Journal of Geography, Environment and Earth Science International
6(4): 1-9, 2016; Article no.JGEESI.27330
ISSN: 2454-7352

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On the Mechanism of Catastrophic Caldera-forming Eruptions: Yellowstone's Approval

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Author's contribution

The sole author designed, analyzed and interpreted and prepared the manuscript.

Article Information

DOI: 10.9734/JGEESI/2016/27330
Editor(s):
(1) Umberta Tinivella, Istituto Nazionale di Oceanografia e di Geofisica Sperimentale, Borgo Grotta Gigante 42C, 34010 Trieste, Italy.
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Complete Peer review History: http://sciencedomain.org/review-history/15408

Original Research Article

Received 28th May 2016
Accepted 6th July 2016
Published 16th July 2016

ABSTRACT

This paper proposes and analyzes a possible scenario of preparation and development of Caldera-forming eruptions of Yellowstone. As a physical mechanism of eruption the imbalance between the column of liquid (magma in the chamber and the conduit) and closed volume of gas (fluid accumulated within the magma chamber) is considered. To demonstrate the mechanism operating a simple experiment with water is realized and described. Theoretical conditions for the supposed Yellowstone super-eruption are formulated and discussed.

Keywords: Yellowstone supervolcano; caldera formation; magma chamber; eruption mechanism.

1. INTRODUCTION

A characteristic feature of the Yellowstone supervolcano is the absence of stratovolcanoes structures in its geological past. It is assumed that it is located above a hotspot, a mantle plume, which is playing the role of a permanent source of magma which is rising to the Earth crust and "burns" the North American lithospheric plate, moving in a South-westerly direction at a

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speed of 2.5 cm/year. The common process of volcanism and tectonics in the past 17 million years resulted in the emergence of many calderas stretched out in a chain for a distance of thousand miles [1-3].

The Yellowstone Calderas themselves were formed 2.1; 1.3 and 0.64 million years ago after a catastrophic eruption on the surface of the Earth respectively of 2.500, 280 and 1.000 cubic kilometers of ash and ignimbrites. Interest to these three Caldera-forming eruptions has increased in recent years because their Dating by the isotope method indicated a probable interval between them of approximately 650 thousand years. Therefore, the supervolcano, perhaps, has got ready for its fourth catastrophe.

Unfortunately the classical theory of volcanism gives no good ideas to explain the processes that determine the eruptive cycle of the Yellowstone [4].

In 2015 the convincing evidence of two Yellowstone's magma chambers, presumably connected to each other, was established with the help of seismological methods [5].

The first, upper chamber is located at a depth of 5-10 km and has a volume of 10,000 km^3. The second, lower chamber is placed at depths of 20-50 km with a volume of 45 000 km^3. The existence of two magma chambers provides a basis for the implementation of GLI-mechanism proposed and analyzed theoretically in [6,7]. This physical mechanism is a type of instability between the contacting volumes of gas and liquid (GLI – Gas-Liquid-Imbalance), when a closed volume of gas begins to push up (erupt) the liquid column above. The equilibrium between gas and liquid becomes unstable if the volume of gas exceeds a certain critical value V_{cr} determined by the formula [6,7]:

$$V_{cr} = \gamma S(H + p_0 / \rho g) \quad (1)$$

where γ is the ratio of specific heats of the gas, H is the height of the liquid column above the point of contact with the gas, S is the cross section of the liquid column in the contact place, ρ is the liquid density, p_0 is the atmospheric pressure, g is acceleration of gravity. Critical conditions of liquid eruption do not depend on the form or irregularity of abovementioned gas volume. They are determined by the volume magnitude comparatively to the critical one (1).

Below we will consider a gradual scenario of supposed preparation of catastrophic eruption of the Yellowstone. But first, we describe a simple experiment, convincingly illustrating the operation of the GLI - mechanism for two connected tanks with water, analogues of two magma chambers. The experiment was carried out in the laboratory of Renewable energy sources of Geographic faculty of Lomonosov's Moscow state University together with the employee of this University Nikolay Zak.

