

Chloritic Rocks and Chloritized Basalts as Plausible Precursors of Metamorphic Peridotites and Pyroxenites in the Kokchetav Massif, Northern Kazakhstan

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The Kokchetav Massif in northern Kazakhstan, a unique manifestation of collisional metamorphism of high and ultrahigh pressures, represents a fragment of the Proterozoic crust within the Central Asian Foldbelt [1]. As a result of Proterozoic subduction, the western part of the massif subsided to a depth of at least 140 km. Under conditions of a pressure of >40 kbar and temperature of >900°C, this led to the formation of diamonds in metasedimentary rocks. Judging from the absence of diamonds, the eastern part of the massif subsided to shallower depths. However, the maximal subsidence exceeded 80 km, which is evident from the occurrence of coesite-bearing schists. Exhumation of the subsided crust in the Late Cambrian resulted in its deformation, splitting into tectonic sheets displaced relative to each other, and retrograde metamorphism. The newly formed megamélange complex represents an ensemble of rocks metamorphosed under ultrahigh to low pressures and exhumed from different depths [1].

Unusual ultramafic and mafic rocks classified as peridotites and pyroxenites were found in two areas of the Kokchetav Massif. Garnet peridotites with Ti-clinohumite occur as a large shapeless isolated inclusion within a stratiform eclogite body in the western part of the massif near Lake Kumdy-Kol. These rocks closely associate with diamondiferous metapelites [2, 3]. In the eastern part of the massif, approximately 3 km west of the Enbek-Berlyk Settlement, schists and quartzites enclose spinel harzburgites and pyroxenites in the form of boudines and stratiform bodies near amphibolites and eclogites. Their bedding attitude and chemical and mineral compositions are described in [2–8]. Garnet peridotites are characterized by nonuniform structure and fine- to medium-grained (locally coarse-grained) porphyroblastic, glomeroblastic, and granoblastic textures. They are composed of variable proportions of garnet, Ti-clinohumite, clinopyroxene, zoisite, spinel, apatite, ilmenite, and magnetite. Garnet usually pre-

vails and sometimes forms granotite. Ilmenite and magnetite occur mostly within olivine and Ti-clinohumite in the form of numerous oriented fine inclusions. Secondary minerals are represented by hornblende, chlorite, and serpentine. Harzburgites are characterized by a gneisslike or parallel-banded structure and fine- to medium-grained (prismatic-grained) porphyroblastic and glomeroblastic textures. The rock consists of olivine, orthopyroxene, spinel, magnetite, and ilmenite. Anthophyllite, hornblende, plagioclase, biotite, chlorite, and serpentine occur as secondary minerals. Together with ilmenite and magnetite, spinel occurs in olivine grains as lamellae oriented parallel to the elongation of grains. If the orthopyroxene content decreases, harzburgites grade into subordinate dunites. Pyroxenites are characterized by nonuniform, banded, or massive structures and fine- to medium-grained porphyroblastic, granoblastic, and glomeroblastic textures. They are composed of the major orthopyroxene and spinel and the subordinate garnet, olivine, ilmenite, and magnetite. Secondary minerals are represented by biotite, anthophyllite, hornblende, plagioclase, zoisite, cordierite, chlorite, and others. Some garnet pyroxenites probably contained tschermakite (clinopyroxene) as an initial phase [8].

In chemical composition, garnet peridotites and spinel harzburgites are very unusual and similar to each other. They differ from typical mantle peridotites in elevated contents of Al₂O₃ (18.0–21.5 wt %), FeO as total Fe (12.2–14.5 wt %), and P₂O₅ (0.2–0.6 wt %) but lower contents of SiO₂ (31–34, occasionally up to 40 wt %) and MgO (20–26 wt %). In addition, these rocks are depleted in CrO₃ (0.0n wt %) and enriched in TiO₂ (1.2–2.6 wt %) [5–7]. Both garnet peridotites and spinel harzburgites are also enriched in REE as compared with usual alpinotype ultramafics. At the same time, peridotites are enriched in IREE and HREE relative to spinel harzburgites. Contents of LREEs are similar in both rock varieties [6, 7]. Pyroxenites resemble usual orthopyroxenites and websterites but differ in the elevated Al₂O₃ and TiO₂ contents (13–18 and 1–2 wt %, respectively). With respect to contents of SiO₂ (47.0–51.5 wt %), FeO (9.0–20.5 wt %), and MgO (6–22 wt %), they are similar to basic volcanics but differ in lowered concentrations of CaO (1–5, sometimes 14.5 wt %) and

