FORMATION OF HYDROTHERMAL-SEDIMENTARY NB-REE MINERALIZATION IN THE TOMTOR COMPLEX (ARCTIC SIBERIA, RUSSIA): SIGNATURES OF BIOTIC CONTRIBUTION

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The Tomtor complex of alkaline peridotitic and carbonatitic rocks occupies about 250 km^2 in the northern Sakha Republic (Yakutia). It exceeds 20 km in diameter and has a concentric zoned structure: a carbonatitic core surrounded with microcline-mica and microcline-apatite-mica rocks and an incomplete ring of peridotitic rocks, foidolites, and alkaline and nepheline syenites on the periphery (Fig. 1). All rocks are weathered, with the thickest eluvium derived from REE carbonatites and consisting of kaolinite-crandallite, siderite, goethite, and francolite layers. Ores with the highest Nb-REE enrichment occur as sheets in eluvium depressions within the Tomtor core (Burannyi, Severnyi and Yuzhnyi sites) (Porshnev and Stepanov, 1980, Tolstov et al., 1995, etc.). The formation of the rich Tomtor ores, especially, those of the Burannyi site, are still a subject of controversy, the choice being between igneous, sedimentary, hydrothermal-sedimentary, volcanic-sedimentary, or biogenic-sedimentary mechanisms. The conditions of superposed alteration of rocks and ores likewise remain debatable: it is unclear whether they experienced oxidation or reduction by waters percolated from the overlying coal-bearing deposits. The previous hypotheses interpreted the ores as (1) altered alkaline carbonatitic-peridotitic tuffaceous lavas (Entin et al., 1990); (2) epigenetically altered topmost eluvium (Lapin and Tolstov, 1993); (3) lacustrine deposits comprising talus and chemogenic sediments (Konoplev et al., 1992, Tolstov et al. 2011); (4) littoral-sublittoral deposits with cyanobacterial communities (Zhmur et al., 1994); or rather (5) products of the joint action of hydrothermalism, low-temperature sideritization, and weathering during the Tomtor history (Kravchenko et al., 1992).