2. EXPERIMENTAL DEMONSTRATION OF GLI-MECHANISM

The plastic tank with a volume of approximately 100 liters has an orifice for water and several nozzles located at different heights (Fig. 1). The tank is analogue of lower magma chamber below Yellowstone. It is filled with water through the orifice, which is then corked up.

Fig. 1. Plastic tank with nozzles. Water is poured by the top orifice. Through the top nozzle an air from the pump is coming in. The lower nozzle where water comes out is attached to the silicon pipe. All other nozzles are plugged

Through the top nozzle the air is pumping inside the tank with a simple pump. Through one of the nozzles the water can be forced into the silicon pipe (20 mm diameter) and then in the upper reservoir (plastic bottle with a volume of 20 liters) attached to the steel beam (Fig. 2). Changing the outlet nozzle, it is possible to change the value of the gas volume in the lower reservoir. The pipe connects the lower nozzle and the upper reservoir (Fig. 2). The water is poured from the upper reservoir through the hole at its top and the speed of water flow corresponds to the speed of the air pumped into the lower tank (Fig. 3).

Fig. 2. The bottom nozzle of the tank is connected by a silicon pipe with the upper reservoir

In accordance with (1) and GLI - mechanism [6,7], the critical volume for this system may be calculated by the formula:

$$V_{cr} = \gamma S(H + 10)$$

Where γ is the ratio of specific heats for air at room temperature ($\gamma = 1,2$), S is the section of the silicon pipe ($S = 3 \cdot 10^{-4} m^2$), H is the height of the steel beam, to which a pipe is attached ($H = 4m$). This critical volume is equal to 5 liters, which is much less than the volume of the tank.

"Eruption" begins when air from the tank through the bottom nozzle is penetrating into the pipe. The rate of water outflow from the upper reservoir is increased, in this moment we have specifically turned off the pump to eliminate additional pressure on the water and to leave the system to its own resources. It was recorded a noticeable increase in rate of water discharge, indicating instability, corresponding to GLI-mechanism. Since the pipe volume is relatively small, the air pressure during extension decreases slowly and the pressure drop between lower tank and upper reservoir increases due to decreasing height of the water column. The eruption is intensifying, the air from the tank actively mixed with water in upper reservoir is thrown out in the form of a two-phase mixture (Fig. 4). Note that there was no “eruption” when water came out from the tank through the uppermost nozzles.

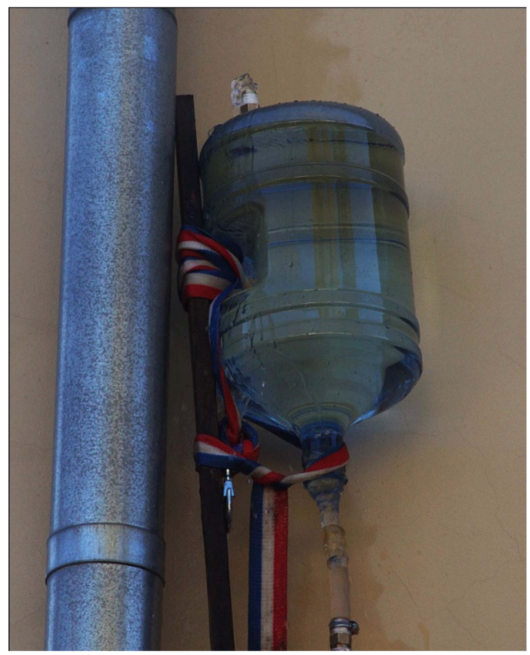

Fig. 3. Water fills the upper reservoir and poured from it with low speed corresponding to the speed of air supply to the lower tank

An experiment described above is very simple and convincing. The mechanism of the eruption of the liquid column under the pressure of gas volume exceeding a certain critical magnitude is quite universal. It does not depend qualitatively neither on nature of liquid and gas nor on their temperature, density and viscosity. It is determined only by the mechanical parameters: the volume of gas, height of the liquid column and the cross-sectional area of the zone of their contact.

