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Magma, Crust and Fluid: Critical Conditions of their Interaction and Types of Volcanic Eruptions

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Abstract

The mechanism of Gas-Liquid Imbalance (GLI-mechanism) is applied to the theoretical description of the behavior of the magmatic system for different types of volcanic eruptions. It is shown that physical interaction of contacting volumes of magma and gaseous fluid under certain critical conditions can lead to the formation of stratovolcano and caldera. With unified theoretical positions the development of Strombolian, Plinian, Hawaiian, areal and high-explosive volcanic eruption is discussed.

Keywords: Magma system, stratovolcano, caldera forming, eruption mechanism, fluid layer, monogenetic cone

1. Mechanisms of Volcanic Eruption

Modern scientific ideas about the structure of the Globe are based on the fact that the Earth's crust was formed due to cooling of juvenile magmatic melt which is still now at depths of several tens of kilometers and from time to time is erupting to the surface as a result of volcano activity. There are many theories of volcanism (Parfitt & Wilson, 2008) but they do not satisfy fully the scientific community. A variety of types of volcanoes creates space for scientific thought, but the need for a simple, clear and physically "universal" mechanism of volcanic eruption is not diminished. Perhaps the knowledge of such a mechanism (if it really exists) could give scientific basis for real predictions of eruptions with disastrous consequences.

There are two most popular models of basaltic volcanism: the Rise Speed Dependence (RSD)-model, where the acceleration and eruption occur due to magma defragmentation and expansion of gas bubbles; the Collapse Foam (CF)-model, where gas bubbles accumulated inside plumbing system attain some critical volume, rise with magma and erupt out from volcano (Parfitt, 2004). RSD-model allows extensive physical and mathematical treatment, since the formation of bubbles, reducing density and viscosity of magma melt, can be adequately considered in the thermo- and hydrodynamics of the process. In the CF-model similar approach is missing. However, in Del Bello et al., 2012 the possibility of bubble instability depending on its linear dimensions is demonstrated. It is important that for RSD-model you need a primary upward movement of magma to bring at lower pressures new portions of gas-saturated melt. Further acceleration of magma (up to supersonic speeds) is explained by its defragmentation and decreasing of average density and viscosity due to gas bubbles. But where does this driving force of the primary magma ascent come from? This question usually remains unanswered. Bottle effect of "Coca-Cola" which supporters of RSD- model like to refer occurs only when you are opening a bottle sharply, that is when you quickly drop the pressure inside the liquid saturated with gas. Real magma rises to the surface slowly, its decompression occurs gradually (this, of course, not talking about explosive eruptions when lava vent is clogged by plug). As for the CF- model, it is unclear how a large volume gas bubble can push out magma column. It can float in the magma as a buoyant object or like a slug and explode near the surface, but that does not explain the lava fountains working for days and even months (Parfitt, 2004).

In our opinion, a physical mechanism of the Imbalance of the contacting liquid and gas volumes proposed and analyzed in (Belousov, Belousova, & Nechayev, 2013) could eliminate contradictions and play the universal role. The essence of this GLI (Gas-Liquid-Imbalance) mechanism is as follows. If the liquid fill to the brim the tank (for example, a vertical channel) with solid walls and at a depth *H* has contact with a closed gas volume, their equilibrium becomes unstable when the volume of gas *V* exceeds a critical value V_{cr} :

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

where *S* is a section of the channel in the contact area, γ is the adiabatic coefficient for the gas, ρ is the density of the liquid, p_0 is the atmospheric pressure, *g* is the acceleration of gravity.

If $V > V_{cr}$ at the expansion of the gas in the channel region (and removing from the channel the corresponding volume of liquid), the pressure in the gas volume will exceed the hydrostatic pressure of the liquid in the contact zone, so the column of liquid will begin to erupt under gas pressure. Critical condition (1) does not depend on the shape of the channel and its dilatations. In (Belousov et al., 2013) the GLI- mechanism explained the features of geyser eruptions, in (Nechayev, 2012) it was extended to the case of volcanoes, and (Nechayev, 2014) demonstrated that this mechanism may explain the eruptive cycle of Etna. In this paper we will try to extend its scope to different types of volcanic eruptions.

