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Fossil travertines and quasi-travertine in the Minusa basin (*West Siberia*): structure, composition, and comparative analysis

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Abstract

We study a carbonate body looking like a classical fossil travertine which was discovered in the Chebaki–Balakhta basin within the Minusa trough (Khakassia, Russia) and called *quasi-travertine*. It is a thin layer sandwiched between a basalt–dolerite sill and calcareous siltstone. Comprehensive studies of the quasi-travertine and its comparison with Devonian fossil travertines located a few kilometers away in terms of structure and composition have made the basis for its formation model. According to this model, the quasi-travertine has had a two-stage history: deposition and subsequent hydrothermal metasomatism. Laminated limestone coexisting with calcareous siltstone of the Early Devonian Shunet Formation formed during the first stage and then experienced hydrothermal metasomatism with precipitation of secondary calcite, prehnite, and pyrobitumen (kerite).

Keywords: fossil travertine; shallow sill; dolerite; basalt; quasi-travertine; sparite; prehnite; Minusa basin

Introduction and problem formulation

Calcareous deposits precipitated from water known as tufa, travertines (*lapis tiburtinus*) or fossil travertines have attracted attention of researchers since long ago. They store important evidence of past environment and climate and have implications for geological history, present or past fluid dynamic regimes and compositions of mineral-forming waters (Baikov et al., 1982; Chafetz and Folk, 1984; Chafetz et al., 1991; Folk, 1959; Pentecost, 2005). Travertine deposits have various uses in construction, agriculture, decorative arts, etc. (Freytet and Plet, 1996; Guo and Riding, 1992; Lavrushin, 2006; Sedletsky et al., 2002; Semenov, 1982, 2011; Sierralta et al., 2010). The presence of fossil travertine deposits was suggested to indicate extrusive origin of sheet-like igneous bodies (Okhapkin, 1961) as travertine often precipitates from CO_2-bearing thermal waters outflowing upon older lava flows within volcanic fields. Specifically, fossil travertines found in the Chebaki–Balakhta basin were interpreted as deposited over eroded surfaces of Early Devonian lava flows (Okhapkin, 1961). However, our studies show that calcareous bodies looking like classical travertines may coexist with sill intrusions, as well as with volcanics and thus cannot be diagnostic of volcanic or subvolcanic origin of sheet-like mafic bodies in the field.

Since their discovery, sheet-like mafic igneous bodies in the Minusa basin had been classified as lava flows for amygdaloidal textures and glassy structures (Edelshtein, 1932; Krasilnikov et al., 1955; Shneider and Zubkus, 1962), before some geologists (K.V. Ivanov, E.E. Razumovskaya, and M.M. Grunin) interpreted them as sill intrusions in a field survey report of the 1940s (Luchitsky, 1960). They mentioned abundant sills of post-Devonian basalts and the lack of Devonian basaltic lava flows in the Minusa intermontane basin. They also inferred typical intrusive origin for a sheet-like body of olivine dolerite and amygdaloidal basalt in the northwestern side of Lake Shunet (Luchitsky, 1960), which we call *Upper Shunet sill*. That interpretation was confirmed later by finds of numerous mafic sills in the Minusa basin (Fedoseev, 2008; Fedoseev et al., 2001; Peshehonov, 1988; Vorontsov and Fedoseev, 2012). In this respect, the origin of

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laminated carbonate crusts that look like fossil travertines and coexist with sills is of special interest, at least in two aspects. First, equal possibility of occurring upon basalts or dolerites (including, upon coarse-grained varieties), upon both erupted lava flows or shallow subsurface sills, means that they cannot be used to discriminate between extrusive and intrusive origin of mafic rocks. Discrimination may be done rather proceeding from vitreous structure, vesicular or amygdaloidal textures, parallel- and radial-columnar jointing, etc. (Fedoseev, 2001, 2015). Second, it is unclear which mechanism may be responsible for the laminated structure and crustified texture of carbonate crusts which armor sills in subsurface conditions. It appears reasonable to focus more on difference of the quasi-travertine from fossil travertines than on their similarity. We use the term *quasi-travertine* for the calcareous body lying over the Upper Shunet sill as the latter shows neither exhumation signatures nor traces of existence in an ancient weathering profile.

Methods

The local geology and tectonics of areas that host sheet-like mafic bodies with exposed upper margins were mapped to a large scale. Major elements were determined by XRF at the Vinogradov Institute of Geochemistry (Irkutsk) on an *MCS-25* multichannel spectrometer following the standard procedure (Afonin et al., 1984). Images of thin sections and microfabric were obtained with Nikon Instruments *Eclipse LV100POL* microscopes at the V.S. Sobolev Institute of Geology and Mineralogy (Novosibirsk) and at the Far East Geological Institute (Vladivostok).