Fig. 4. "Eruption": Water and air mixture is emitted from the upper reservoir. The pump is turned off

The theory of GLI-mechanism for two magma chambers [6] imposes on the volume V_m of magma in the lower chamber the following condition necessary for the onset of the eruption:

$$V_m > \frac{\gamma g S(h_m)^2}{(k_0 - k_m)RT_m} \quad (2)$$

Where h_m is the depth of the lower chamber, $(k_0 - k_m)$ is the part of fluid passed into the gas phase during the ascent of magma from mantle plume into the lower chamber, γ is the ratio of specific heats of the fluid, R is the universal constant of the fluid, T_m is the temperature of magma, S is the cross section of the conduit that connects the chambers.

If (2) is satisfied the volume of fluid, released to the gas phase in the lower chamber, exceeds a critical value, and the start of the eruption needs the fluid to be accumulated in a united volume which has a contact with a conduit connecting the chambers and the surface.

3. SUPPOSED STAGES OF PREPARATION AND DEVELOPMENT OF THE YELLOWSTONE SUPER-ERUPTION

The first stage of the supervolcano birth is the formation of large chamber above the Moho at depths of 20-50 km. Magma comes from the mantle plume due to yet unknown physical mechanisms [2]. It is important that there is an accumulation of liquid magma in the mobile state at depths significantly smaller than the upper limit of the mantle plume. Perhaps this is due to the buoyancy of magma or to the lithostatic pressure. Anyway, on some level the ascent of magma ends, and it is accumulated in a vast reservoir [6]. Further moving and eruption of magma is possible only in the presence of a certain excess pressure, the origin of which may be explained by the following processes. During the ascent of magma to the lower depths its decompression occurs: throughout all its volume the portion of dissolved fluids (mainly CO_2 and H_2O) pass in the gas phase. During this "boiling" fluid bubbles form with an equilibrium pressure equal to that of lithosphere P_l and with density ρ_f that satisfy the ideal gas law : $\rho_f = P_l / R_f T_m$, where R_f is the fluid universal gas constant, T_m is the temperature of the magma. Obviously, if $\rho_f < \rho_m$, where ρ_m is the density of the magma ($\rho_m \approx 3000 kg/m^3$), the bubble begins to rise up, bringing upward its pressure exceeding the pressure of the surrounding magma. It is easy to verify that at a depths exceeding 50 km the density of water vapor ($R_{H_2O} = 461 \, J/kgK$) will be greater than the magma density. The same is true for carbon dioxide ($R_{CO_2} = 189 \, J/kgK$) at depths more than 20 km. Hence after the ascent of magma from the upper mantle at depths of 20-30 km some amount of fluids (in the form of bubbles) should be capable to ascent and to accumulate in the apical part of the magma chamber. The speed of bubble ascent u is determined by the size of the bubble, by the density and viscosity of the liquid substance in which bubble is located. It can be evaluated by the well-known Stokes formula: $u = r_f^2 g \rho_m / 3\mu_m$, where r_f is the bubble radius, g is the acceleration of gravity, ρ_m, μ_m are density and viscosity of magma. For magma density of 3000 kg/m^3, its dynamic viscosity 10^8 Pa.s and bubble radius equal 1 mm the speed of bubble ascent will be equal to 3 mm/year. In other words, over 500, 000 years, this bubble of fluid will overcome 15 km, the possible thickness of the Yellowstone lower chamber. Accumulation of fluid at the arch of the lower chamber forms an isolated volume of fluid with compact zone of excess pressure that can overcome the strength of rocks and provide the motion of magma toward the Earth's surface. So, the conditions for forming the second, upper magma chamber can be obtained. In Yellowstone it is located at depths of 5-10 km. Thus, two processes can proceed simultaneously: 1) the rise and accumulation of fluid under the arches of lower chamber; 2) forming of the upper chamber under the action of the excess pressure in the lower chamber. Two chambers should have a contact area in the form of a conduit, dike or system of dikes and conduits. This area is not investigated. We consider the Yellowstone plumbing system in the simplest form according to [5]. Possible details of chamber configuration are not interesting in our case. Fig. 5 shows the supposed simple scheme of the magmatic system of Yellowstone. Orange color mark the gas "cap", a superheated fluid that was accumulated under the arch of the lower chamber.