For the case of volcano magma is a liquid. A fluid (for example, water fluid) in a supercritical state (for water this condition occurs when $T > 647K$ and a pressure exceeds 220 bar) behaves as an ideal gas and determines accordingly the work of GLI-mechanism.

In this paper, we want to link a variety of types of volcanic eruptions with the conditions of the behavior of magma and fluid substances under GLI-mechanism operating within a rigid "framework" that forms the Earth's crust. We will show how this mechanism can naturally explain the "standard" stratovolcano formation as well as such non-trivial phenomena as Caldera forming eruptions and the formation of monogenetic cinder cones.

2. The Birth of a Stratovolcano

It is recognized that the primary magma ascent from the asthenosphere to the Earth's surface is caused by lithostatic pressure that push magmatic melt through the existing faults and fractures. If the crust is relatively heavy (the basaltic crust of the ocean floor may have a density of 3.2 g / cm^3), it may have enough pressure to push more light magmatic melt (its density is less than 2.8 g / cm^3) to the ocean bottom. In the continental crust the thickness of layers of sedimentary rocks and granite is sufficiently high and their density is less than 2.5 g / cm^3, so magma usually can’t reach the earth's surface. It should stay on the level H_m where the weight of the magma column is balanced by the lithostatic pressure of the crust, satisfying the condition:

$$\int_0^{H_m} \rho_c(z)dz = \int_0^{H_m} \rho_m(z)dz$$

where ρ_m, ρ_c are density of magma and crust, H_m is measured from the asthenosphere ($z = 0$).

Thus, on its way upward magma forms magma chambers, reservoirs of magma, which, as shown by direct geophysical data, are confined with active volcanoes. Important part of functioning of magmatic system, in addition to magma chamber, is the feeding and output conduits, a cylindrical or rectangular "tubes" through which magma, rocks and gas is supplied from the source to the crater of a volcano and thrown out. To advance magma to the surface and implement the eruption (both primary and subsequent) an overpressure should appear in the magmatic system. It can be caused by both internal and external reasons. Most scientists agree that this overpressure is caused by the volatile components of the molten magma, dissolved therein fluids which, passing into the gas phase and expanding, are capable of transporting its high pressure from deep layers to the upper levels. It should be noted that the source of this excess pressure can be exogenous, or external to the magma chamber: for example, fluid-saturated layer heated to a supercritical temperature. Model of eruption at the interaction of exogenous fluid layer and magmatic system was considered in (Nechayev, 2012) and we will use it to illustrate the mechanism of formation of a stratovolcano. Then we show how GLI- mechanism works in the case of endogenous fluid, and apply the results of our theoretical analysis to the different types of volcanic eruptions.

2.1 Exogenous Fluid.

Thus, we assume that the fluid layer is under the peripheral magma chamber at a distance $(h_f - h_m)$ and has contact with the magma conduit (Figure 1).

