Koltsov A.B. Ruby-bearing metasomatites in marbles: conditions and numerical model of the formation

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Ruby deposits localized in marbles are widely known in history as a source of precious stones for many countries during many ages (Birma, Kashmir, Afghanistan). Number of deposits in the Urals and the Pamirs are related to the same type. Until now, their genesis is still unclear. There are following hypotheses on the formation of the rocks: 1) metamorphism of lime-stones primarily contaminated by aluminous products of weathering (Okrusch et al., 1976; Rossovskiy et al., 1982); 2) metasomatic transformations of terregenous layers in marbles by metamorphic solutions (Dmitriev, 1982; Kisin, 1991); 3) influx of Al into marbles by endogenic solutions related to the alkalic magmatism (Terekhov et al., 1999). All the above hypotheses face problems on explanation of compositional peculiarities of the corundum-bearing rocks.

The ruby deposits in marbles have similar compositional and structural features. They include an overall Mg-enrichment and almost complete absence of iron in silicates; an attachment of ruby crystals to more or less continuous layers, which locally turn to usual crystalline schists; a zoning expressed in transformation of the host lime-stones or dolomites to Mg-rich varieties and subsequently to marbles with dissipated ruby or phlogopite, and finally to polymineral carbonate-silicate assemblages within the thin layers (zones). Wide variations of mineral compositions across the zones are also evident. Biotite composition varies from phlogopite to eastonite, plagioclase is anorthite in one cases, and albite, in others. All these features imply the significant gradients of chemical potentials of components.

A stability of corundum-bearing assemblages is limited by the following equilibria

$Par = Crn + Ab + H_2O$

$Ms = Crn + Kfs + H_2O$

$Phl^{Bt} + Crn + 3CO_2 = Ms + 3Mgs^{Cal}$

$3An + Cal + H_2O = 2Zo + CO_2$

$Crn + Mgs^{Cal} = Sp + CO_2$

$2Prg + Crn + 9CO_2 = 3An + 2Ab + Cal + 8Mgs^{Cal} + 2H_2O$

which, using the data on calcite, biotite and plagioclase (scapolite) compositions, correspond to $610<T<660^{O}C$, $4.5<P_{tot}<6$ kbar, $0.16<X_{CO2}<0.46$. Such high concentration of CO_2 is not characteristic for the most of fluid systems forming at regional metamorphism in the epidote-amphibolite and amphibolite facies. It is unusual for degasing of magmatic chambers, where CO_2 amount is several times lower. That is in favor of an intensive, probably, deep-seated source of CO_2.

Calculations show that a presence of one or another mineral in corundum-bearing marbles is determined by fluid alkalinity, by the K/Na ratio in a fluid, and bulk Mg-content in a rock (calcite or dolomite marbles). The most common Mg-rich calcitic marbles with biotite, scapolite, muscovite form in the alkalic environments. Presence of these parageneses, as well as a constant presence in marbles of K, Na, Mg-bearing minerals at an absence of Fe, corresponds to the metasomatic origin of these rocks.

A numerical modeling of a fluid-rock interaction was carried out by the method of the stage penetrating reactor using the GBFLOW program (Grichuk, 2000) at constant $T=600^{O}C$ and P=5 kbar, $X_{CO2}=0.2$ in accordance with the above data; concentration of Ca equilibrated with calcite at given T, P, X_{CO2}. Concentrations of other components (Na, K, Mg, Al, Si), as well alkalinity fixed by additions of NaOH, could vary in the model.

A composition of the initial rock was formed by mixing of calcite or dolomite with kyanite-garnet-biotite schist in different proportions. Such mixtures model the observed gradual change of layers of terrigeneous rocks to pure marbles through the varieties with dissipated admixture of silicate minerals.

If the initial fluid is not saturated in Al and Si with respect to any silicates, then silicate minerals gradually disappear being replaced by carbonates from outer zones to inner zones of the model columns. In calcic marbles, Mg is extracted from silicates and enters into carbonates, that results in zones of dolomitization and an enrichment of calcite in Mg. In contrast, in dolomitic marbles, Mg is extracted from dolomite and enters into silicate, mostly in phlogopite. That explains a constant attachment of the corundum-bearing deposits to marbles consisting of Mg-calcite with dolomite or without it, which is observed in all deposits.

