcareous ooze. These minerals are always fine-grained, especially in biomorphic aggregates, and contain pelitomorphous intergranular particles. The primary sedimentation texture of carbonates has been significantly obliterated in the process of diagenesis and under the effect of solutions and brines.

The telescoping of mineral assemblages related to the variation of fluid composition within a wide interval of postmagmatic mineral formation is typical of contacts of dolerite with carbonate–saliferous rocks. Therefore, products of high-temperature alteration are preserved only in exceptional cases. The contact of a

porphyritic dolerite dike with rock salt shown in Fig. 3 is an example. The groundmass of this rock is aphanitic in outer appearance. The glomeroporphyritic texture is visible under a microscope. The microdoleritic and locally spherulitic groundmass testifies to the rapid solidification of magma. Segregations of phenocrysts consist of zonal, twinned, and deformed bytownite crystals. Sporadic olivine phenocrysts (Fo_{74-68}) partly or completely replaced by lizardite and granular augite phenocrysts with $X_{\text{Fe}} = 0.24-0.30$ are noted. The pyroxene–feldspar groundmass is impregnated with disseminated Fe and Ti oxides (up to 10%) and contains dispersed sulfide grains (~2%).

Dolerite passes to the skarn zone, clearly distinct in color, via a narrow zone of disintegration that equally affects the groundmass and phenocrysts (Fig. 4). This zone is composed of a fine mixture of mineral phases indistinguishable under an optical microscope. Plagioclase and pyroxene particles are discernible from SEM/EDS spectra; relict titanomagnetite is detected locally. On the basis of these data, we define this zone as the pyroxene–feldspathic endoskarn zone of the metasomatic column, typical of plutonogenic magnesian skarn of the postmagmatic stage (*Metasomatism...*, 1998). The next, spinel–fassaite zone is replaced farther by a forsterite–spinel–magnetite zone and then by halite as a fine-grained aggregate of halite with sporadic grains of forsterite, magnetite, apatite, chlorite, sulfides, and other minerals (less than 5% in total). In the literature, such a variety of halite is called black or gray salt irrespective of its contact-metasomatic or catagenetic origin.

In the case under consideration, halite at the contact with dolerite is represented by two generations. Halite of the first, high-temperature, contact-metasomatic generation is fine-grained, polygonal, and light gray and distinguished by the occurrence of anhydrous solid phases ($\text{CaCl}_2 \cdot \text{KCl}$, CaCl_2 , $n\text{MgCl}_2 \cdot m\text{CaCl}_2$) and high-density gases (CO_2 , H_2S , N_2 , CH_4 , etc.) as inclusions. Solid inclusions of complex Ca-bearing chlorides may precipitate only from brine that contains more than 50% CaCl_2 and has a total salinity higher than 60 wt %. According to the EPR data, iron in solid inclusions in halite from reaction zones concentrates in ferromagnetic magnetite and pyrrhotite; the paramagnetic admixture of Mn^{2+} occurs as microinclusions in carbonate phases, and the dispersed organic matter, in graphite-like particles. The second generation of halite is low-temperature and is comprised of colorless, transparent, relatively large grains with rare aqueous or mineral inclusions. Aqueous three-phase inclusions with anisotropic crystals $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ were found in one sample. The temperature of dissolution of these phases is 30–40°C, and complete homogenization occurs at 30–50°C. A low salinity of the aqueous fluid and the absence of inclusions of sylvite, iron hydroxides, and organic matter are characteristic features of hydrothermal halite. The late halite as pockets and veinlets occurs in both skarnified and unaltered contacting rocks.

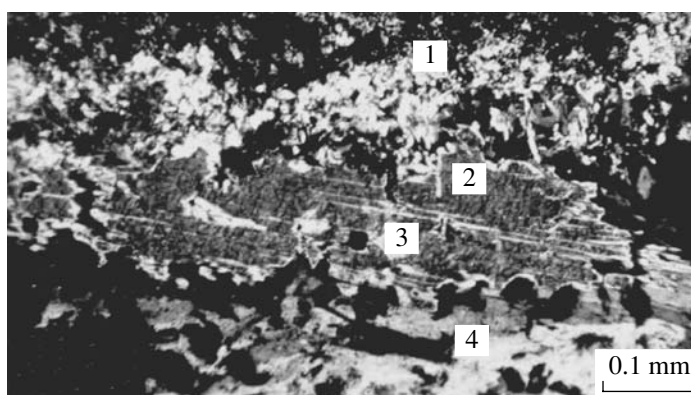


Fig. 5. Mineral assemblage of altered magnesian skarn. (1) Pargasite, (2) phlogopite, (3) halite, (4) chlorite. Plane line.