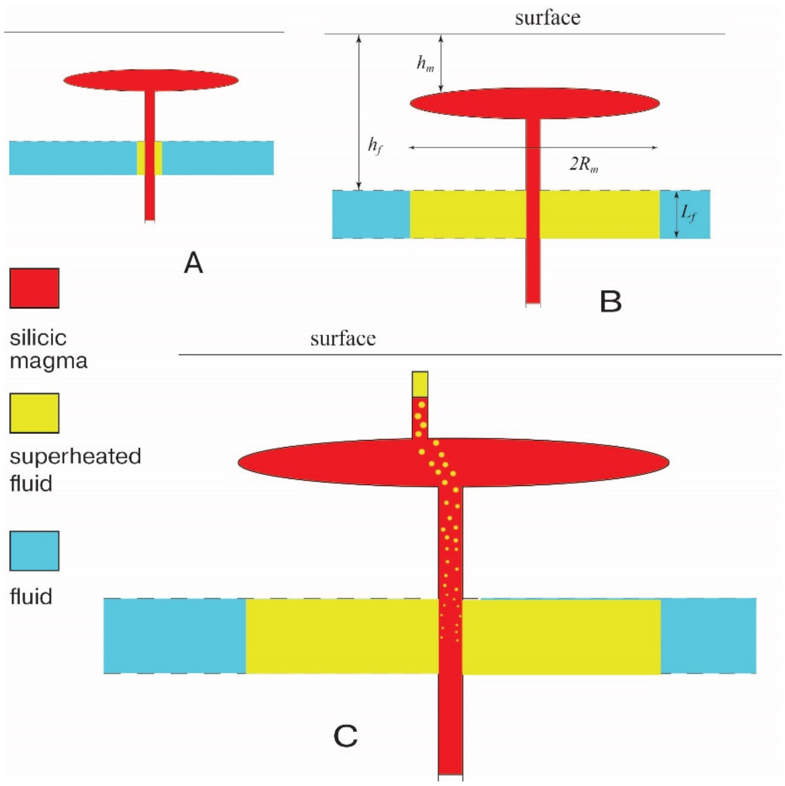

Figure 1. Magmatic system with exogenous Fluid layer

A – formation of the magma chamber; superheated fluid volume is small.

B – warming of the fluid layer by magma chamber to supercritical temperatures.

C – formation of output conduit due to excess fluid pressure.

Magma chamber is a heat source with a temperature of 1300 K or higher. Flat front of elevated temperature moves up and down from the chamber, warming over time new layers of rock. The characteristic time of this process is inversely proportional to the thermal diffusivity of the rock and proportional to the square of the distance. For example, warming up the 100-meter depth of sediment to temperature 700 K may take 200 years, and at a depth of 1 km – 20,000 years! Maximum depth of warming is determined by the transverse dimensions of the magma chamber.

Assume that the heat that spreads from the magma chamber encounters the fluid-saturated layer. The subsequent behavior of the whole magma-crust-fluid system will depend on what temperature gets the fluid substance. If its temperature exceeds the critical value, the fluid begins to behave as an ideal gas (up to 10% (Nechayev, 2012)), and its pressure p_f will satisfy the appropriate law:

$$p_f = \rho_f R T_f = (M_f / V_f) R T_f \tag{2}$$

where ρ_f, M_f, V_f, T_f are density, mass, volume and temperature of the fluid; *R* is the ideal gas constant. We believe that the porous rocks equalize the fluid pressure over its volume. During warming the fluid pressure in accordance with (2) will rise to obtain some surplus value compared to the primary lithostatic pressure. This overpressure can cause the cracking of surrounding rock. As the fluid layer is in contact with magmatic system (Figure 1), we should expect the ascent of magma to the surface through fractures or faults, since the pressure of the fluid will create excessive pressure in the magma column. Part of the fluid in the form of "bubbles" can emerge at the top of magmatic system, bringing its excess pressure and forming gas "tip" facilitating magma the motion to the surface (Figure 1C). Of course, we assume that the fluid layer, as well as the magma chamber, retains its spatial position within the crust.

If the magma reached the surface and if the volume of superheated fluid, pressing the bottom of the magma column, exceeded the critical value (1), according to the GLI-mechanism magma in the conduit receives positive acceleration and the eruption starts. Critical volume is approximately equal to $\gamma S h_f$ where h_f is the depth of the fluid layer, S is the section of the magma conduit in the fluid-magma contact zone, γ is the adiabatic coefficient of fluid. So, for the model Figure 1B the superheated fluid volume will be equal to $\pi R_m^2 L_f$. If we take the radius of the conduit, the radius of the chamber and the depth of the corresponding fluid layer equal to 10m, 2000m and 5000m, we find for water fluid $(\gamma = 1,4)$ that for critical volume we need the thickness of the fluid layer 17 cm only!