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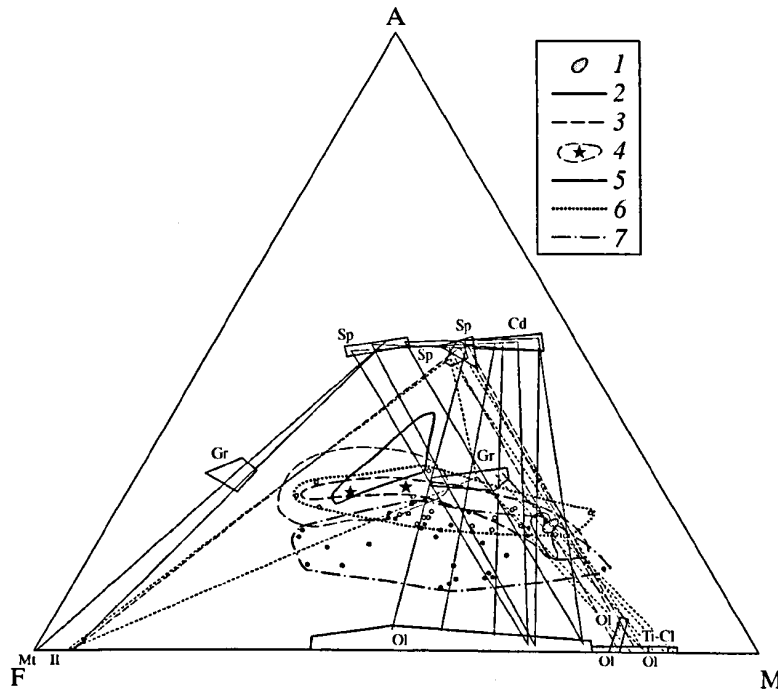


Fig. 1. AFM phase diagram for Kokchetav peridotites and pyroxenites showing minerals coexisting in garnet peridotites [3, 7] (dotted lines), spinel harzburgites [5] (dashed lines), and pyroxenites subjected to retrograde metamorphism in coronites [4, 5] (solid thin lines). Compositional fields of minerals: (Gr) garnet, (Cd) cordierite, (Ol) olivine, (Op) orthopyroxene, (Ti-Cl) Ti-clinohumite, (Il) ilmenite, (Mt) magnetite. Closed contours outline compositional fields: (1) spinel harzburgites [5], (2) garnet peridotites [3, 7], (3) pyroxenites/coronites [4, 5], (4) Siberian traps representing continental basalts (asterisks designate average compositions of rocks from two different provinces) [14], (5) amphibolites from the Enbek-Berlyk area [4], (6) chlorites from greenschists (circles designate compositions of individual minerals) [9], (7) chlorites from basic volcanics (black dots designate compositions of individual minerals) [9].

alkali metals ($\text{Na}_2\text{O} + \text{K}_2\text{O} = 0.1\text{--}0.8$, sometimes 2 wt %) [5]. In terms of REE contents, pyroxenites from the Enbek-Berlyk area are close to some Kumdy-Kol garnet peridotites. However, they differ from spinel harzburgites in higher concentrations of LREE and IREE. Some pyroxenites and harzburgites are similar in the HREE content [6, 7].

Garnet peridotites of the Lake Kumdy-Kol area formed as a result of Middle Cambrian subduction presumably experienced maximum metamorphism under the *PT* parameters similar to those for the associated diamondiferous dolomitic marbles and gneisses ($T = 900\text{--}1000^\circ\text{C}$, $P \geq 40$ kbar) [2, 3]. Harzburgites and pyroxenites of the Enbek-Berlyk area formed during the same subduction at lower temperatures ($780\text{--}840^\circ\text{C}$) and pressures (14–15 kbar) [8]. This is probably explained by the subsidence of the Earth's crust to different depths during the collision of continental plates.