The total volume of fluid released into the gas phase is determined by the solubility of fluid in magma and the depth difference between the lower chamber and mantle plume. This volume, including the water (in a supercritical state), carbon dioxide and sulfur gases may considerably exceed the critical volume necessary to trigger the mechanism. The critical volume is approximately equal to γSH , where γ is the ratio of specific heats (for carbon dioxide and water vapor is 1.2), H is the depth of the lower chamber ($H \approx 25km$), S is the average cross-section of the conduit or dike at the place of contact with the lower chamber (S remains unknown). If we assume that the radius of the conduit does not exceed 100 m, the critical volume will be $\approx 1km^3$. With regard to the total volume of fluid (may be water vapor) released by

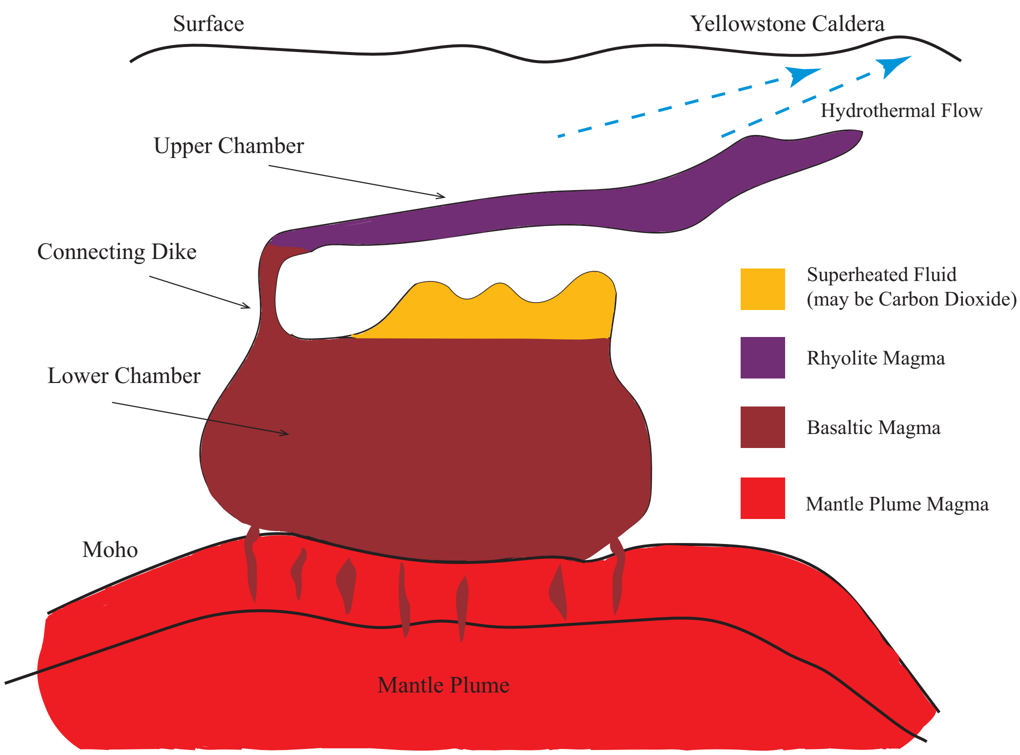

Fig. 5. Primitive scheme of the supposed magmatic system of Yellowstone. The pressurized fluid accumulated under the arches of the lower chamber may have a critical volume but until it has no contact to the conduit, the eruption of magma from the upper chamber must be effusive, without catastrophic consequences

the magma volume from lower chamber (close to 45000 km^3 [5]) when it moved from a depth of 50km at a depth of 30 km, it can exceed one percent of total moved magma volume [8], that is not less than 450 km^3, which is much greater than the critical volume, even if the total cross-section of the dikes is equal to 1 km^2. Therefore, nothing prevents for the formation of a giant (by volume) gas "cap" at the apical part of the lower magma chamber, if gas has found no way to the surface. If the fluid overpressure overcomes the resistance of the overlying rocks, it will push magma upward (along fractures and faults) to a new level, and the second, upper, magma chamber will be formed (over the millennia of its formation and storage it may become rhyolite). So the beginning of the catastrophic Caldera-forming eruption needs three conditions:

1. The volume of the gas "cap" at the lower chamber must exceed a critical value.
2. Gas "cap" must have a contact with a conduit or dike connecting the chambers.
3. Magma from the upper chamber has reached the Earth's surface.

The first two conditions can define the intervals between Caldera-forming eruptions. During this time Yellowstone can demonstrate "quiet" effusions of lava provided by the excess pressure in the lower chamber. Though the third condition (magma found a way out to the surface) is fulfilled, the critical volume of the fluid is still not obtained, or this volume has no contact with the conduit. The critical volume of the gas "cap" may be obtained in two ways: accumulating rising bubbles at the apical part of the chamber and increasing of fluid volume due to squeezing out the magma from the lower chamber to the upper one or to the surface of the Earth. As noted above, the ascent of bubbles in magma is a slow process and it may take hundreds of thousands of years. However, the critical volume is not so great, and it may be provided by fluid bubbles coming from the upper part of the lower chamber: their ascent require less time. Since the Caldera-forming eruption of Yellowstone was relatively rapid and had a catastrophic nature, we can assume that the volume of the gas "cap" before the eruption had exceeded considerably the critical value. This is evidenced by the huge volumes of erupted material. The difference between them (from 2,500 km^3 to 280 km^3) could be determined by the difference in the volumes of fluid accumulated in the gas cap. In all cases, the expanding fluid retained its excess pressure, easily penetrated into the upper chamber and freed it from the mobile magma.

Once the fluid with overpressure and a supercritical volume penetrates into the conduit and forces magma out of the upper chamber to the surface, the movement of magma through the conduit and the fractures begins to accelerate, the pressure drop acting on the magma flow increases (because the height of magma column decreases and fluid pressure remains nearly constant), and eruption becomes catastrophic. Emptying completely or partially the upper chamber, a superheated fluid (with a temperature of about 1000 C) will break out in scorching clouds, bringing down to the Earth the rain of fire! The space of the upper chamber released from magma will be filled by the overlying rock, forcing by its weight the remaining rhyolite magma on the bottom of the Caldera formed.

As a result of this eruption the lower chamber loses its gas cap with excessive pressure which not only pushed magma in the upper layers of the crust, but also blocked new arrivals of mafic magma from the mantle plume. Now the way for it is free, and the lower chamber gets a new batch of magma saturated with fluid and the process of preparing the next eruption resumes. If at the time of eruption preparing the crust above the "hot spot" has moved a sufficient distance (about 25 km in a million years), the connection of mantle plume with the lower chamber could be broken, and the magmatic system with two chambers will be formed at new location.

4. DISCUSSION

Nobody knows exactly what is happening in the depths of Yellowstone, so we cannot draw any certain consequences. We can only make our modest assumptions about the mechanisms for the preparation of the eruption, trying to build chain of events physically clear, logically consistent and simple as far as possible. Unfortunately, information about the processes occurring at such depths is minimal. But assuming the validity of our theoretical interpretation concerning the mechanism of Caldera-forming eruptions, we can draw some suppositions on volcanic activity of the Yellowstone and possible precursors of its eruptions.

Existing methods of predictions of possible eruptions (for example, [10]) are based on the "precursors" resulting from magma movement to the surface, which in turn is caused by the excess pressure in the magma chamber. However, the nature of the supposed eruption (effusive or eruptive), according to the GLI-mechanism, depends on the realization of critical conditions (2) for a system of magma-fluid-crust [6]. If the volume of fluid accumulated in the lower chamber will be less than the critical one or slightly exceeds it, the catastrophic acceleration of magma flow in the conduit does not happen, although magma has reached the surface.