So, we have necessary conditions (the critical volume of superheated fluid $\gamma S h_f$ is exceeded and magma column reached the surface), and the eruption starts. The pressure difference in the magma-fluid contact zone increases as the fluid enters the conduit pushing magma out and reducing the pressure of magma column. For the volume V_f of superheated fluid $V_f >> V_{cr} = \gamma h_f \pi R_c^2$ the fluid pressure decreases slightly and remains close to $\rho_m g h_f$ until the fluid starts to penetrate into magma chamber and to expand (Figure 2).

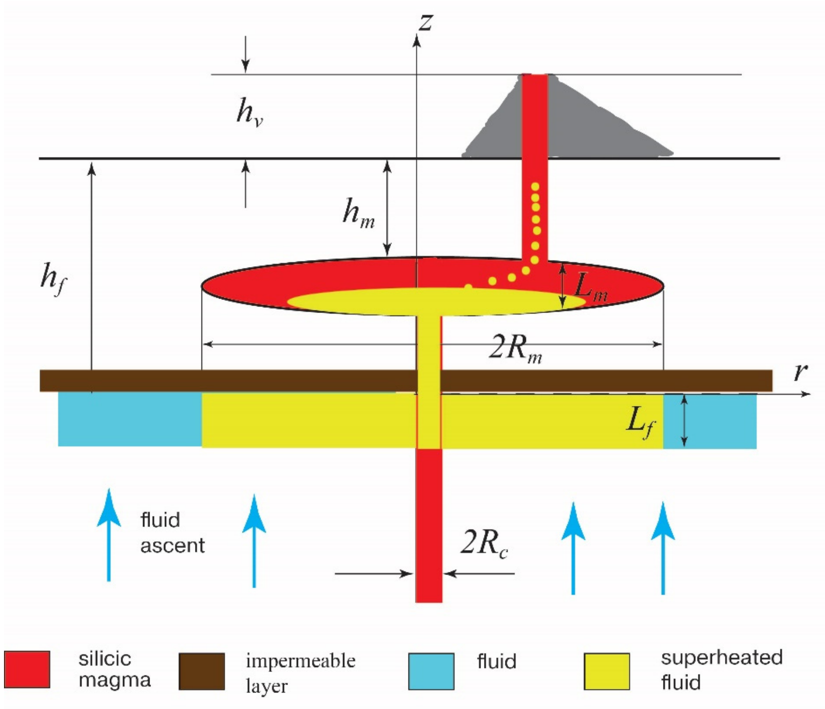

Figure 2. Magmatic system with superheated fluid expanded into the magma chamber

Mixing with magma under pressure fluid is erupted on the surface in the form of a two-phase melt which cools and turns into a porous slag forming the primary cone of a volcano. Ejection velocity v of magmatic mixture is determined by the simplified equation of hydrodynamics, which for the output conduit can be written as:

$$\rho_m \frac{dv}{dt} = -\frac{dp}{dz} - F(v) \approx \frac{p_f - \rho_m g z - p_0}{z} - F(v) \tag{3}$$

where $p = (p_f - \rho_m g z)$ is the difference between the pressure of the fluid and the overlying magma column, $F(v)$ is the friction force per unit length of the conduit depending on the magma velocity (linear for the laminar flow and quadratic for the turbulent one). Equation (3) follows that the eruption stops when the height of the growing volcano cone h_v becomes equal to the distance $(h_f - h_m)$ between the magma and fluid layers (thickness of the magma chamber is neglected) (Figure 2).

If erupted rocks are dispersed the growth of a cone is slow, and the eruption must end when the pressure in the enlarged fluid drops to the pressure of the magma column in the conduit (Figure 2). Using the equation (2) and assuming that the mass of the fluid during its expansion does not change, and the process is isothermal (the fluid temperature is close to the temperature of magma), we can estimate the volume V of fluid when eruption stops. It is equal to:

$$V = \frac{h_f}{h_m} V_f \tag{4}$$

The difference $(V - V_f)$ between the amount of the original and the expanded fluid, obviously, must be equal to the volume of all magma erupted.