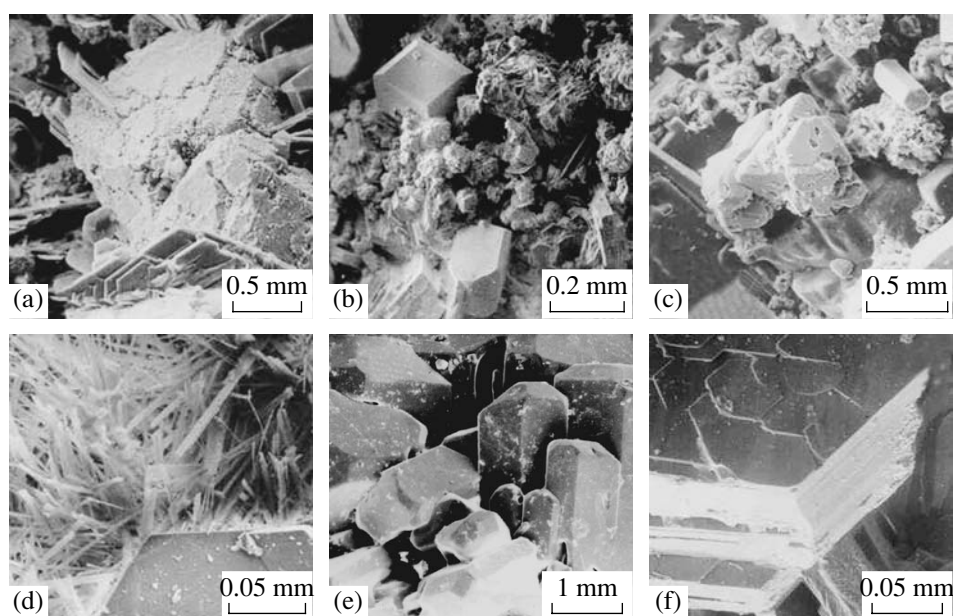


Fig. 6. BSE image of minerals at the surface of halite veinlets in skarnified dolerite. JSM-35 scanning electron microscope. (a) Anti-skeletal rhombic dodecahedron of magnetite intergrown with phlogopite; (b) euhedral titanite crystals in pargasite and chlorite; (c) octahedrons of magnetite, prisms of apatite, and spherical aggregates of serpentine; (d) thin acicular tremolite and tabular clinocllore; (e) euhedral crystals of forsterite; (f) steps of growth of clinocllore crystals.

Newly formed assemblages of boron minerals and complex crystal hydrates may serve as indicators of hydrothermal metasomatic alteration of salts and connate brines incorporated therein. As has been established at the Korshunovsky deposit, ludwigite crystallizes in calciphyre, skarnified dolomite, and halopelitic interlayers. Datolite and danburite appear in calcic skarnoids that replace evaporites of the Verkholsensk Formation. Szaibelyite (ascharite), ekaterinite, shabynite, strontiohilgardite, and fluoborite are formed in the slightly metamorphosed carbonate-saliferous rocks of the Angara Formation at a distance from the contact with dolerite and in veinlets that cut dolomite of the overlying Litvintsevo Formation (Lisitsyn et al., 1982). The group of low-temperature crystal hydrates com-

prises korshunovskite, iowaite, chlormagaluminite, nesquehonite, sepiolite, hydrotalcite, meixnerite, thau-masite, pyroaurite, sjögrenite, hibbingite, and kempite.

The metasomatic zoning of anhydrous magnesian skarn is inherited by hydrated mineral assemblages, including phlogopite, pargasite, tremolite, clinocllore, and serpentine. Pargasite crystallizes in the spinel-fassaite zone; phlogopite and clinocllore, at the boundary of the fassaite and forsterite zones; and serpentine surrounds metasomatized dolerite as wide selvages. Pargasite-phlogopite-clinocllore zoning (Fig. 5) is often observed in thin veinlets far from the contact.

Serrate boundaries are a characteristic feature of contacts between dolerite and rock salt. Such bound-

Table 1. Chemical composition of silicates, wt %

Component	Analysis number														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
SiO ₂	41.36	41.40	42.20	48.56	48.87	38.83	40.28	32.58	31.22	29.41	38.79	38.91	40.12	31.08	31.01
TiO ₂	0.00	0.02	0.02	1.04	0.95	1.08	0.78	0.01	0.02	0.02	0.48	0.48	0.45	37.41	37.33
Al ₂ O ₃	0.00	0.03	0.02	6.39	5.93	16.13	16.01	17.21	18.94	21.27	17.57	17.37	17.36	2.26	2.22
FeO*	7.06	3.63	2.47	7.90	7.87	5.64	5.56	2.18	2.80	6.24	2.70	2.71	2.58	0.69	0.74
MnO	0.18	0.08	0.07	0.16	0.17	0.02	0.03	0.01	0.02	0.02	0.03	0.00	0.01	0.01	0.00
MgO	50.99	54.16	54.91	13.96	14.18	19.40	19.07	35.92	34.88	31.00	26.57	26.52	25.52	0.02	0.00
CaO	0.15	0.03	0.02	21.15	20.92	13.17	12.37	0.00	0.00	0.02	0.02	0.01	0.00	28.37	28.59
Na ₂ O	0.00	0.00	0.00	0.41	0.54	3.25	3.51	0.02	0.00	0.00	1.32	1.19	1.17	0.00	0.00
K ₂ O	0.00	0.00	0.00	0.00	0.00	0.13	0.14	0.00	0.00	0.00	8.52	8.59	8.56	0.00	0.00
H ₂ O**	—	—	—	—	—	2.00	2.00	12.00	12.00	12.00	4.00	4.00	4.00	—	—
Total	99.74	99.35	99.71	99.57	99.43	99.65	99.75	99.94	99.88	99.98	100.00	99.78	99.77	99.84	99.89
Fe/(Fe + Mg), %	7.1	3.5	2.5	24.8	24.3	22.5	22.6	3.0	4.4	10.1	5.5	5.5	5.4	1.0	1.0

Note: (1–3) Forsterite, (4, 5) pyroxene, (6, 7) amphibole, (8–10) chlorite, (11–13) phlogopite, (14, 15) titanite. Analyses were performed on a Camebax Micro microprobe at the Analytical Center of the Institute of Geology and Mineralogy, Siberian Division, Russian Academy of Sciences, analyst O.S. Khmel'nikova.