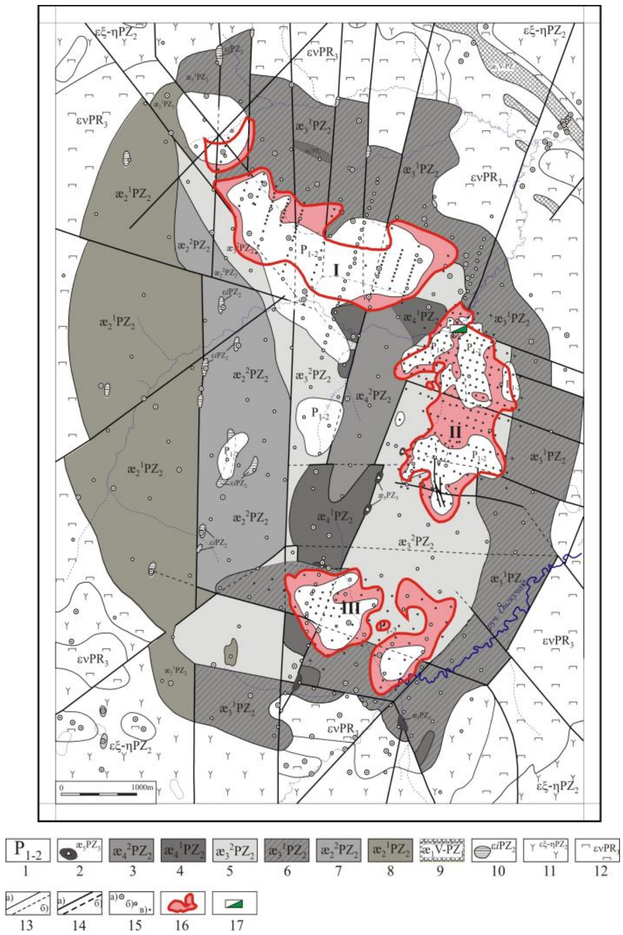

Fig. 1. Geological sketch map of pre-Jurassic rocks in the central Tomtor complex, after Tolstov and Tsybul'skaya, (1998). 1 = sediments: Paleozoic (undifferentiated lower–upper Permian) igneous rocks of the Tomtor complex; 2–9 = carbonatite suite: carbonatite breccia (2); rare-metal carbonatites (3); ankerite–chamosite rocks (4); polymineral phosphorus–rare-metal carbonatites (5); apatite–microcline–micaceous rocks (6); barren carbonatites (calcite and dolomite–calcite) (7); calcite–microcline–micaceous rocks (8); kamaphorites (9); 10–12 = silicate rocks: alkaline alnoite–tinguaite peridotites (alnoite, alkaline picrite, tinguaite, etc.) (10); alkaline and nepheline syenites (11); foidolite (nepheline–pyroxenite rocks of the jacupirangite–urtite series) (12); 13 = observed (a) and buried and inferred (b) geological boundaries; 14 = observed (a) and buried and inferred (b) faults; 15 = boreholes drilled before 1985 (a), in 1985–1990 by Ebelyakh geological survey (b), and in 1991–1994 (pilot holes), at the Burannyi site (c); 16 = Severnyi (I), Burannyi (II), and Yuzhnyi (III) sites; 17 = site of ore sampling (pilot hole).

The reported research led to the inference that the rich Tomtor ores were deposited in a shallow thermal lake as a result of hydrothermal-sedimentation and/or volcanic-hydrothermal-sedimentation processes, with mediation of thermophilic microbial communities (Lazareva et al., 2015). The lake formed by a hydrothermal geological event that postdated the emplacement and exposure of magma and its weathering (Entin et al., 1990; Kravchenko et al., 1995; Vladykin et al., 2014). The results that confirm this inference are specifically as follows.

1. The rich Nb, REE, Sc, Th, P, and Ti ores (natural concentrates) formed in surface conditions, under the effect of thermal waters, in a relatively shallow outflowing lake (in a limnic-paludal setting).

2. The rich ores are composed of authigenic ultrafine mineral particles and aggregates (90% <10 µm particles) of REE and trace element phosphates (monazite and crandallite group minerals), free from traces of mechanic wear, and notably less abundant detrital minerals (pyrochlore, Ti oxides, etc.).

3. The rich ores have a layered structure and a micro-layered texture produced by alternation of crandallite group minerals, monazite (and locally rhabdophane), Ti-Fe-Nb oxides, clay minerals (kaolinite, smectite, etc.), and goethite; they include angular and undeformed grains of detrital pyrochlore.

4. The relatively rich ores (including the Buranniy site) preserve bacteriomorphic nano- and microstructure, with remnants of microbial communities and plants showing close relationship on the micro- and nano-level (fig. 2 a,b,c,d).

5. Goethite-siderite ores contain microscopic layers of framboidal pyrite (fig. 2 e,f) known to form with microbial mediation (Schieber and Baird, 2001).

