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Carbonatite melts and genesis of apatite mineralization in the Guli pluton (*northern East Siberia*)

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Abstract

Inclusions of mineral-forming environments in apatite-containing ijolites and magnetite–phlogopite–apatite ores in carbonatites were studied to elucidate the genesis of apatite mineralization in the Guli alkaline ultramafic carbonatite massif. Primary inclusions of carbonate–salt and carbonate melts have been discovered and studied. The carbonate–salt melt inclusions are of alkaline high-Ca composition and are enriched in P, Sr, SO_3, and F (wt.%): CaO—30–40, Na_2O—5–12, K_2O—2–4, P_2O_5—1–3, SO_3—1.5–3, and SrO—1–3. They also contain minor MgO, FeO, BaO, and SiO_2 (tenths and hundredths of percent). The homogenization temperature of these inclusions is 850–970 °C. The carbonate inclusions contain predominant CaO (54–67 wt.%) and minor MgO, FeO, SrO, Na_2O, and P_2O_5 (tenths of percent). Their homogenization temperature is 840–860 °C. Similar primary carbonate–salt and carbonate inclusions were found in garnet, and secondary ones were detected in silicate minerals (clinopyroxene and nepheline) of ijolites. Clinopyroxenes of ijolites also contain primary inclusions of alkaline ultramafic high-Ca melts similar in composition to melilitite-melanephelinites highly enriched in P, SO_3, and CO_2 (wt.%): SiO_2—41–46, Al_2O_3—8–16, FeO—2–8, MgO—3–6, CaO—12–20, Na_2O—2–9, K_2O—1–6, P_2O_5—0.4–2.1, SO_3—0.2–2.3, and Cl—0.02–0.35. According to the obtained data, apatite of the magnetite–phlogopite–apatite ores and ijolites of the Guli pluton crystallized from phosphorus-rich alkaline carbonate–salt melts at 850–970 °C. The generation of these melts was, most likely, due to the silicate–salt immiscibility in melilitite-melanephelinite melts highly enriched in salts, which occurred either at the final stages of clinopyroxene crystallization or during the formation of melilite. The presence of alkalies, S, F, and CO_2 in spatially separated carbonate–salt melts contributed to the concentration and preservation of phosphorus in them at low temperatures, which led to the formation of apatite mineralization in ijolites and ore deposit in carbonatites.

Keywords: apatite; ijolites; carbonatites; silicate inclusions; alkaline carbonate–salt inclusions; carbonate inclusions

Introduction

Alkaline ultramafic complex carbonatite massifs bear various, including apatite. Apatite ore occurrences in such massifs are diverse by mineral assemblages and the relative time and way of formation. Earlier, apatite ores were subdivided into types and subtypes, and the principles of their genetic classification were developed (Dudkin, 1977; Kukharenko et al., 1965). At present, the genetic classification proposed by Egorov (1991) is considered the most complete and reasoned. It includes three types of apatite ores according to mineral assemblages: (1) silicate-apatite (ijolite); (2) silicate-magnetite-apatite (phoscorite); and (3) carbonate-apatite (carbonatite). In terms of this classification, apatite ores at the front of ijolitization, phoscoritization, and carbonatization are related to contact metasomatism, and the rest apatite ores are produced at the magmatic and autometasomatic stages of intrusion formation. Though the terms of this classification are generally accepted, not all researchers agree with Egorov's (1991) genetic concepts. According to their opinion, only apatites of ijolite type are magmatic minerals, whereas all other apatites are products of postmagmatic alteration of the massif rocks.

The ambiguity in the genetic concepts is due to the fact that they are based mostly on geological and mineralogical research, i.e., on indirect evidence.

Today, specific qualitative and quantitative information about the mineral-forming environments and its chemical composition, fluid saturation, evolution, and *PT*-conditions of crystallization can be obtained by comprehensive thermobarogeochemical studies of melt and fluid inclusions preserved in minerals. Melt and fluid inclusions have the unique property

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to preserve the information about the temperatures and pressures of the mineral-forming environments, the chemical compositions of parental and generated melts and solutions, the conditions of their evolution, the behavior of elements during the melt ascent and crystallization, and the liquation and mixing of melts (Bazarova et al., 1975; Roedder, 1984; Sobolev, 1996). In other natural systems this information is totally or partly lost because of the widely developed superposed processes in rocks.

Applying thermobarogeochemistry, we have established the physicochemical conditions of formation of apatite mineralization in the Guli pluton in the Maimecha–Kotui province (northern Siberian Platform).