FeO* is total iron in the form of FeO; H₂O** is the inferred content of water.

aries are observable by the naked eye in plane sections of samples (Fig. 3), where they separate zones of different colors. Corrosion boundaries of particular zones and minerals are discernible under a microscope. For example, a serrate boundary between a fine-grained aggregate of clinocllore and a larger phlogopite grain is clearly seen in Fig. 4. Such a structure is commonly deemed to be a typical attribute of metasomatic replacement. At the same time, at the contact with halite, mineral grains have regular crystallographic outlines, having undergone recrystallization. When halite is dissolved, the following features may be revealed at the surface of pockets and veinlets: (1) antiskeletal magnetite crystals intergrowing with phlogopite (Fig. 6a), (2) euhedral titanite crystals (Fig. 6b), (3) magnetite octahedrons with apatite and split clinocllore crystals (Fig. 6c), and (4) thin acicular tremolite crystals (Fig. 6d). The halite-bearing magnetite ore contains transparent and perfectly faceted forsterite crystals (Fig. 6e); clinocllore crystals with steps of face growth (Fig. 6f); and pyrrhotite, pyrite, and other minerals. Multiphase inclusions in forsterite consist of a fine crystalline translucent aggregate (10–20%), halite (50–80%), a transparent anisotropic salt phase (5–10%), and a gas bubble (<5%). On heating, the daughter phases dissolve stepwise, up to melting of halite at 670–720°C. The residual salt melt-brine with gas and xenogenic solid phases is homogenized into a salt melt at 740–820°C, and the xenogenic solid phases (mainly magnetite) start to disappear at 950–1010°C. These data refine and supplement the previously published information on inclusions in forsterite from halite–

magnetite ore and magnesian skarn (Zhitova et al., 1999).

The chemical composition of metasomatic silicates at the contact of dolerite with rock salt (Table 1) is close to the composition of minerals in the metasomatic column at the contact of dolerite with dolomite (Mazurov and Titov, 1999). X_{Fe} of forsterite is 0.025–0.071. Pyroxene is enriched in Al₂O₃ as is typical of fassaite; its $X_{\text{Fe}} = 0.243$ –0.248. Amphiboles from the endoskarn zone pertain to pargasite with $X_{\text{Fe}} = 0.225$ (optical properties and chemical composition), while the acicular mass in halite is tremolite (SEM/EDS spectra). Chlorite corresponds to clinocllore in composition; the FeO content in this mineral is not high (2.18–2.80 wt %) and increases to 6.24% in the areas with sulfide disseminations. The specific feature of phlogopite is the presence of Na₂O (up to 1.32 wt %). Scanning in characteristic X-rays corroborated that this admixture has a structural nature and is not related to the halite inclusions. Titanite contains insignificant admixtures of Al and Fe, while the major components occur in stoichiometric proportions.

The composition and structure of oxides at the contact of dolerite with rock salt have particular genetic implications. The primary rock salt contains chemogenic hydrogoethite, goethite, and hematite along with a terrigenous admixture of magnetite, ilmenite, and leucosene. Accessory oxides in dolerite include sporadic grains and intergrowths of ilmenite, ulvospinel, and titanomagnetite that occur in the pyroxene–feldspathic groundmass, often in association with sulfides. These oxides are characterized by a crystal

Table 2. Chemical composition of oxides, wt %

Component	Analysis number												
	1	2	3	4	5	6	7	8	9	10	11	12	13
TiO ₂	0.97	0.99	1.46	1.59	20.80	8.22	5.82	3.64	0.60	3.07	49.83	11.29	6.45
Al ₂ O ₃	53.00	53.13	51.32	28.18	9.97	0.46	2.44	1.58	0.58	1.85	0.00	0.69	0.40
FeO*	20.35	20.59	24.63	24.49	54.02	80.02	82.97	84.51	91.20	86.07	48.11	80.66	86.18
MnO	0.06	0.08	0.22	0.20	0.64	0.84	0.38	0.37	0.15	0.29	0.48	0.21	0.21
MgO	23.21	23.38	20.84	21.10	13.62	2.69	0.82	4.30	0.25	1.77	0.10	0.10	0.02
CaO	0.06	0.05	0.06	0.05	0.04	0.19	0.95	0.02	0.00	0.00	0.02	0.04	0.05
ZnO	0.06	0.06	0.10	0.09	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cr ₂ O ₃	0.01	0.00	0.01	0.01	0.00	0.01	0.00	0.01	0.00	0.00	0.12	0.18	0.20
Total	97.72	98.28	98.64	99.71	99.09	92.43	93.38	94.43	92.78	93.05	98.66	93.17	93.51
End members, %													
FeFe ₂ O ₄	4.7	5.2	16.0	15.5	1.6	74.2	83.3	70.0	97.4	83.9	–	64.8	86.3
MgFe ₂ O ₄	–	–	–	–	46.1	8.7	–	20.2	–	6.2	–	–	–
MgAl ₂ O ₄	59.0	59.0	79.0	79.0	18.9	1.1	4.6	3.3	1.4	4.0	–	–	–
FeAl ₂ O ₄	35.0	34.5	2.0	2.5	–	–	0.9	–	–	–	–	–	–
MnFe ₂ O ₄	–	–	1.0	1.0	–	–	–	–	–	–	–	–	–
FeTiO ₃	–	–	–	–	32.3	14.3	10.3	5.7	0.9	5.3	94.5	–	12.1
MnTiO ₃	–	–	–	–	1.1	1.8	0.9	0.8	0.3	0.6	1.0	–	0.5
MgTiO ₃	–	–	–	–	–	–	–	–	–	–	0.5	–	–
Fe ₂ TiO ₄	1.3	1.3	2.0	3.0	–	–	–	–	–	–	–	33.3	–
(Fe,Mg)(Cr,Al) ₂ O ₄	–	–	–	–	–	–	–	–	–	–	0.2	1.9	1.1
FeO	–	–	–	–	–	–	–	–	–	–	3.8	–	–