As was mentioned, garnet peridotites and spinel harzburgites are very unusual and similar in their chemical composition, which implies the similarity of their protoliths. Their occurrence within the same geological structures and close spatial association with eclogites and amphibolites, which formed during the metamorphism of stratiform basic intrusions, apparently allow us to consider their protoliths as cumulates of basic

magma. However, the elevated Al_2O_3 , FeO, and TiO_2 contents and lowered SiO_2 , MgO, and Cr_2O_3 contents are inconsistent with this assumption. A composition similar to that of Kokchetav peridotites can be obtained as a result of the accumulation of pyrope–almandine garnet from basic magma crystallized under high pressure. However, relicts of the ophitic texture in central parts of stratiform garnet amphibolites in the Enbek-Berlyk area indicate that the basaltic magma intruded in the form of sills and dikes cooled at a shallow depth [2, 7]. The alternative mechanism responsible for accumulation of large quantities of Fe–Mg spinel during crystallization of shallow-depth basic magma is unlikely and examples of such ultramafic (Cr_2O_3 -poor) cumulates are unknown.

In our opinion, metasomatized stratiform basalts served as protoliths for garnet peridotites and spinel harzburgites. The initial chemical composition of basalts can probably be inferred from the following composition of amphibolites developed in the Enbek-Berlyk area [4], wt %: SiO_2 47.1–50.2, TiO_2 1.0–1.7, Al_2O_3 12.5–17.5, FeO (as total Fe) 9.0–16.2, MnO 0.16–0.22, MgO 6.0–7.7, CaO 10.0–12.7, Na_2O 1.5–2.5, K_2O 0.1–0.5, and L.O.I. 0.2–3.5. The effect of recalculation to 100% volatile-free composition is insignificant. Variations in the contents of these compo-

