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Catastrophic Volcano Explosive Eruptions: Causes and Mechanisms

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How and why catastrophic explosive volcano eruptions occur? These explosions are accompanied by the ejection of vast amounts of gases and pyroclastic material, glowing clouds, surges, etc., and lead to great human and material losses, as well as exerting a significant, in some cases, long-term impact on the Earth's atmosphere and climate. It is assumed that this phenomenon is considered with degassing of magmas in relatively shallow transitional magma chambers beneath volcanoes, i.e. decreasing of gas solubility in the melt due to decrease of temperature and pressure. If the melt is saturated in volatiles, it can spontaneously expel the gas, i.e., begins to resurgent (retrograde) boiling. The scale of this process evidently depends on initial volatiles saturation in the melt and its energy state related to the formation and growth of gas bubbles in the melt because it is energy-consuming process (Sharkov, 2004). However, it is not clear yet why does magma degassing occasionally lead to catastrophic explosions which can last 2–4 months.

Most geologists suggest that catastrophic explosions are related to an abrupt increase of magma volume in shallow chambers owing to degassing. The relevant models suggest the following causes of explosions: groundwater penetration into magma chamber, collapse of volcanic cone, emplacement of gas-saturated basaltic magma into dacite magma chamber, penetration of magma chamber by fractures–conduits, etc. Unfortunately, none of these models explains the vast scale and long duration of the process, as well as specific mechanism of the large-scale bubble formation required for such explosions. The above phenomena actually can affect the eruption style in some cases; however, they cannot cause the catastrophic scale. All these hypotheses consider the explosion itself, but do not explain the high gas content in melts and the mechanism of practically simultaneous separation of gas bubbles in a significant volume. We believe that the process is mainly controlled by kinetic factors, because the formation of a new interface requires significant energy consumption. This is typical of any phase transition, including resurgent boiling of melt, which is considered here. Therefore, the formation of numerous nuclei of a new phase (crystals, melt, or gas) in the previously homogeneous medium can occur only after an energy barrier is overcome. Then, the process proceeds without problems, since it operates within the stability field of the new phase. The formation of a few nuclei owing to fluctuations cannot be developed to a large-scale process, because the increase of an existing bubble-melt interface is energetically more favorable than the formation of a new one. Therefore, for example, local decompression because of a fracture in the chamber's roof, can cause the growth of group of bubbles or lead to local magma foaming during filling of this fracture.

According to experimental data (Fluids, 1991), the solubility of water and CO_2 in mafic and felsic melts increases with pressure up to 3 GPa without extremes (Fig. 1). Unlike water, CO_2 solubility significantly depends on the melt composition, being the lowest in the felsic and intermediate magmas. In other words, water should be the dominant component of the gas phase in rhyolites and dacites of calc-alkaline series, typical for convergent tectonic settings, whose eruptions are typically catastrophic. The experimental data also indicate that water solubility in the melts remains nearly constant during pressure decrease to about 0.1 GPa and then abruptly decreases. Unlike water, the CO_2 solubility gradually decreases with decreasing pressure, and only weakly depends on the initial $CO_2/(CO_2 + H_2O)$ ratio.

From this follows that subduction-related water-bearing andesite–dacite magmas can become oversaturated in H_2O owing to abrupt pressure decrease under shallow conditions in peripheral chambers of volcanoes at depths of 3–4 km. In this case, melt in the magma chamber presents a "blasting" mixture, which is ready to explode at any moment owing to rapid degassing. Seismic observations show that the upper magma chambers beneath the most andesite–dacite volcanoes are located at these depths (2–8 km) (Macdonald, 1972). Hence, such situations frequently occur in nature.

However, as follows from experimental data, even the water-oversaturated melt cannot boil spontaneously without any additional impact or can boil only by scoria formation, as it takes place during the eruption of intraplate basalts. Large-volume separation of gas bubbles requires a mechanical shock-type impact: the melt must be abruptly compressed and subsequently decompressed (Stolper, 1982). In this case, gas bubbles begin to form over the entire magma volume in chamber. We believe that this mechanism can be applied to catastrophic volcanic eruptions. The volatile-saturated melt in a shallow chamber can explode owing to a strong earthquake, when pressure abruptly increases in the compression front and abruptly decreases in the subsequent expansion front. So, presence of volatile-rich magma as well as some energy pulse behaving as a "trigger," which causes the rapid and extensive formation of gas phase nuclei, are necessary for a catastrophic explosion.

