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Free thermal convection model for formation of the largest uranium field in the Streltsovka caldera (Transbaikalia, Russia)

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INTRODUCTION

The Streltsovka collapse caldera hosts the largest U ore field associated with volcanism in the world. Its total ore resource of more than 250,000 tU is distributed in 19 deposits. The dominant hypotheses of the origin of these Mo-U deposits, as proposed by exploration geologists, suggest that uranium was transported to the sites of ore deposition by ascending flow of magmatic fluids separated from the deep-seated intracrustal or subcrustal magmatic source [1]. According to this concept, the origin of deposits is only paragenetically related to the volcanic process of caldera formation, since such a distinctive feature of volcanic collapse calderas as the shallow source magma chamber was not taken into consideration in the deep source hypotheses. However, from the standpoint of general ideas about the relationship of uranium ore deposits with continental volcanism, an alternative hypothesis suggesting genetic relationship between caldera volcanism and Mo-U ore formation has been proposed in the Russian scientific literature already more than 40 years ago: "magmatic chambers, at an early stage of their development supplying volcanic material, at the consolidation stage were a source of uranium, fluorine, molybdenum and other associated components of molybdenum-uranium deposits" [2]. The authors of this early caldera- related genetic concept envisaged as paleohydrodynamic conditions of ore formation "thermo-artesian systems of volcanic depressions that determined the conditions for mobilization of dispersed ore components, their migration and position of the sites for discharge of productive hydrotherms" (page 17). In a more modern formulation, the caldera-related concept of the uranium deposits formation implies "the existence of the relatively shallow magmatic chamber inducing convective hydrothermal fluid circulation lasting over a long period of time allowing an important alteration of rocks and thus remobilization of the U from the volcanic rocks"[3, page 136]. In this article we present the summary of preliminary results of numerical simulation of the process of free thermal convection of fluids specifying this hypothesis with reference to the formation conditions of the deposits Streltsovka and Antei. The short information about the simulation results obtained is published in [4].

PROBLEM FORMULATION

The Streltsovska deposit is localized in the volcanic-sedimentary cover of the caldera. The Antei deposit is the lower continuation of the central section of the Streltsovka deposit in granitoid rocks of the caldera basement. Thus, structurally conjugate deposits Streltsovka and Antei with the unique total uranium reserves of about 90,000 tons, can be regarded as a product of a single Antei–Streltsovska ore-forming system. According to the geochronological data given in [5] and the results of the thermophysical calculation given in [6], the magma chamber under the caldera must have been fully crystallized by the beginning of ore formation process, but a residual locally elevated geothermal gradient should still be preserved. We developed a 2-D computer simulation model for the Antei–Streltsovska ore-forming system with the geothermal gradient of 60oC/km.

The total thickness of the volcanic-sedimentary sequence of the Streltsovka caldera filling is up to 1200 m. The ore bodies of the Streltsovka deposit are localized within it mainly in the depth interval above the caldera bottom to 150-300 m beneath the present-day surface. The morphology of the "blind" ore deposits, the mineral and geochemical zoning of the hydrothermal rock alteration haloes [7] permit to suggest that the upper horizons of the caldera rock section played the role of a hydraulic screen that prevented the outflow of ascending ore-bearing fluids to the caldera paleosurface. With this assumption, we adopted in the simulation model a two-layer structure of the caldera filling with the thickness of the top screening horizon, including its eroded part, equal to 500 m, the thickness of the lower ore-bearing horizon of 1000 m, and the total thickness of the two-horizon volcanic-sedimentary rock sequence equal to 1.5 km.

The Streltsovka collapse caldera is borded by a system of ring faults with the vertical displacement of up to 700 m. Based on the results of tectonophysical (thermomechanical) modeling of the collapse caldera structure [8], the caldera ring faults are specified in the model as vertical zones extending from the magma chamber roof to the caldera paleosurface or to the bottom of the screening horizon of the caldera filling. The fault zone of the Antei deposit is represented as a vertical fault extending from the magma chamber roof to the caldera base in the middle between the ring faults. The zone of the Antei fault traces the vertical line of the model symmetry what permits to consider in simulation as a modeling domain only a half of the caldera cross section with the one ring fault and the half width of the Antei fault zone. The distance between the faults in the modeling domain is 5 km, the width of the ring fault zone and the half width of the Antei fault zone are taken to be 100 m, as in the Antei deposit [1].

The boundaries of the consolidated magma chamber are traced by the caldera ring faults. The critical value of the dimensions of the magma chamber at which the caldera ring faults are formed is D/d > 5, where D is the chamber diameter and d is the depth of the chamber roof [8]. Taking the value D ˜ 12 km for the Streltsovka caldera, we obtain as an estimate of the depth of the magma chamber under the caldera bottom, d ˜ 2.5 km. Taking into account these data and the 1.5 km of the caldera volcanogenic-sedimentary filling, the depth of the magmatic chamber under the paleosurface of the caldera can be estimated approximately equal to 4 km. This estimate corresponds to the results of gravimetric studies, according to which the magmatic chamber was located at a depth of about 5 km [1].