Note: Spinel: (1, 2) from the spinel–magnetite–forsterite zone, (3, 4) from halitite, (5) intergranular segregation of magnetite exsolution products. Magnetites: (6) from the spinel–fassaite zone, (7–9) from the spinel–magnetite–forsterite zone at the contact with apatite (7), forsterite (8), and spinel (9); (10) from chlorite–apatite–magnetite pockets in halitite. Accessory oxides in dolerite: (11) ilmenite, (12) ulvospinel–magnetite solid solution, (13) titanomagnetite. Analyses were performed on a Camebax Micro microprobe at the Analytical Center of the Institute of Geology and Mineralogy, Siberian Division, Russian Academy of Sciences, analyst O.S. Khmel'nikova. FeO* is total iron in the form of FeO.

morphology and a microstructure of staged exsolution typical of hypabyssal basic rocks (Haggerty, 1991).

Magnetite from the reaction zone at contacts of dolerite with rock salt has characteristic compositional and structural features that distinguish it from primary oxides in dolerite and metasomatic magnetite from other types of contacts. According to the set of attributes, two generations of magnetite are recognized. The first generation is represented by sporadic inhomogeneous crystals localized in the spinel–fassaite zone, abundant impregnations in the spinel–forsterite zone, and pockets and disseminations in halitite. The small size of individual grains and the polygonal structure of their aggregates testify to confined conditions of crystallization. In the exozone, the magnetite grains become larger, euhedral, and rhombic dodecahedral in habit. In some places, a kind of geometric selection is noted. The second generation of magnetite is associated with phlogopite, clinocllore, pargasite, titanite, and halite. The euhedral octahedrons of this generation grow over

rhombic dodecahedrons of the first generation and also occur at the clinocllore–halite boundary. Fine-grained apatite is associated with both generations of magnetite.

Characteristic features of the first generation of magnetite are interstitial and endotaxial segregations of ilmenite and spinel formed as a result of exsolution in the Fe–Ti–Al–Mg–Mn–O system. Magnetite of the first generation also contains relict silicates and apatite. Inclusions of skarn spinel serve as a basis for heterogeneous nucleation of early exsolution products. In chemical composition, magnetites of the first generation are distinguished by high Ti, Mg, and Al contents along with moderate amounts of V, Mn, Zn, and Ni (Table 2). Si and Ca are detected locally, marking inclusions of silicates and apatite. The detailed study of inhomogeneities in the composition and structure of magnetite, including the usage of TEM and microprobe analysis (Mazurov et al., 2004), allowed recognition of the specific composition of magnetite in different segments of

the metasomatic column. The highest combined TiO_2 , MgO , and Al_2O_3 contents have been established in the magnetite of the spinel–fassaite zone associated with large ilmenite lamellae and conjugated tiny grains of spinel. In the spinel–magnetite–forsterite selvage, the content of admixtures is lower than in the preceding zone. Magnetite grains at the contact with apatite contain more TiO_2 and less MgO and Al_2O_3 than grains enclosed within or between forsterite grains. The minimal concentration of admixtures has been established near inclusions of skarn spinel in magnetite. The most homogeneous areas of magnetite grains with a uniform network of exsolved spinel and ilmenite contain (wt %) 2–4 TiO_2 , 1–3 Al_2O_3 , and 1.5–3.0 MgO . This composition is the closest to the average bulk composition of magnetite of the first generation at the contacts of dolerite with rock salt. In magnetite of the first generation from halitite, the admixture content is comparable with that in the spinel–magnetite–forsterite zone. The products of the earliest stage of magnetite exsolution are complex in composition. In calculation to end members, they are defined as a mixture of magnesioferrite, spinel, and ilmenite (Table 2, analysis 5).

The formation of phlogopite, clinocllore, pargasite, titanite, and serpentine is accompanied by transformation of boundaries of magnetite grains and dissolution of intergranular particles of ilmenite and spinel. Examination with a transmission electron microscope demonstrates perfection of grain boundaries and ordering of phases. The second generation of magnetite crystallizes simultaneously with the above minerals pertaining to the assemblages of transformed (hydrated) magnesian skarn. The specific features of magnetite II are its homogeneous structure and composition, zoning controlled by the mechanism of layer-by-layer growth of faces, and octahedral habit. The trace element contents in this generation of magnetite are at the level of the detection limit of the microprobe.

In chemical and end-member compositions, magnetites of the first generation differ from oxides in both dolerites and dolerite–dolomite contacts (Mazurov and Titov, 1999). Magnetite, magnesioferrite, aluminospinel, and ilmenite are the main end members of magnetite under consideration; hercynite and pyrophanite are of subordinate importance. In contents of magnesioferrite and aluminospinel, the metasomatic magnetite at contacts of dolerite with rock salt is close to magnetite at dolerite–dolomite contacts but sharply differs in the amount of exsolved ilmenite. The accessory oxides in dolerite as a product of crystallization of tholeiitic basaltic magma pertain to the Fe–Ti series of solid solutions. The late magmatic magnetite that occurs in the contaminated variety of dolerite clearly differs in the absence of magnesioferrite and aluminospinel end members from magnetite of reaction zones.