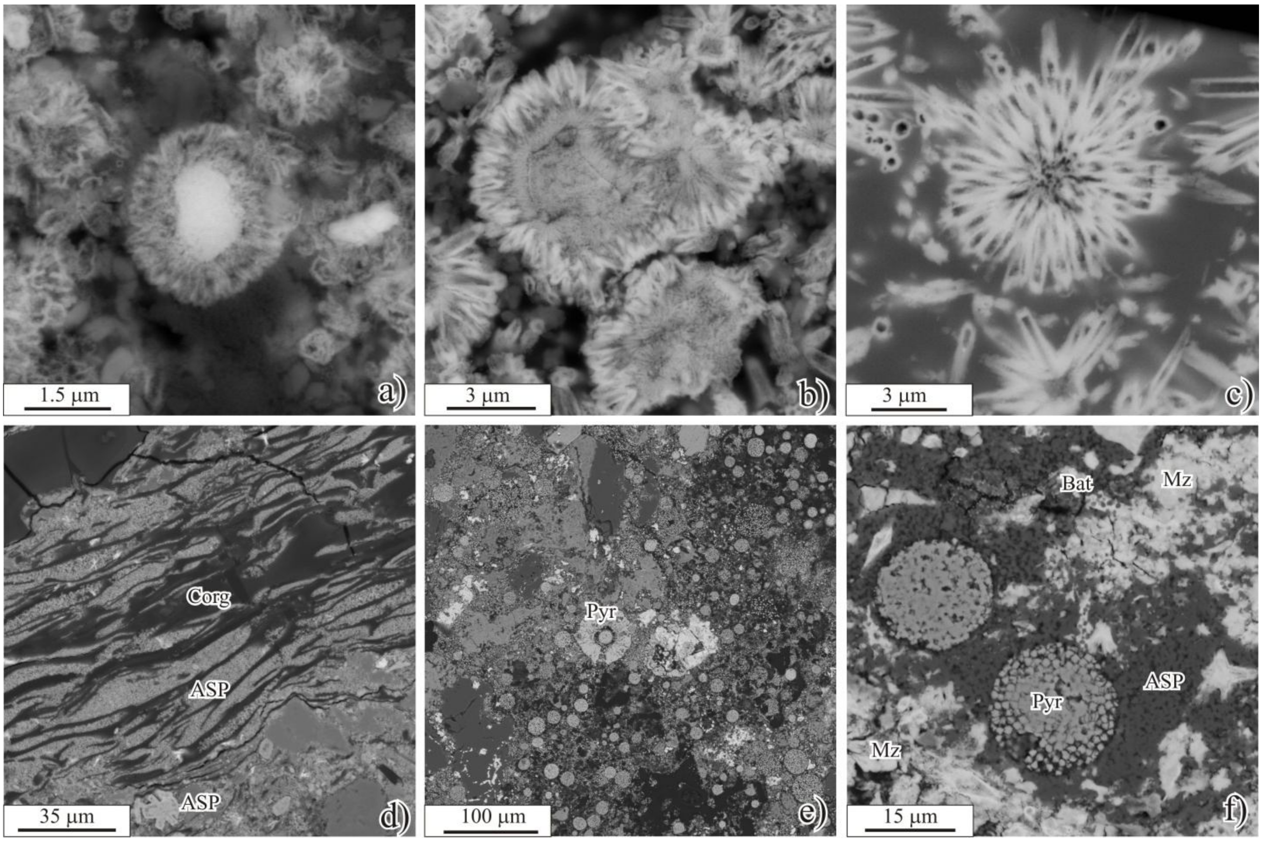

Fig. 2. Scanning electron microscope (BSE) images of the Tomtor ore samples with signatures of biotic activity and organic remnants. a-c: biomorphically released monazite (Mz); d: plant remnants filled with fine aggregate of crandallite (ASP) minerals; c-f: framboidal pyrite in ores coexisting with monazite (Mz).

6. Almost all ores contain sulfide minerals (pyrite, chalcopyrite, galena, sphalerite) which indicate a reduced setting of precipitation.

7. Carbon and oxygen isotope compositions in ores and related rocks vary in large ranges. The $\delta^{13}C$ – $\delta^{18}O$ diagram shows six fields (trends). Field I near primary igneous carbonatite (Taylor et al., 1967): carbonatites, autometasomatic carbonatites, often with abundant sulfides, as well as rocks from the lower ore zone (Kravchenko et al., 1995). Field II: mainly siderite massive rocks (with rhodochrosite, columbite, apatite, and ASP). Field III: Nb-REE sheet-like ores. Field IV: clacite-ankerite-dolomite and dolomite carbonatites and some siderite (spherolite and oolite) rocks. The trends III and IV correlate well with the hydrothermal trend and with the trend that represents interaction of alkaline rocks with meteoric water (Moore et al., 2015). Field V: Proterozoic and Cambrian sedimentary carbonates, including marbled carbonates of the Ulakhan-Kurung Fm. (NP or R1uk) which host the Tomtor intrusion, and fenitized rocks and ores with fluorite, Ti oxides, basnaeisite, pyrochlore, and Fe, Zn, and Pb sulfides. The same field

includes the isotope compositions of siderite-micaceous rocks with crandallite, calcite, and kaolinite. Of special interest is Field VI, with -24.8 to -39.2‰ $\delta^{13}C$, which are typical of biogenic organic matter. The lowest $\delta^{13}C$ values reaching -54.6‰ and -56.7‰ (at $\delta^{18}O$ = +10.5‰ and 9.4‰, respectively) correspond to fine contorted layered rocks composed of Fe-Mg-chlorite (shamosite), rhodochrosite, and lesser amounts of siderite, Nb-bearing Ti oxides, monazite, pyrochlore, sphalerite, and galena. The biogenic origin of this signal is consistent with recent published evidence of microbial mediation in the formation of hydrothermal-sedimentary rich ores in limnic (limnic-paludal?) settings, with methane inputs from seeps (Loyd et al., 2016) or from bacterial activity in plant remnants (Raghoebarsing et al., 2005).

Although the hydrothermal systems responsible for the formation of the rich Tomtor ores differ from their modern counterparts in island arcs (or back-arc basins, such as the Uzon-Geyser depression), they share some features of similarity. Namely, Ca, Fe, and Mn phosphates often precipitate over bacterial cells in the microbial communities of hot springs within the Uzon-Geyser depression, at low P contents in the waters (under 160 ppm) (Lazareva et al., 2015), while the bottom sediments of thermal lakes (e.g., Lake Fumarolnoe) consist of biogenic material (mostly diatom frustles) and framboidal pyrite.

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