Geology and petrography of apatite-containing rocks and ores of the Guli pluton

The Guli pluton is the world's largest alkaline ultramafic carbonatite massif. It is composed mostly of dunites and peridotites. There are a sheet-like body and veins of pyroxenites in the northeast of the massif and a lava field of meymechites in the southwest. In the north, there are two carbonatite stocks, with jacupirangites and apomelilitic rocks containing lenticular ijolite bodies between them. The ijolites and apomelilitic rocks bear veins of ijolite–pegmatites tens of centimeters to ≥5–10 m in thickness and tens to hundreds of meters in length. The dunites also contain small bodies and dikes of olivine melanephelinites, picrites, and meymechites.

Apatite occurs in almost all rocks of the massif but concentrates mostly in ijolites and carbonatites. Following Egorov's (1991) classification, these apatite clusters belong to the ijolite and apatite–carbonatite types, respectively. The goal of our work was to study the above rocks.

Ijolites rich in apatite (especially those localized near carbonatites) are highly calcareous: The rock-forming minerals include not only nepheline, clinopyroxene, and phlogopite (typical of these rocks) but also garnet and, more seldom, xenomorphic grains of sphene and wollastonite. Apatite occurs in the rock as small prismatic grains or, seldom, as inclusions in large nepheline grains. The latter are usually xenomorphic. Clinopyroxene is present mainly as euhedral grains and is spatially associated with red–brown palmate segregations of Fe–Mg-mica. The garnet grains are reddish–brown xenomorphic and fill the interstices between the minerals. The ijolites are medium- to coarse-grained. *Ijolite–pegmatites* contain nepheline, clinopyroxene, and minor garnet and carbonates. Apatite forms radiate aggregates cutting the rock-forming minerals. Apatite clusters in ijolites and ijolite–pegmatites are of veinlet–nest type. *Carbonatites* bear apatite grains in paragenesis with magnetite (up to 5–25 vol.%), phlogopite (up to 5–15 vol.%), carbonates, clinopyroxene (up to 10–25 vol.%), garnet, and olivine and form vein- and stock-like bodies of different thicknesses. This apatite is either short-prismatic or (more often) sugar-like and sometimes composes more than 40–45 vol.% of the ore shoot. The carbonatites are of banded or, locally, fluid-linear structure.

Methods

The composition of rock-forming minerals in the apatite-containing rocks under study was determined with a Camebax-Micro probe.

To reconstruct the physicochemical conditions of crystallization and concentration of apatite, we used common geological, mineralogical, and petrographic methods as well as thermobarogeochemistry based on study of primary and secondary melt and fluid inclusions sealed in minerals during their growth and cooling. Using optical microscopes, we detected inclusions and examined their distribution for the substantiation of their primary or secondary nature and visual identification of their phase composition. To determine the temperature of sealing of the mineral-forming environments by the host mineral and the temperatures of homogenization and quenching of the inclusion substance (for the subsequent analysis of its composition), we applied a stage with a silite heater, combined with a microscope, which made it possible to heat the inclusions to 1350–1400 ºC and follow the process of heating and cooling.

The quantitative and qualitative compositions of crystalline phases and glasses in the heated and nonheated melt inclusions were determined with a Camebax-Micro probe. Operating conditions: beam diameter—2–3 μm, accelerating voltage—20 kV, and current—40 nA. Synthetic homogeneous glasses and minerals with known contents of elements and with a composition similar to that of the samples under study were used as standards. During the analysis, the contents of major rock-forming elements as well as S, Cl, Ba, and Sr were estimated. The detection limits of elements were calculated (Lavrent'ev et al., 1974) by the 2σ criterion (wt.%): SiO_2—0.009, TiO_2—0.036, Al_2O_3—0.012, FeO—0.019, MgO—0.013, MnO—0.022, CaO—0.010, Na_2O—0.020, K_2O—0.010, BaO—0.105, SrO—0.019, P_2O_5—0.008, Cl—0.011, and SO_3—0.011. No less than two measurements were made at each point. Fine crystalline phases in the inclusions were examined with an LEO1430VP scanning electron microscope equipped with an OXFORD energy spectrometer, which helped to perform a semiquantitative chemical analysis using the INCA Energy 300 program. Glass and daughter phases in the inclusions were identified by Raman spectroscopy providing preliminary data on the phase composition of melt and salt inclusions without their decrepitation.

All examinations and analyses were carried out on the setups at the Institute of Geology and Mineralogy, Novosibirsk.

Major minerals of the considered rocks

The chemical compositions of the same minerals in the standard ijolites and in their high-Ca high-apatite varieties are similar but at the same time show a significant difference. For example, *clinopyroxene*, the most abundant mineral of ijolites, is referred to as diopside, but in the apatite-enriched ijolites it is more magnesian (Mg# = 0.86 against 0.84) and contains