Movement of liquid inclusions in crystals – formation of kimberlites and the Yellowstone Supervolcano

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Движение жидких включений в кристаллах – образование кимберлитов и Йелоустонский супервулкан

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Abstract

In the context of geothermal gradient, liquid contained in inclusions in crystals and mainly in pores between them moves towards increasing temperature. The liquid is accumulating elements with distribution coefficients <1 with respect to major rock minerals, volatile and rare, particularly for platforms, elements – material for forming magmas of kimberlite composition. Inflow of volatiles to depth implies a decrease in temperature of solid rocks transition in semi-liquid state, pressure increase, and, upon exceeding the "roof" strength, leads to eruption. Inflow of aqueous solutions to volcanic magma chambers is one of the reasons for their awakening. Cycle of water movement is distinguished: atmosphere-soil-pores-mantle (volcanoes)-atmosphere. The phenomenon of water transfer into magma is directly related to the preparing Yellowstone Supervolcano eruption.

Keywords: geothermal gradient, rock porosity, intergranular substance, water cycle, separation during crystallization, concentration of admixtures, kimberlites, adiabatic temperature release, Yellowstone Supervolcano, volcanic eruption, hydrothermal explosion

0. Introduction.

In 1952, G.G. Lemmlein [1] published the results of experiments on aqueous inclusions behaviour in $NaNO_3$ crystals. He showed that microscopic inclusions in macroisothermic conditions move towards larger ones located nearby. The movement was explained by heat release during transformation of nearby large irregular-shaped inclusion into a negative crystal.

In the late 60-ies and early 70-ies, professor of the Leningrad Mining Institute V.A. Mokievsky (1920-1979) informed the author in a personal conversation about the movement of inclusion in solution, a few cubic millimeters in volume, in the obtained potassium alum crystal [$KAl(SO_4)12H_2O$] towards the heat source (from a table lamp). Over 3-4 months, inclusion covered the distance of about 25 mm and came to the surface. Later, the author learned that by that time there had been a large number of papers on inclusion movement in crystals under the influence of external forces. [2] There are other options for inflow of mobile components to depth: plate movement with enwrapping of sedimentary rock strata below them [3]; movement of light elements to depth can be provided by thermal diffusion - Soret effect. [4] The latter option is used in solving the problem of ijolite-carbonatite complex genesis [5]. The concept of "molecular flow" is developed to explain the features of volcanic rock formation [6].

Purpose of the paper is to show the high importance of transportation of water and substances dissolved in it encompassed in closed pores-cavities towards the heat source for such geological processes as volcanism in its various manifestations, in particular, exemplified by kimberlite formation and life of the Yellowstone Supervolcano.

1. From crystal to the Earth's crust: pore-cavity moves in geothermal gradient

On V.A. Mokievsky's death, the author associated his observation with the fact that acquisition of crystals in laboratory at low temperatures and industrial hydrothermal method involve crystal heating from the bottom, where the charge is. Solution transfers the matter by convection in the upper part of casting mold, where crystals grow. In this case, which has not been noticed, the total mass of liquid moves to a hotter area, towards the heat source. Tons of quartz are moved bottom up in industrial autoclaves in place of tons of water within a year. When lower parts of solution-filled glass tubes (40-50 mm in diameter and 250-300 mm long) with source material lying on the bottom were heated to T = 40-70°C, and upper parts of tubes with germs were cooled by the lab air, crystals of dozens of different substances 1,000-2,000 mm^3 in volume were grown over several days [7]. That is, *in closed volumes in a temperature gradient, transfer of liquid less*

dense than crystalline substance occurs against the direction of buoyancy force towards the temperature increase.