Spinel is not abundant at the contacts of dolerite with rock salt. This mineral occurs as small (0.01–0.05 mm) grains in the spinel–fassaite zone, as well as in inter-

stices and magnetite inclusions in the spinel–magnetite–forsterite zone and in halitite. In the endoskarn zone, spinel is more magnesian and aluminous and corresponds to an aluminospinel–hercynite solid solution with a 5% admixture of magnetite end member (Table 2, analyses 1, 2). In halitite, spinel is enriched in Fe, Mn, Zn, and Ti (Table 2, analyses 3, 4). The crystallochemical formulas demonstrate that spinel is a solid solution of aluminospinel and magnetite with an admixture of hercynite and other end members (~5% in total). Spinel as a product of exsolution of magnetite I displays diverse patterns of particles differing in size and shape and incorporated into magnetite matrix, including (1) isometric particles about 0.2 mm in size localized in interstices and defects within magnetite, (2) isometric microcrystals about 0.3 mm in size located at margins of elongated ilmenite laths, (3) lamellae up to 1.5 μm long that make up a dense network regularly oriented along planes of cubes and rhombic dodecahedrons, and (4) dense coherent micrograins and dotty segregations tenths of a micrometer in size. The first and second varieties crystallized by the mechanism of heterogeneous nucleation, and the third and fourth varieties, by the mechanism of homogeneous nucleation. They have a characteristic shape and a coherent junction with the magnetite matrix, as well as an ordered but, in contrast to spinodal exsolution, irregular distribution. Microdiffraction on a JEM-1000 transmission electron microscope and examination on a JSM-35 scanning electron microscope equipped with a Kevex EDS system allowed us to establish phase heterogeneity and relative mobility of elements in the course of ordering of solid solutions. The first group of particles comprises transitional members of the aluminospinel–hercynite series with inclusions of jacobsonite, franklinite, magnetite, and ilmenite blocks. The second group of particles, which originated on ilmenite laths, contains Mg, Fe, Al, and traces of Mn. The lamellae of the third group reveal variable proportions of Mg, Fe, and Al. The smallest particles and dotty segregations are close to hercynite in composition. The series of diffusion mobility in the process of exsolution of ferrite is as follows: $\text{Zn} > \text{Mn} > \text{Mg} > \text{Al}$.

Sulfides reveal a systematic compositional variation at the contact of dolerite with rock salt. In dolerite, magmatic sulfide and oxide disseminations are closely conjugated. Sulfides are largely composed of either quenched or exsolved monosulfide (pyrrhotite–chalcopyrite–pentlandite) or intermediate (chalcopyrite–cubanite) solid solutions. Hydrothermal generations of pyrrhotite, chalcopyrite, pyrite, sphalerite, galena, and other sulfides occur in veinlets and pockets located in areas of autometasomatic alteration. No sulfides were detected in high-temperature reaction zones at the contacts of dolerite with carbonate–saliferous rocks. Pyrrhotite, chalcopyrite, and less abundant pyrite and marcasite replacing pyrrhotite along with late magnetite are noted in halitite and calciphyre. In comparison with skarn deposits in foldbelts, sulfide mineralization at the

deposits of the Angara–Ilim type is suppressed and commonly occurs at a distance from bedding plane intrusive sheets.

GENETIC INTERPRETATION

A survey of previous publications (Pavlov, 1975; Knipping, 1989; and others) and the original data presented here allowed us to substantially clarify the evolution of metasomatism at contacts of dolerite with saliferous rocks. This phenomenon is an element of the general evolution of the ore-magmatic system related to the formation of an intermediate magma chamber hosted in the Lower Cambrian carbonate–saliferous sequence under a screen of Cambrian–Ordovician terrigenous formations (Mazurov and Bondarenko, 1997). The total thickness of the platform sedimentary cover that overlies the saliferous members of the Lower Cambrian Angara Formation is 1–3 km (Pukhnarevich, 1986), and hence the total pressure at the level of metasomatic reactions was ~1 kbar. The porphyritic appearance of dolerite, with phenocrysts incorporated into the fine-grained groundmass, testifies to the rapid crystallization and exchange reactions was estimated from compositions of minerals. Thus, the globular dolerite in the zone of magma mingling with saliferous rocks contains plagioclase crystals of several generations, including zonal phenocrysts of the first generation (An_{80} in the core and An_{65} in the outer zone), sheath and skeletal crystals of the second generation (An_{65-50}), and laths in the microdoleritic groundmass (An_{55-50} , down to An_{43}). Olivine phenocrysts (Fo_{74-68}) and augite (En_{76-70}) in association with plagioclase I comprise less than 15 vol % in total. As follows from calculation with the COMAGMAT 3.0 package, olivine of this composition crystallizes first at 1219°C and plagioclase joins olivine at 1193°C; clinopyroxene appears at 1170°C, and magmatic titanomagnetite, at 1150°C in association with plagioclase and clinopyroxene. The solidus of basaltic magma is close to 900°C.