Geophysical studies in recent years allowed to identify two magma chambers in the Yellowstone system [5]. However, soundings do not give any information about the contact zone of these two chambers: the presence of channels and dikes, their quantity and cross-section, what is important for evaluating the critical volume. There is no possibility now to detect the accumulation of fluid inside the chamber. Note that the supposed gas "cap" with a volume of 450 km^3 can have (if the square of the lower chamber is 40x50 km) average thickness of 200 meters only! The reduction of velocities of P-waves in the upper chamber is interpreted in [2] as an indication of magma saturation with gas, the same can be expected in the lower chamber located at great depths. There may be numerous gas bubbles in the stage of coming up.

Earthquakes in the Yellowstone Caldera, facts of uplift and subsidence of its sections [1-3], calm outpouring of rhyolite lava 70 000 years ago [9], forced to think about the underground movements of magma, its introduction into the upper layers of the lithosphere. At the same time these facts (or rather, the lack of others) indicate that the abovementioned three conditions of the catastrophe are not implemented.

If you associate deep long-period earthquakes, known for Caldera zones [1], with the release and accumulation of gaseous fluids in a magmatic system (lower chamber) during vertical movement and decompression of magma, this process may already be terminated in Yellowstone, as such earthquakes were not recorded here [1]. Typical of Yellowstone seismic swarms localized mainly at shallow depths (3-5 km) and appears to be caused by the rocks cracking due to magma intrusion into the crust in the zone of the upper chamber. It can be assumed that during hundreds of thousands of years that have passed since the last catastrophe, the magmatic system of the Yellowstone was fully recovered (or formed anew). In any case, rhyolite eruption 70,000 years ago can be considered as a "try-out" (or test) of the efficiency of this system. This eruption wasn't catastrophic, but powerful enough for the volume of lava flows (82 km^3) [9]. In accordance with GLI- mechanism it had stopped, when the volume of expanded fluid V reached the value defined by the formula [6]: $V = V_f \, {h_{m2}}/{h_{m1}}$, where V_f is the volume of fluid in the gas "cap"; h_{m1}, h_{m2} - are the depths of the upper and lower chambers. Since ${h_{m2}}/{h_{m1}} \approx 2$ and the volume of the fluid expansion $(V - V_f)$ must correspond to the volume of erupted lava, you can assume that $V_f \approx 82 km^3$. Relatively quiet outpouring of lava 70000 years ago could mean that the excess of V_f over the critical volume $\gamma S h_{m2}$ was insignificant. And therefore the average section of a dike (or channel) connecting two chambers could be of the order of one square kilometer. As extensive emissions of ash and ignimbrites during this eruption was not detected [9], it can be assumed that the fluid from the lower chamber gas "cap" lost its overpressure and remained in the channel and in the part of the upper chamber, pressing slightly on the magma and resulting in its movement to the surface with the corresponding uplift of some Yellowstone's areas. This state of the magmatic system (when the fluid from the lower chamber has penetrated the channel and then stopped being expanded into the upper chamber), in our opinion, is stable, as it excludes further triggering of the GLI-mechanism. The fluid bubbles may rise up and accumulate in the upper chamber, transporting its excess pressure, and then safely evacuate into the atmosphere through cracks and fissures. This hypothetical scenario is most encouraging, since it "cancels" the impending catastrophe of Yellowstone.