As a direct proof of the stated provision, an experiment was set up in the simplest conditions. It showed the effect of temperature gradient on a reagent layer, in this case [KAl(SO4)2], which is below a layer of saturated solution on heated vessel bottom. A bottle 50 mm in diameter was placed on a room radiator for one month. The diagram (see Figure) shows the layer profiles with an interval of 2 weeks.
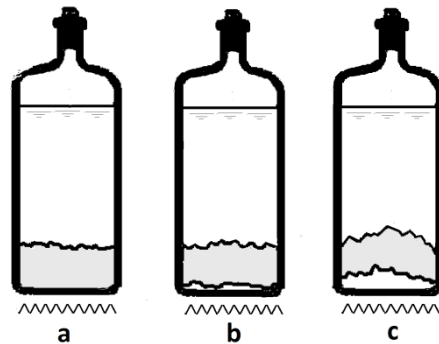

Fig. Change of alum layer profile (gray) from a) to c) with an interval of 2 weeks

Let us consider the issue in detail.

2. Pores are always present and generated in geothermal gradient

All rocks have pores-cavities filled with ruling in the crust aqueous solution. At a sufficient time of curing at certain temperature, the solution is saturated with respect to all substances of walls of pore, open or closed. The solution becomes oversaturated at temperature decrease, the excess material is released from it on pore walls; solution concentration decreases. When temperature rises, the solution becomes undersaturated and partial dissolution of the walls takes place; solution concentration increases. Liquid can be removed from a pore open to the atmosphere and containing aqueous solution by evaporation, or by external unilateral gas pressure. Removal of liquid from a closed pore isolated from the atmosphere occurs only through the disturbance of pore impermeability at sufficiently high temperature during its explosion, or by dissolving the wall.

In case of open pore, channel having no feeding from the bottom, the longer it is along the direction of thermal gradient, the greater the necessity and faster, as a result of crystallization in decreased temperature region, the channel portion is closed and a closed cavity emerges. Thus, *in the field of geothermal gradient, open pores-channels generate pores-cavities closed for the atmosphere*. Crystallization pressure exerted on the contacts between the growing crystals at channel closure provides a high sealing degree of the pore-cavity separated from it, since it reaches 100 kg per cm^2 even for highly soluble substances [8].

From this point, cavity with its contents advances towards the heat flow and moves until it reaches a fracture with lower pressure, or creates it by itself, or disappears from dissolving the contents in the met cavity already filled with water, supercritical fluid, or magma. Pore content may chemically combine with substances encountered along the way, which leads to their hydration, and dissolved substances can be recorded as an "unconformity occurrence".

3.   Pores become larger

Velocity of pores-cavities is directly dependent on the internal temperature difference, that is, on their length along the temperature gradient and its value. That is, large pores are moving faster, smaller ones may be almost immobile without internal difference in temperature sufficient for significant movements. While moving, pores-cavities may overtake slower ones, or appear on the way of others, overtaking ones. In both cases, there is an association, *enlargement of pores-cavities* and increase in their velocity. The foregoing helps to explain detection of cavities at greater depths, found in particular when drilling the Kola ultradeep well and known as rootless veins.

4.   Movement of fluids between grains can be of paramount importance

Intergranular substance found between mineral crystals in xenolith of spinel lherzolite [8] in the form of interlayers to tens of hundreds of microns thick is a product of pushing by growing crystals of the most mobile components (with distribution coefficients less than unity), specific for each mineral. As has been established, composition of ultramafic intergranular matter is dominated by

elements peculiar to acid rocks, and magnesium content has appeared 40 times (!) lower than in lherzolite composition. In the paper context, it is more important that, judging by the low sums of chemical analyses (according to microprobe data: 84-96% for intergranular substance, 100.78% for lherzolite), this material contains significant amounts of volatiles (H_2O, CO_2 ...), which have a high dissolvent capacity. In addition, volume contraction in the transition from liquid to solid state should lead to a substantial microporosity of material located between mineral grains. Therefore, porosity of intergranular material should be considered the most significant of the ways to move aqueous solutions by the described mechanism at elevated temperatures. This is reinforced by higher dissolution rate of small crystals compared to large ones [10].