Since metasomatic zones replace both phenocrysts and groundmass, it is evident that dolerite was altered after its solidification. The exchange reactions at the dolerite–salt contact began at the temperature of rock salt melting (~800°C). Taking into account the composition of inclusions detected in halite and forsterite, it may be suggested that the mineral-forming fluid was a highly concentrated brine or salt melt with a total salinity of >60%. This fluid contained high-density reduced gases. Thermometric estimates outline the following steps of mineral formation: (1) forsterite + fassaite + spinel + magnetite I (820–740°C); (2) phlogopite + titanite + pargasite + apatite + magnetite II (600–500°C); and (3) clinocllore + serpentinite + tremolite + pyrrhotite + chalcopyrite (450°C and lower). The temperature of homogenization of fluid inclusions is 420–70°C in calcite, 300–260°C in anhydrite, and 140–60°C in hydrothermal halite. The upper temperature limit of

crystallization of magnetite I can be estimated from the solvus of spinel solid solutions (Mazurov and Titov, 2001; Mazurov et al., 2004). The compositions of magnetite I plotted on the corresponding diagram fall on the line that bounds the miscibility gap in the $FeFe_2O_4$ – $MgFe_2O_4$ – $MgAl_2O_4$ – $FeAl_2O_4$ system at 800°C (Lehmann and Roux, 1986; Neil et al., 1989). The temperature estimates based on homogenization of fluid inclusions and breakdown of solid solutions of composite oxides coincide; therefore, the temperature interval 750–800°C may be accepted as optimal for magnetite I crystallization.

The structure of contact zones furnishes additional evidence for the phenomena that accompanied emplacement and solidification of dolerite in the carbonate–saliferous sequence. The intruding heterogeneous basic melt consisted of olivine, plagioclase, and pyroxene phenocrysts; immiscible silicate and sulfide–oxide liquids; and a gas mixture. The country carbonate–saliferous sequence contained solutions, brines, and gas–oil mixtures in the pore space and within mineral grains. The mingling and combined disintegration of magma and country rocks and their reaction and thermal interaction (Sharapov et al., 1992) gave rise to mutual alteration. The contaminated melts differed from ordinary tholeiitic basalts in chemical composition. The fluid formed in reaction zones was the main agent of metasomatic processes. This fluid consisted of the gas derived from the magmatic melt and the components of the salt solution–melt as a product of melting and dissolution of saliferous rocks.

In contact zones differing in permeability and composition of country rocks, the exchange processes proceeded differently. The bodies of spinel–forsterite skarn that occur near the central magma conduit and above laccoliths were formed at the magmatic stage as a result of replacement of dolomite by magma-derived fluids. Magnesian skarn in the halos of offsets and at their heads was largely developed after dolerite globules. The sharp contact and the dispersion zone that separates the spinel–fassaite zone of the metasomatic column from dolerite indicate that the solidified igneous rock has been replaced. The structure of the metasomatic column and the composition of magnetite were controlled by the migration properties of various elements at the contacts of dolerite with dolomite and rock salt. In both cases, Fe, Si, P, Ti, and Al were extracted from silicate rock with enrichment of this rock in Mg and Ca. The high-Mg magnetite is predominant at the dolerite–dolomite contact, whereas the content of the magnesioferrite component at the dolerite–rock salt contact is limited. The behavior of aluminum, a rather actively migrating element, in both cases is similar. Titanium, which is an inert component in plutogenic ore-forming systems (Pertsev, 1977), where it does not occur beyond endoskarn zones, is highly mobile at the contacts under consideration. Magnesian ilmenite in association with magnesioferrite was found in exoskarn at the dolerite–dolomite contact. At the contact with

rock salt, Ti is detected in magnetite from both endo- and exoskarn zones. When low-temperature processes are superimposed, titanium is fixed in titanite and rutile.

The iron extracted by high-temperature fluids was a source of ore deposited in the conjugated zones of precipitation. The occurrence of so-called halite–magnetite ore at deep levels of the Korshunovsky deposit (Vakhrushev, 1981, 1985) is direct evidence for this statement. The reserves of particular halite–magnetite orebodies amount to tens of millions of tons. According to the results of geological exploration, two groups of orebodies enriched in halite are distinguished. The first group comprises the orebodies that adjoin the central part of the ore-bearing system at the level of contact between skarnified rocks belonging to the Angara saliferous and Litvintsevo dolomitic formations. The ores of this group are breccia-like, impregnated, and spotty. Dolerite fragments make up the framework of the breccia-like ore. In large dolerite fragments, the core with relict magmatic microstructure is surrounded by a metasomatic rim, so that each fragment mimics in miniature the zoning at the contact of dolerite with rock salt described above. These orebodies initially were zones of mingling and interaction of globular dolerites with rock salt. The ore mass is composed of inhomogeneous rhombic dodecahedrons of magnetite I, which are intergrown with forsterite and overgrown by magnetite II devoid of impurities. The ore is cemented by hydrothermal halite in association with calcite, anhydrite, and chlorite.

The second group of halite-bearing orebodies has been explored at deep levels of the Tret'ya Gora (Third Mountain) area. These are bedding plane sheets of magnetite ore incorporated into alternating dolomite and rock salt members of the Angara Formation. The ores are banded, breccia-like, and massive. The gangue minerals pertain to magnesian skarn assemblages with a predominance of chlorite and serpentine plus secondary carbonates and halite. Magnetite is also represented by two generations. In contrast to immediate contacts of skarn with dolerite, the early generation of magnetite does not contain titanium. The ore is enriched in pyrite and chalcopyrite disseminations. These skarn orebodies are distant zones of the contact aureole of the intermediate magma chamber.

In the central, near-vertical ore-bearing system and related pinnate orebodies, magnetite is associated with altered magnesian and calcic skarn. The ore mineralization pertains to the accompanying type. The multiple brecciation of rocks and telescoping of mineral assemblages, recrystallization, and filling of fissures and cavities are typical. Thereby, ore masses were undoubtedly rearranged with a gain of ore material from reaction zones at contacts of dolerite with carbonate–saliferous rocks. The region of interaction of dolerite with saliferous sedimentary rocks occupies the uppermost levels of the Cambrian saliferous sequence of the Siberian Platform. The echelon arranged systems of similar interme-

mediate chambers inferred from geophysical data allow the suggestion that the region of removal of ore matter and formation of conjugated orebodies extends to deeper levels of the platform cover.