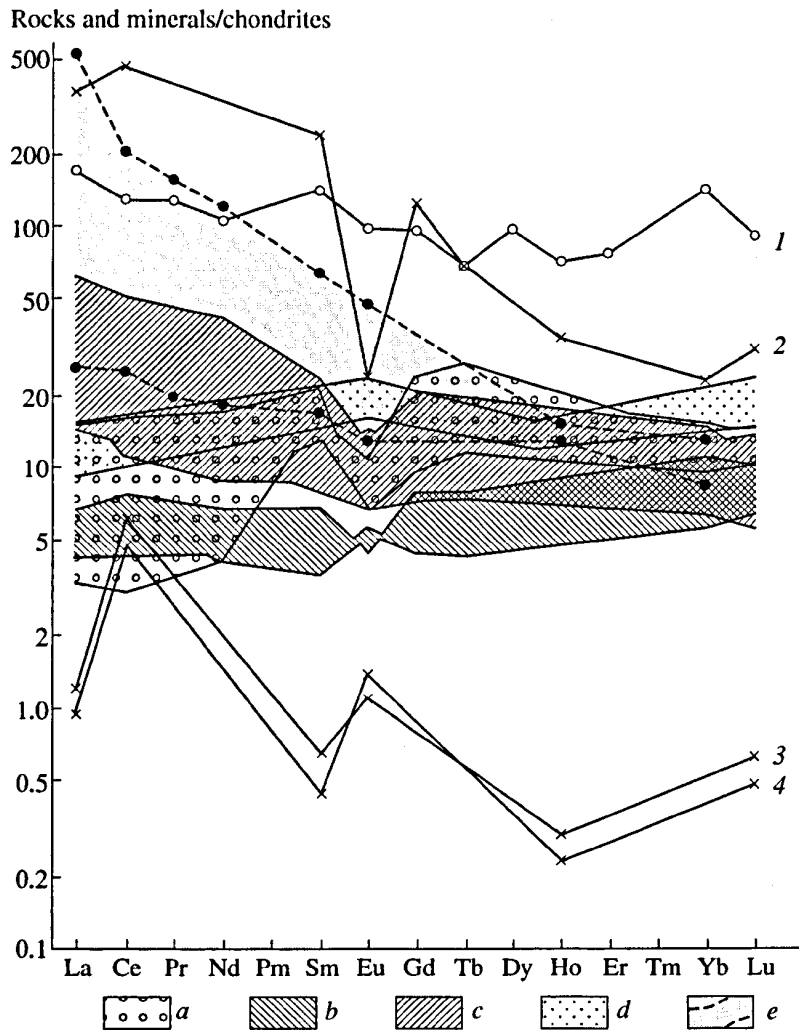


Fig. 2. Chondrite-normalized distributions of REE contents in Kokchetav metamorphic mafic/ultramafic rocks in comparison with chlorites and continental basalts: (a) garnet peridotites [7], (b) spinel harzburgites [6], (c) pyroxenites [6], (d) chlorites [10], (e) continental basalts [13]; (1-4) REE distribution in minerals: (1) chlorite [11], (2) prochlorite [12], (3) penninite [12], (4) clinocllore [12].

nents virtually remain unaltered. Based on these peculiarities of the chemical composition, the most probable process of hydrothermal alteration of basalts is Mg-Fe metasomatism manifested as chloritization. Chlorites from greenschist rocks are characterized by the following composition [9], wt %: SiO₂ 22.5-29.8, TiO₂ 0.01-0.6, Al₂O₃ 19.2-26.7, Fe₂O₃ 0.8-4.0, FeO 6-31, MnO 0.04-1.13, MgO 8.6-27.7, CaO 0.06-0.7, and H₂O 11-13. Chlorites from altered basic volcanics have the following composition [9], wt %: SiO₂ 25.1-33.7, TiO₂ 0.05-2.0, Al₂O₃ 10-22, Fe₂O₃ 1.2-12.7, FeO 6.8-31.9, MnO 0.1-3.1, MgO 9.5-23.0, CaO 0.02-1.8, and H₂O 10.7-12.5. Chloritization of basalts should be accompanied by an influx of MgO, FeO, Al₂O₃, and H₂O and removal of SiO₂, CaO, Na₂O, and K₂O. In order to obtain a chemical composition similar to that of Kumdy-Kol garnet peridotites and Enbek-Berlyk spinel harzburgites, primary basalts should be transformed into substantially

chloritic rocks. Water is naturally removed from the system during metamorphism. Partly chloritized basalts are compositionally similar to Enbek-Berlyk pyroxenites (Fig. 1). The assumption of chloritic precursors for the studied metamorphic rocks is also supported by similar distribution patterns of average REE contents in chlorites [10-12] and Kokchetav peridotites and pyroxenites [6, 7]. Concentrations of LREE and IREE in continental basalts [13] substantially decrease in the course of chloritization, while HREE contents remain virtually unchanged (Fig. 2).

The possibility of peridotite formation from chloritic rocks is confirmed by experimental data and thermodynamic calculations. Mg chlorite is transformed into enstatite, forsterite, and spinel at water pressures ranging from 3 to 18-20 kbar and $T > 750^{\circ}\text{C}$. At $P_{\text{H}_2\text{O}}$ ranging from 18-20 to 35 kbar and $T > 850^{\circ}\text{C}$, the Mg

chlorite is transformed into forsterite, pyrope, and spinel [15]. The temperatures of corresponding reactions for Mg–Fe chlorites should be 50–150°C lower. These parameters are consistent with *PT* metamorphism conditions of spinel harzburgites and garnet peridotites from the Kokchetav Massif, where chloritized basalts were transformed into pyroxenites composed mainly of orthopyroxene, garnet, and spinel.

CONCLUSIONS

Garnet peridotites and spinel harzburgites have unusual similar compositions, suggesting their formation from chloritic rocks contained in the upper section of the Earth's crust. Subduction of these rocks to a depth of 100–150 km resulted in their metamorphism. Pyroxenites associated with peridotites were derived from chloritized basalts. This is the most plausible formation model inferred from their geological position, association with eclogites and amphibolites, and composition of petrogenic and rare earth elements in metamorphic rocks and chlorites.

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