At Na/K = 1 and high alkalinity of a fluid, the following column forms after the rocks consisting of calcite and schist (1:1):

Cal | Cal Crn | Cal Crn Bt | Cal Ms Bt | Cal Scp Bt |…

A decrease of clastic content in marble at similar fluid composition results in appearance of muscovite instead of biotite in assemblage with corundum or without it, and subsequently to the formation of muscovite+scapolite assemblage. Thus, the zoning

Cal | Cal Crn | Cal Ms Crn | Cal Bt Crn|…

forms in marble sequence with varying amount of clastic material at a constant fluid/rock ratio. In contrast to metasomatic zoning, this zoning can be defined as primary or inherited. Both these types of zoning exactly reproduce the observed relations in the rocks of the Central Pamirs, where the outer aureole is built of dissipated corundum grains in marbles, whereas biotite, muscovite, and scapolite appear near to the interlayres.

An increase of the Na/K ratio in the initial fluid up to 9:1 at similar alkalinity results in formation of corundum, pargasite, and scapolite-bearing parageneses. As an amount of clastic compound in marble increases, biotite appears with the formation of primary zoning:

Cal | Cal Crn | Cal Crn Prg| Cal Crn Bt|…

Such sequences model the formation of corundum-bearing metasomatites (CM) in South-Western Pamirs and Afghanistan.

At neutral initial fluid (without addition of alkalis) and Na/K = 1, an stabilization of corundum is established. The model biotite and anorthite-bearing parageneses appear. At Na/K = 9, pargasite and anorthite are stable. At X_{CO2} below 0.2 and T up to $550^{O}C$, chlorite and margarite form instead of anorthite. These variants reproduce a structure of CM in Kashmir, where all the above phases are present.

The metasomatic alteration of dolomitic marbles containing terrigeneous material is characterized by some peculiarities. If such marble is affected by alkalic fluid under-saturated in Al and Si, a rock consisting of dolomite, Al-poor biotite (close to phlogopite, Al^{IV}= 1.1-1.2 f.u.) and some calcite forms at different Na/K values. Corundum does not form in this model. That is related to expanding of biotite stability, which extracts all Al, owing to an increase of MgO activity in the presence of dolomite. Appearance of dolomite+biotite paragenesis in most of reactor cells is also characteristic. That should correspond to relatively large thickness of the zone. In fact, dolomitic marbles with dissipated phlogopite are widely developed in the western part of the Muzkol'skii Complex of the Central Pamirs.

An influence of neutral fluid on dolomitic marble results in the formation of the model columns with corundum and biotite or pargasite in dependence on Na/K ratio in the fluid. The former column models the formation of corundum-bearing dolomitic marbles with biotite form the Yakhont and Mramorny Zub occurrences in the Central Pamirs.

In all the above variants, Al and Si saturate the fluid during its interaction with silicate-carbonate rocks. Concentration of Si in the initial fluid is critical for the formation of CM and its value for the given conditions is about 0.07 M. At slightly higher concentrations of Si, the first non-carbonate mineral is biotite or amphibole, at some more higher, diopside. In order to recognize the possible sources of such fluid, concentrations of Al and Si in the fluids equilibrated with the main types of magmatic rock are calculated. The necessary low concentrations of Al and Si are related to fluids equilibrated with alkalic or alkali-ultrabasic rocks. Fluids equilibrated with granitic, basitic, and syenitic rocks, as well as with crystalline schists, are enriched in silica. Their interaction with marble should result in deposition of any other alumosilicates instead of corundum.

Thus, the process of corundum formation in marbles is described as the metasomatic de-silication of marbles, containing an admixture of clastic material. This process occurred under influence of high-temperature carbonic fluid. Variations in alkalinity and potassium activity determine the facial diversities between CM in different occurrences.

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