CONCLUSIONS

The emplacement of traps and formation of an intermediate magma chamber hosted in saliferous rocks were accompanied by large-scale metasomatic processes at iron deposits of the Angara–Ilim type. Not only country rocks but also solidifying igneous masses were affected by alteration. The disintegration of the melt into globules and its fragmentation and mingling with melted saliferous rocks were accompanied by the dissolution of rock salt. The salt solution–melt formed thereby was the major agent of contact metasomatism. Spinel–forsterite skarn and calciphyre impregnated with magnesian magnetite were formed at the magmatic stage at the dolerite–dolomite contact. The mineral assemblages of postmagmatic magnesian skarn at contacts with dolomite and rock salt are similar in assortment of mineral species but slightly differ in chemical composition and quantitative proportions of particular minerals. Magnetite at the contact with rock salt contains more Ti and less Mg than at the contact with dolomite and is sharply distinct from magmatic oxides in dolerite. Rock salt is transformed into halite as an analogue of calciphyre in the outer zone of the metasomatic column of magnesian skarn. The metamorphosed halite markedly differs from the sedimentary and the late hydrothermal halite in type and composition of inclusions and EPR parameters. Iron that was extracted from dolerite is the main source of ore matter in the conjugated reaction zones and in the distant areas. This conclusion is readily apparent from the systematic variation in the composition and microstructure of magnetite, from the textural patterns of ore, and from the localization and structure of orebodies. The involvement of connate brines at the late stage of postmagmatic mineral formation follows from the structural and lithologic control of localization of boron minerals and crystal hydrates. Thus, at the ore deposits of the Angara–Ilim type, metasomatism at the contacts with saliferous rocks began to develop at the magmatic stage and was completed at the low-temperature hydrothermal stage. This long-term evolution predetermined a great diversity of mineral assemblages and specific features of skarn, ore, and accompanying hydrothermal metasomatic rocks.

ACKNOWLEDGMENTS

We thank B.P. Fitsev, V.M. Speshilov, and L.M. Zhivotova for their assistance in conducting fieldwork and examining borehole cores from deep levels and flanks of the Korshunovsky and Rudnogorsky deposits; A.G. Polozov and G.S. Von der Flaass, who kindly placed samples from the Nepa deposit at our disposal;

L.G. Bishaeva for her assistance in preparation of the manuscript; and V.N. Sharapov and E.G. Distanov for participation in discussion and helpful advice. This study was supported by the Russian Foundation for Basic Research (project no. 05-05-64262) and the Ministry of Education and Science of the Russian Federation (grant no. DSP.2.1.1.702).