Now it is appropriate to try to explain the absence of the Yellowstone distinct stratovolcano structures. In accordance with GLI-mechanism, the single magmatic chamber with volume greater than the critical one (2) can provide the formation of the stratovolcano as a result of regular eruptions with emission of relatively small amounts of magma contained in the output conduit [6]. Two magma chambers "facilitate" the formation of the volcano and can "provide" its eruptive cycle corresponding to that of Mount Etna [6]. Thus there is the possibility of Caldera-forming eruptions, if the volume of the lower chamber exceeds the critical one (2). In the case of Yellowstone, we can assume that the stratovolcano formation was prevented by two unusual factors. First, too large volume of the lower magma chamber, so the corresponding volume of gas "cap" significantly exceeded the critical value. The latter circumstance guaranteed catastrophic eruptions, reaching "to the end' and devastating the upper magma chamber. Second, the fluid in the upper magma chamber, apparently, is not accumulated in a closed space, and finds a way to the surface, spending on fumarolic and hydrothermal activity. The reason for the formation of such chambers under Yellowstone should, obviously, be found in the geological features of the crust, its high permeability in the upper layers and, conversely, the impermeability at the deeper levels where significant volumes of magma and fluid can be accumulated in the lower chamber.

One of the most important factors that needs to be examined is abnormally high emissions of CO_2 (up to 45 000 tons/day [5]). Unlike water vapor (which is abundant near the surface), carbon dioxide emission carries important information (question: what?) on deep magmatic processes. The origin of these CO_2 emissions can be: a) magma decompression; b) a leakage from the places of fluid accumulation. Decompression of magma when it moves from the lower chamber to the upper chamber can lead to carbon dioxide release (according to its solubility in a basaltic magma at a depth of 10-30 km [8]) in the amount of up to 1/1000 of the weight of the displaced magma. Therefore, in order to provide CO_2 emissions of 45,000 tons/day, the necessary arrival of a new magma (from lower to the upper chamber) must be up to 45 000 000 tons/day or in the volume expression about 5 km^3/year. So, for 100 years, this volume should be 500 km^3, which is considerably more than lava volume erupted to the surface 70 000 years ago (82 km^3 [9]). Unfortunately, we don't know whether this abnormal emission was in the distant past. If the corresponding displacements of magma in the respective volumes is not observed (although it is not clear how to set it up), it can be assumed that the anomalous source of CO_2 emissions is a leakage from gas "caps" in the lower chamber or (more likely) from the zone of the upper chamber, where the expanded fluid after the eruption 70,000 years ago might be stored. Both correspond to the above-described "hopeful" scenario, the removal of the catastrophe and, possibly, the “extinction” of the Yellowstone. However, it should be noted that the sharp increase of CO_2 emissions in comparison with the average values may indicate the penetration of a large quantity of fluid from gas "caps" in the conduit and the beginning of catastrophic events.

5. BRIEF CONCLUSIONS

1. The presence of two large magma chambers in the magmatic system of Yellowstone [5] provides a basis for the implementation of the eruption in accordance with the instability mechanism (GLI- mechanism), in which the leading role should play fluid, accumulated in the lower chamber.
2. Catastrophic circumstances of the last three Caldera-forming eruptions of Yellowstone indicate that the volume of fluid accumulated in the lower chamber was much higher than the critical volume.
3. The relatively calm nature of the last eruption of the Yellowstone 70,000 years ago may indicate that the volume of fluid accumulated in the gas "cap" of lower magma chamber of Yellowstone was slightly higher than the critical one, so the eruption was calm and effusive, the expanded fluid, remaining in the system, lost its original overpressure and configuration necessary for the catastrophe.
4. The anomalous emission of CO_2 in Yellowstone may result from the "leakage" of fluid "trapped" in the upper chamber after the eruption of 70,000 years ago or from the decompression of magma moving to the Earth surface. In any case, a noticeable intensification of this emission with a simultaneous acceleration of uplift inside the Caldera could be "a precursor" of the approaching catastrophe, indicating the formation of a new lower chamber gas "cap" and its penetrating into the conduit.

ACKNOWLEDGEMENTS

The work was supported by the Ministry of Education and Science of the Russian Federation (in accordance with the requirements of the contract №14.577.21.0109).

COMPETING INTERESTS

Author has declared that no competing interests exist.

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Peer-review history:
The peer review history for this paper can be accessed here:
http://sciencedomain.org/review-history/15408