Trace elements were determined by mass spectrometry with inductively coupled plasma (ICP-MS) on an *ELEMENT-2 Finnigan MAT* high-resolution spectrometer at the Baikal Shared-Used Center of the Irkutsk Science Center (analysts E.V. Smirnova and N.N. Pakhomova). The measurements were run at standard operating parameters: plasma conditions of 1350 W forward power and <4 W reflected power; 0.8–0.95 l/min nebulizer gas flow, 16 l/min plasma (argon) outer gas flow, and 0.9–1.2 l/min auxiliary gas flow; 0.8–1.0 ml/min sample uptake (pumping) rate; Meinhard nebulizer type; time: 400 s total acquisition time (60 s settling, 100 s dwell, and 240 s flush time); 9 to 240 amu mass range; internal standard 103 Rh 2.

The Rh internal standard was added at a concentration of 2 ng/ml and used in matrix correction and in correction for signal instability and/or fluctuations during acquisition. Calibration was performed using SPEX multielement certified solutions CLMS-1, -2, -3, -4 (USA).

The samples were preconditioned with the standard procedure of acid digestion using open systems, in a $HF/HNO_3/HClO_4$ mixture, with pure 60% HNO_3 and 40% HF purified by subboiling distillation, suprapur 70% $HClO_4$ (MERCK, Germany), as well as deionised water purified on a *Simplicity Elix Millipor SA* system (France). The accuracy and reproducibility of the analysis were checked against the certified external standard of GSR-6 limestone (USA).

The chemical and qualitative mineralogical compositions of carbonate samples were determined at the Laboratory for XRF analytics of the IGM Analytical Center (Novosibirsk) on an Oxford Instruments *Leo 1430 VP* scanning electron microscope (analyst A.T. Titov) and at the Laboratory for X-Ray Analyses, FEGI (Vladivostok) on a *JEOL JXA 8100* four-channel microanalyzer (analyst N.I. Ekimova), using the standard techniques in both cases, at an accelerating voltage of 20 kV and a beam current of 10 nA, with an Oxford Instruments *INCA-sight* (UK). A nondestructive local technique with a spot diameter of 5–10 µm was applied to C-coated polished thin sections for qualitative and quantitative analyses of elements with concentrations as low as 0.01–100 wt.%; the resolution of images in secondary electrons and backscattered electrons was about 400 A.

Geological setting

The quasi-travertine was found on the top of the Upper Shunet sill within the Krasnogorsk–Matarak field located in the southwestern Chebaki–Balakhta basin, a part of the Minusa intermontane basin (see inset in Fig. 1*A*). The Chebaki–Balakhta basin is filled with Lower–Middle Devonian sediments lying discordantly on Early–Middle Cambrian limestones metamorphosed to different grades and intruded by granitoids of the Tigertysh complex (Parnachev et al., 2009; Tomashpolskaya, 1976; Vorontsov et al., 2013). Mafic sills occur among Early Devonian sediments that belong to the Matarak and Shunet Formations (Fig. 1*A*, *B*).

The Matarak Formation consists of felsic and intermediate pyroclastics in its lower part and clastic sediments with intercalations of ash and crystalloclastic tuff of similar compositions in the upper part. Sills that intrude the Matarak Formation enclose sporadic xenoliths of Early Paleozoic medium-grained granodiorites and deformed laminated limestones. The Shunet Formation has a uniform calcareous-siltstone composition with rare thin clastic layers of sandstone, siltstone, and marl (Fig. 1*C*); the siltstones enclose thin layers and lenses of limestone with conodonts (Izokh et al., 2011). The overlying Aramchak Formation consists of coarse molasse: conglomerate and gravelstone with sandstone and siltstone interbeds. No sills have been found within the formation so far but their existence cannot be excluded. Dolerite sills have pre-Middle Eifelian geologcail ages and $^{40}Ar/^{39}Ar$ ages for bulk samples between 389 ± 4 and 395 ± 2 Ma (Fedoseev, 2008).

Note that most of sheet-like mafic bodies encountered in the Minusa basin were previously interpreted as extrusive facies (Kovalev, 1980; Luchitsky, 1960; Parnachev et al., 2009; Shneider and Zubkus, 1962). Following that interpretation, the Tona and Marchengash formations and other stratigraphic units consisting mostly of extrusives prevalent over sedimentary and volcanic-sedimentary rocks were distinguished in areas adjacent to and distant from the Krasnogorsk–Matarak area. This approach is, however, debatable: the existence of such lithostratigraphic units lacks solid proof and