REFERENCES

1. A. I. Anatol'eva, *Evaporite Red-Bed Association* (Nauka, Novosibirsk, 1972) [in Russian].
2. A. S. Baryshev, G. S. Vakhromeev, A. N. Zhitkov, and V. B. Kovalevich, *Geophysical Exploration of Iron Deposits in the Southern Siberian Craton* (Nedra, Moscow, 1980) [in Russian].
3. V. A. Dunaev, "Vertical Zoning of the Korshunovsky Iron Deposit," *Geol. Rudn. Mestorozhd.* **34** (3), 92–98 (1992).
4. *Prospecting Criteria for the Noril'sk-Type Sulfide Ores*, Ed. by V. S. Sobolev (Nauka, Novosibirsk, 1978) [in Russian].
5. G. D. Feoktistov, *Petrology and Formation Conditions of Trap Sills* (Nauka, Novosibirsk, 1978) [in Russian].
6. G. S. Von der Flaass and V. I. Nikulin, *Atlas of Structures of Iron Ore Fields* (Irkutsk State Univ., Irkutsk, 2000) [in Russian].
7. S. Grishina, J. Dubessy, A. Kontorovich, and J. Pironon, "Inclusions in Salt Beds Resulting from Thermal Metamorphism by Dolerite Sills, Eastern Siberia, USSR," *Eur. J. Mineral.*, No. 4, 1187–1202 (1992).
8. S. Grishina, J. Pironon, M. Mazurov, et al., "A. Organic Inclusions in Salt. Part 3. Oil and Gas Inclusions in Cambrian Evaporite Deposits from East Siberia. A Contribution to the Understanding of Nitrogen Generation in Evaporates," *Organic Geochem.* **28** (5), 297–310 (1998).
9. S. E. Haggerty, "Oxide Textures: A Mini Atlas," *Rev. Mineral.* **25**, 129–220 (1991).
10. V. E. Istomin, M. P. Mazurov, and S. N. Grishina, "Typomorphism of Paramagnetic Admixtures in Halites from of Basic Rock–Evaporite Interaction Zones," *Geol. Geofiz.* **41** (1), 126–134 (2000).
11. B. Knipping, *Basalt Intrusions in Evaporates* (Springer, Berlin, 1989).
12. J. Lehmann and J. Rouex, "Experimental and Theoretical Study of $(\text{Fe}^{2+}, \text{Mg})(\text{Al}, \text{Fe}^{3+})_2\text{O}_4$ Spinel: Activity–Composition Relationships, Miscibility Gaps, Vacancy Contents," *Geochim. Cosmochim. Acta* **50**, 176–178 (1986).
13. A. E. Lisitsyn, S. V. Malinko, V. V. Rudnev, and B. P. Fitsev, "Polygenic Nature of Borate Mineralization in the Korshunovsky Iron Deposit," *Geol. Rudn. Mestorozhd.*, **24** (2), 14–19 (1982).
14. M. P. Mazurov and P. M. Bondarenko, "Structural Genetic Model of the Angara–Ilim-Type Ore-Forming System," *Geol. Geofiz.* **38** (10), 1584–1593 (1997).
15. M. P. Mazurov and A. T. Titov, "Magnesian Skarn in the Areas of Bedding-Plane Injections of Basic Magma into Evaporites of the Platform Cover," *Geol. Geofiz.* **40** (1), 82–89 (1999).
16. M. P. Mazurov and A. T. Titov, "Spinel Composition, Crystallization, and Transformation at Contacts between Dolerite and Dolomite and Rock Salt," *Geol. Geofiz.* **42** (7), 1100–1109 (2001).
17. M. P. Mazurov, S. N. Grishina, and A. T. Titov, "Magnetics from Magnesian Skarn at Contacts between Dolerite and Rock Salt," *Geol. Geofiz.* **45** (10), 1198–1207 (2004).
18. *Metasomatism and Metasomatic Rocks*, Ed. by V. A. Zharikov and V. L. Rusinov (Nauchnyi Mir, Moscow, 1998) [in Russian].
19. J. Neil, B. J. Wood, and T. O. Mason, "High-Temperature Distribution in Fe_3O_4 – MgAl_2O_4 – MgFe_2O_4 – FeAl_2O_4 Spinels from Thermopower and Conductivity Measurements," *Am. Mineral.* **74**, 339–351 (1989).
20. D. I. Pavlov, *Magnetite Ore Formation with Participation of Exogenic Chloride Waters* (Nauka, Moscow, 1975) [in Russian].
21. D. I. Pavlov and A. A. Pek, "Formation of the Angara–Ilim-Type Iron Deposits as a Result of the Thermal Mobilization of Formation Salt Brines by Regional Trap Sill," in *Main Parameters of Natural Processes of Endogenic Ore Formation* (Nauka, Novosibirsk, 1979), Vol. 1, pp. 178–186 [in Russian].
22. D. I. Pavlov and I. D. Ryabchikov, "Dolerite Solidified in a Salt Sequence," *Izv. Akad. Nauk SSSR, Ser. Geol.*, No. 2, 52–63 (1968).
23. D. I. Pavlov and I. D. Ryabchikov, "Iron Extraction as a Result of Dolerite Interaction with Concentrated Chloride Solutions at High Temperature and Pressure," *Dokl. Akad. Nauk SSSR* **195** (3), 704–706 (1970).
24. N. N. Pertsev, *High-Temperature Metamorphism and Metasomatism* (Nauka, Moscow, 1977) [in Russian].
25. G. L. Pospelov, *Metasomatism: Paradoxes, Geologic–Geophysical Nature, and Mechanisms* (Nauka, Novosibirsk, 1973) [in Russian].
26. M. M. Pukhnarevich, *Formation Conditions of Endogenic Iron Deposits in the South of the Siberian Platform* (Irkutsk State Univ., Irkutsk, 1986) [in Russian].
27. L. K. Semeikina and V. N. Kozlova, "Mineralogical and Petrographic Characteristic of Potassium-Rich Rocks of the Nepa Basin," in *General Problems of Halogenesis* (Nauka, Moscow, 1985), pp. 143–148 [in Russian].
28. L. I. Shabynin, N. N. Pertsev, and I. A. Zotov, *Origin of Metalliferous Skarn at Dolomite Contacts* (Nauka, Moscow, 1984) [in Russian].
29. V. N. Sharapov, G. S. Von der Flaass, and A. V. Khomenko, "Thermal Contact Interaction between Country Rocks and Basic Melt during Its Injection into the Bedded Sequences of the Platform Cover of the Siberian Platform," *Geol. Geofiz.* **33** (3), 43–57 (1992).
30. L. G. Strakhov, *Ore-Bearing Volcanic Edifices in the Southern Siberian Platform* (Nauka, Novosibirsk, 1978) [in Russian].

31. D. I. Tsarev, "Fragmental Metasomatism," in *Metasomatism and Ore Formation* (Nauka, Moscow, 1984), pp. 309–320 [in Russian].
32. V. A. Vakhrushev, "Halite–Magnetite Ores of the Siberian Platform," *Geol. Rudn. Mestorozhd.* **23** (6), 100–104 (1981).
33. V. A. Vakhrushev, "Skarn-Type Iron Deposits in the Siberian Platform," in *Skarn Deposits* (Nauka, Moscow, 1985), pp. 186–234 [in Russian].
34. V. I. Vinogradov, G. A. Belenitskaya, M. I. Buyakaite, et al., "Isotopic Characteristics of Depositional Environments and Transformation of Lower Cambrian Saliferous Rocks in the Irkutsk Amphitheatre. Communication 1: Sulfur Isotopic Composition," *Litol. Polezn. Iskop.* **41** (1), 96–100 (2006) [*Lithol. Miner. Resour.* **41** (1), (2006)].
35. T. M. Zharkova, *Types of Rocks from the Cambrian Saliferous Sequence of the Siberian Platform* (Nauka, Novosibirsk, 1976) [in Russian].
36. L. M. Zhitova, V. V. Sharygin, and M. P. Mazurov, "Salt Inclusions in Forsterite from Magnesian Skarn on the Contact between Dolerite and Evaporites of the Siberian Platform," in *Abstracts of ECROFI XV* (Potsdam, 1999), pp. 328–329.
37. I. A. Zotov, *Origin of Trap Intrusions and Metamorphic Rocks of the Talnakh* (Nauka, Moscow, 1979) [in Russian].