The diameter and vertical thickness of the caldera magma chamber were assumed to be 12 km and 4 km, respectively, what gives for its volume about 450 km3. This estimate is consistent with the extruded volume of rhyolitic ignimbriete estimated to be not less than 50 km3 [9]. According to the estimate obtained in the analysis of US geothermal resources, from 3 km3 to 9 km3 of molten rocks remain in the feeding center for each cubic kilometer of erupted volcanic material in the process of caldera formation [10]. Taking this estimate into account, the volume of 50 km3 of the erupted ignimbrite corresponds to the residual volume of rhyolitic magma in the caldera chamber from 150 km3 to 450 km3, the last value corresponding to the adopted magma chamber vertical thickness of 4 km. The structural scheme with the above geometric parameters of the modeling domain is given in [4, Fig. 1].

RESULTS

In the numerical simulation, the structure of the fluid flow and the distribution of temperature in the modeling domain were determined. In addition, the velocity value of the fluid upward flow along the Antei fault at the depth of its top termination in contact with the volcanic-sedimentary rocks of the caldera filling was calculated. To determine the main features of thermoconvective fluid heat and mass transfer, the following simplifying approach was implemented. Based on the results of test calculations, the basic model was identified, after which we examined what influence exert variations in permeability values of the main structural elements of the model on calculation results.

In the basic model, the following permeability values were adopted: for the caldera basement rocks 10-15 m2, for the ore-bearing lower horizon of the caldera filling 10-14 m2, for the top screening horizon 10-16 m2, for the ring fault 10-14 m2, for the Antei fault 10-13 m2. The simulated fluid flow self-organizes into a convective cell with a descending branch along the ring fault and an ascending branch along the Antei fault. The heat input by fluids of the ascending branch leads to an increase in temperature in the range of 400-340℃ in the zone of the Antei fault and in the range of 340-200℃ in the caldera filling rocks. The calculated value of the fluid flow velocity along the Antei fault is 7.5 m/year. The descending branch of the fluid convection cell penetrates deeply into the caldera basement rocks, thus providing the conditions for mobilization of uranium from both the host granitoids in the caldera basement and the consolidated magma chamber rocks. The representative pattern of the fluid flow configuration in the basic model is given in [4, Fig. 2].

The numerical simulation experiments with variation in the permeability values of the structural elements of the basic model were carried out for checking what influence exert permeability contrast between the caldera ore-bearing and screening horizons and the changes in permeability values of the ring fault zone and of the Antei fault zone on fluid circulation. The results obtained permit to conclude that the favorable conditions for ore formation in the Antei–Streltsovka thermoconvective system could be realized only under certain and narrow range of permeability values of its main structural elements. This limiting factor, as the authors believe, is one of the distinctive paleohydrodynamic conditions that predetermined the uniqueness, among the volcanic-related uranium deposits, of the exceptional uranium reserves of the Streltsovka ore field.

DISCUSSION AND CONCLUSIONS

The potential ore-producing capacity of the Antei–Streltsovka thermoconvective system can be estimated from data on rate of ore-forming solutions discharge from the Antey fault zone into the volcanic-sedimentary sequence of the caldera filling. With the calculated value of fluids flow velocity along the Antei fault 7.5 m/year, its along-strike extent of about 1000 m [11] and the fault zone thickness of 100 m, the rate of fluids discharge from the fault zone to the caldera filling is 7.5 105 m3/year. The equilibrium concentration of the ore-forming fluids, as estimated by the results of thermodynamic modeling, in the process of the medium-temperature leaching of uranium from leucocratic rocks is within the range between 1·10-6 and 2·10-5 mol U [12]. With this range of uranium concentration, the time period needed for the formation of total uranium reserves about 90,000 t U of the Streltsovska and Antei deposits is from 500,000 to 25,000 years, respectively. At exceptionally high uranium concentration of 1·10-4 mol U [13], established in the fluid inclusions of Canadian unconformity-related uranium deposits, the assessment of the duration of the ore deposition process is reduced to 5000 years.

A distinctive feature of thermoconvective systems with a closed circuit of convective circulation is the absence of restrictions on the amount of fluids. However, since ore loading of fluids should be extracted from the enclosing rocks, the limitation on the resources of the ore material within the contour of the convective cell is maintained. As noted above, the convective circulation of fluids penetrates deeply into the rocks of the Streltsovka caldera basement, thus providing the conditions for mobilization of uranium from the both available sources: the host granitoids and the anomalously enriched rocks of the consolidated magma chamber. According to the data on differences in the uranium content between the rhyolite magma [14] and in the geochemically similar granite massifs in the Southern Transbaikal Region [15], the possible scale of uranium extraction from the rocks of the consolidated magma chamber by the thermoconvective circulation of post-magmatic fluids can be estimated at U content of ˜ 13-14 g/t or, at a granite density of 2.6 t/m3, as ˜ 35,000 t/km3. Assuming that the volume of the magma chamber under the caldera was 450 km3, an estimate of the total amount of uranium mobilization from the consolidated magma chamber will be ˜ 16 million tons of uranium, which is approximately 60 times greater than the total reserves of uranium deposits of the Streltsovka ore field. This huge uranium source can be summed with uranium leached from the caldera basement the potential amount of which, as evaluted in [14], can also exceed several times the uranium resources of the Streltsovka ore field.

Thus, the proposed thermoconvective model of the Antei-Streltsovka ore-forming system ensures the formation of the uniquely large uranium reserves without restrictions both on the required amount of the ore-transporting fluids and on the amount of the accessible source of uranium for its leaching, transport and deposition by fluids convection. According to the general geological-genetic classification, such a model of the ore-forming system is close to the conceptual models of ore-forming systems of epithermal deposits.

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