5.   Composition of pore content evolves during movement

Average temperature and pressure are increasing in pore-cavity with growing depth; respectively, concentration of dissolved material in fluid grows. However, ***everything met and dissolved at the frontal zone of solution portion is subjected to separation, sorting on the rear, cooler surface, where the crystals grow***. Crystals capture elements (radicals) with high bond energies, distribution coefficients K>1, and displace those with low (K<1) in pore-cavity fluid. Thus, low pore velocity, respectively, low crystal growth rate at the "cold" (upper) wall provide a high efficiency of solution components separation [11, 12].

Concentration of substance with K<1 is a consequence of displacement of a pore-cavity filled with fluid in temperature gradient. This process corresponds to purification of substances by crystallization in zone melting and, simultaneously and inevitably, is always accompanied by concentration (!) of "admixtures" in a small volume. In quiet tectonic (platform) conditions, continuous movement of compressed fluid to depth enables it to achieve the field of supercritical temperature, which leads to a partial transition of crystalline rocks in a heterogenic mixture of the most hardly soluble crystals and liquid, that is in lava state, and causes frequently observed etching of coarse grain surface – resorption of mantle minerals. Formation of gaseous inclusions conventional in diamond is a result of crystal growth in a liquid saturated with gas under conditions of low diffusion rates and, consequently, slow removal of solution decomposition

products from the face of growing crystal, which is natural for crystallization at higher pressures.

Upon reaching pressure sufficient to overcome the "roof" strength, there is a possibility of local fluid breakthrough to the surface with the removal of overlying rock debris, typical of kimberlite pipes formation. Judging by the absence of explicit cones over the place of pipe outcropping, excess energy and "explosion" matter were small. Fluid energy reserve can be insufficient for its outbreak.

6.   Results of evolution of inclusions composition

Processes of dissolution, substance transfer, and crystallization, constantly running in a pore-cavity preserve and accumulate in fluid elements with K <1 registered in diamond inclusions, that is non-isomorphic with the elements of rock-forming minerals of platform rocks, a conventional container of kimberlite pipes. More specifically: mobile "low-boiling" substances [13], including hydrocarbons [14]; relatively inert (N, Ar); rare − atypical for mantle elements, but typical of platform rocks − sedimentary, metamorphic, granitic. Thus, according to [15], "platform" element content in kimberlites is tens or hundreds of times higher, that is, ***kimberlite composition manifests not the process of averaging platform and upper mantle compositions, but the directed concentration of "platform" elements in the upper mantle***. This mechanism does not contradict the known conclusions: "processes of fluid and magma chamber formation were spatially separated" [16], and "… data are consistent with the concept of diamond crystallization from a COH-rich multicomponent supercritical fluid…"; "… a fluid is more consistent with a local crustal source rather than that of a mantle origin." [17].

7.   "Cold" diatreme contacts, high velocity of "kimberlite magma" cooling

With the breakthrough start, at a rapid increase in volume, pressure release takes place, and as a consequence, ***temperature decreases adiabatically*** in the fluid bulk. This explains 1) existence of "cold" contacts of kimberlite mass with host rocks [18], 2) existence of fine-grained mass arising from fast crystallization

of highly concentrated fluid, 3) preservation of mobile components with high contents in consolidation products.

Particular attention should be paid to the latter circumstance. Neglect of the volatile components is traditional for petrography and reinforced by the existing (up to international) rock classifications. This is expressed, firstly, in the admission for publication of chemical rock analyses with LOI, where H, C, F, Cl components paramount for ore genesis remain undivided. Authors refer to such data as to "representative" on a regular basis, without thinking about the meaning of words. Secondly, the requirement of "drying", removing "volatile" components from data analysis when identifying rocks. As a result, numerous kimberlite analyses do not give details on the "ore" component content.