This mechanism is especially efficient during a series of earthquakes, which usually precede catastrophic explosions; resurgent boiling begins at the moment when the energy barrier is overcome. During a further (stronger) impact, many homogeneously scattered gas bubbles are formed in magma. It is highly improbable that the entire chamber volume is spanned by this process, since pressure in the chamber can increase downward to 0.15–0.3 GPa (Macdonald, 1972), thus blocking further formation of bubbles. However, this pressure is sufficient for explosion and ejection of the material. At the moment of explosion, the magma chamber is impacted by the explosion-related shock wave, which is followed by the expansion front, thus again allowing large-volume degassing and a new explosion, and so on.

Such a mechanism determines the layer-shape resurgent boiling zone related to frontal propagation of shock waves. However, in any case, this zone, owing to explosions, will migrate downward, primarily develop at the shallower sections of the magma chamber, and gradually remove the melt from it. If the chamber has a significant vertical extent, it can be emptied to depths of about 5–6 km, since the melt at larger depths may be undersaturated in H_2O and retrograde boiling will stop. Calderas can form owing to the chamber emptying, and the volcano will become inactive until the formation of a new chamber by water-saturated magma replenishment, after which the process can repeat.

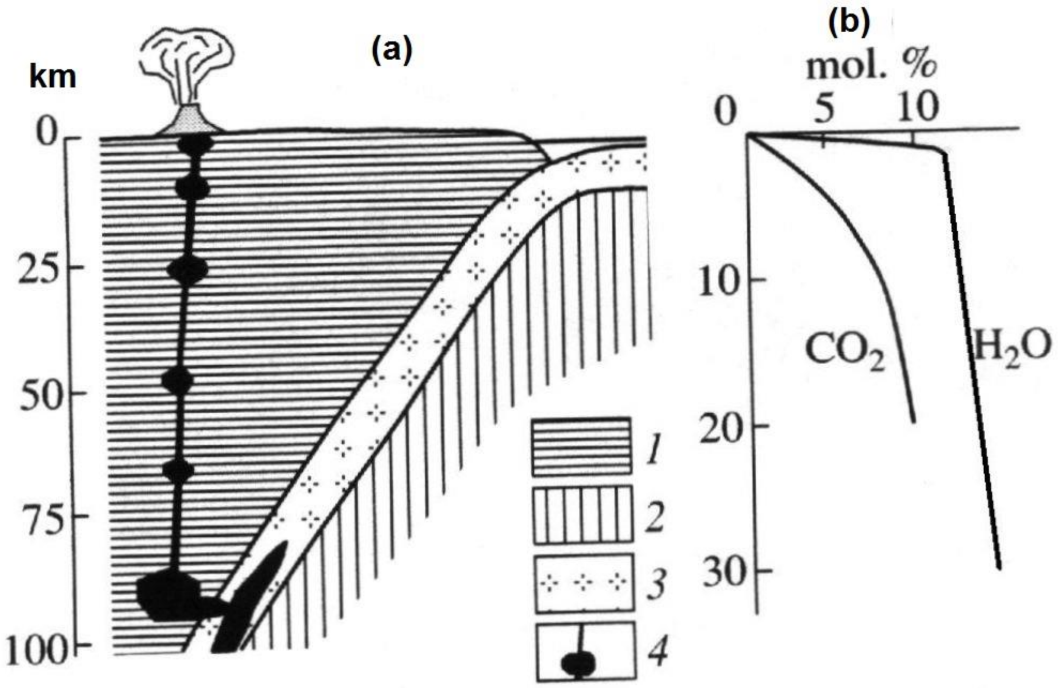

Fig. 1. Scheme illustrating the structure of the magmatic systems related to subduction zones at the active margins of continents and oceans. (a) Structure of the system: (*1*) continental lithosphere, (*2*) oceanic lithosphere, (*3*) subducted plate, (*4*) magma chamber. (b) Variations of H_2O and CO_2 solubility in silicate melt versus pressure (simplified after (Fluids, 1991).

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