8. Movement of aqueous solutions with specific composition to depth is significant

Established fact of liquid inclusion movement in crystals; presence of widespread porosity in rocks of different genesis, experimental and industrial production of crystals of various substances by using thermal gradient; million years of existing geothermal gradients in porous sedimentary, metamorphic, and igneous rocks; concentration of admixtures in "cleaning" of substances by directional crystallization; high concentrations of elements rare for mantle, but typical of platforms in kimberlite; i.e. fragmentation of magma chamber and fluid formations; cavity detection in silicate rocks at kilometer depths – that should be enough to say that *the processes of formation and delivery of highly concentrated, specific in composition aqueous solutions at greater depths until reaching supercritical temperature and subsequent breakthroughs to the Earth's surface are implemented and geologically significant in the Earth's crust history*.

Described embodiment of aqueous solution movement - from the surface to the heat source, mantle, or any other capable of returning water and other volatiles back to the surface is a particular *cycle of mobile, relatively inert elements, as well as elements non-isomorphic with the elements of major rock minerals*.

9. Hydrothermal explosions and awakening volcanoes

These considerations are relevant to the problems of hydrothermal explosions and volcanic activity recovery after long pauses.

Water-filled cavities may be the cause of hydrothermal explosions when pressure in them reaches values sufficient to overcome the roof strength. Water flowing to the surface in such a way and having low mineral content not exceeding 1 g/l is not the product of magma chamber. Mary Bay crater formed in the Yellowstone caldera in such a way; weaker hydrothermal explosions occur regularly [19]. Opening of a cavity filled with water to a crater of active volcano should lead to explosions in the background of calm lava outpouring; such explosions occur during Kilauea volcano effusions.

High volatile content is found in magma chamber of a dormant volcano. Thus, in Elbrus area, "fluid-saturated magmatic formations that occur in instrumentally distinguished magma chamber and focus contain volatiles (to 30% or more)." [20]

Stated should be applied directly to the Yellowstone Supervolcano, having erupted several times with shrinking intervals, which is considered evidence of a plume approaching the surface. This should increase the geothermal gradient and thus accelerate water arrival to depth, reducing intervals between eruptions, in accordance with the described mechanism of water movement towards the heat source.

Water inflow to depth, where its temperature reaches supercritical values, involves *decrease in temperature of solid rock transition to liquid state with accompanying thinning of existing solid crust* and reduction in its strength. Currently, large amounts of water are emitted to the surface through hot water springs in the Yellowstone caldera; some of this water is removed by a single river, and some returns to magma and, thinning the roof and increasing pressure in the chamber, approaches its awakening.

10.   What can and should be learned

Clarification of the scale of aqueous solutions transfer to depth requires special experiments to assess the process velocity. The following experiments can be offered for this. Plates of quartz, calcite, or the same "mice" of crystal geneticists - alum containing inclusions are placed under a microscope with a

horizontal draw-tube and protection of optics against high temperatures. In the direction normal to the observation axis, temperature gradient is generated in crystal and shooting is made, the results of which enable to estimate inclusions velocity. It is desirable to obtain data in a wide range of average temperatures and inclusion sizes. Evaluating the effect from real gradients in crystals of poorly soluble substances probably would require more time. Therefore, using higher gradients and putting several microscopes to study the behaviour of inclusions of different sizes, one can assess the velocity, let not always very reliable, by extrapolation of experimental data to the gradients, typical of volcanic areas.

In low temperature conditions, it is possible and necessary to simulate in transparent flat molds (unlike that described in the beginning) the process of inclusion movement on a polycrystalline material, primarily registering: a) trends in cavity shape alteration until a stationary form, and b) conditions of channel closure. Experiments will deal with the focal issues concerning major factors: 1) determining water transfer velocity by the mechanism discussed to the Yellowstone magma chamber; 2) significance of the mechanism in impending disaster, and 3) possible ways of reducing its scope, which is shown in (Petrov, 2015).

11.   Conclusion

A priori statements about the meaninglessness of experiments, with respect to argument of effect nullity due to the nullity of inclusions and velocities should not be accepted, since, according to the provision long accepted in mathematics, the result of multiplying infinitely small by infinitely large can be anything. In geology, small is notional.

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