When the pressure drop in the output conduit is maximum (fluid just beginning to enter the magma chamber) the rate of emission of magmatic mixture is maximum too; melt is saturated with gaseous fluid which high overpressure provokes explosions. With the growth of the cone and the expansion of the fluid the pressure drop in the conduit and velocity of magma decrease. At some point the fluid pressure is enough only to push magma through the crater edge or through the flank fracture. The introduction of magma into volcanic cone by dikes and sills occurs, thus a "skeleton" of stratovolcano is forming (A.Khrenov, personal communication). This formation need repeated recurrence of the eruption. To do this, first, the magma from the upper mantle and intermediate chambers has to be lifted in the peripheral chamber. Second, fluid layer must restore the critical volume either through the fluid ascent from the mantle (Figure 2), or by diffusion of fluid from the periphery. In any case, the temperature of the superheated fluid can increase further. In accordance with (2) the overpressure in the magma chamber will increase too, allowing the new portions of magma to rise to the crater of the growing volcano. All these processes require time forming the interval between eruptions. Once superheated fluid regains its critical volume and its pressure exceeds the pressure of the magma column from the fluid layer to the crater of the volcano, a new eruption begins, and it will be repeated as long as the supply of fresh magma is stop or fluid layer is exhausted.

If magma column in the conduit of the volcano does not reach the central crater (critical volume of superheated fluid is exceeded but the fluid overpressure is not large enough), it may cause side breakthrough of lava when the pressure inside the column exceeds the tensile strength of rocks that form the volcano. The development of this eruption will go similarly to the eruption from the central crater as second necessary condition for the GLI-mechanism is fulfilled: lateral breakthrough just allows the magma column pressure primary decreasing.

2.2 Endogenous Fluid.

The assumption about the real existence of fluid layers that can cause a volcanic eruption according to the GLI-mechanism is still the assumption only. The mass of fluid substances contained in the earth's crust (especially water fluid in subduction zones) is sufficient to run the GLI- mechanism, however, its operation need fluid to be accumulated in a separate layer, be located at the correct depth to receive a supercritical temperature and finally to be successfully recovered after the eruption. Consequently, many conditions must be fulfilled in one place to form a stratovolcano. Meanwhile, the volcanoes in the world are not rare natural objects. In this section we recall the principle of the GLI-mechanism in the presence of endogenous fluid contained directly in the juvenile magma (Nechayev, 2014).

Rising to the surface, magma "boils" dissolving its "volatiles" (for example, the water, which can be up to 20% at 30 Kbar) in the gas phase dramatically increasing the pressure on the magma and surrounding rocks. This pressure helps magma to move up. The mechanism of generation of gas bubbles, causing an overpressure, can be represented as follows. The proportion *k* of fluid dissolved in the magma increases with depth *h*. At the lifting of a volume V_m of magma at a distance Δh a mass of fluid which has passed into the gas phase will be equal to:

$$\Delta M_f = V_m \rho_m \frac{\partial k}{\partial h} \Delta h \tag{5}$$

It will represent an aggregate of microbubbles containing a fluid with a density ρ_f that satisfies the ideal gas low (2): $\rho_f = P_l(h)/RT_m$, where $P_l(h)$ is the lithostatic pressure at a depth of *h*; T_m is magma temperature; *R* is the gas constant. With decreasing of lithostatic pressure a gas bubble will seek to expand but if it is impossible to increase its volume (due to the rigidity of the crust) the bubble will retain its original pressure that is greater than the magnitude of the ambient pressure. This, in our view, gives us the physical nature of the internal overpressure in the magma. The total mass of the fluid transformed in the gas phase due to the magma moving to the new level will be equal to the corresponding integral of expression (5). The first fluid bubbles will be distributed relatively uniformly over thick magma. But because their density is always less than the density of magma, they will float and accumulate in the appropriate places such as roof and arch of magma chamber (Figure 3).

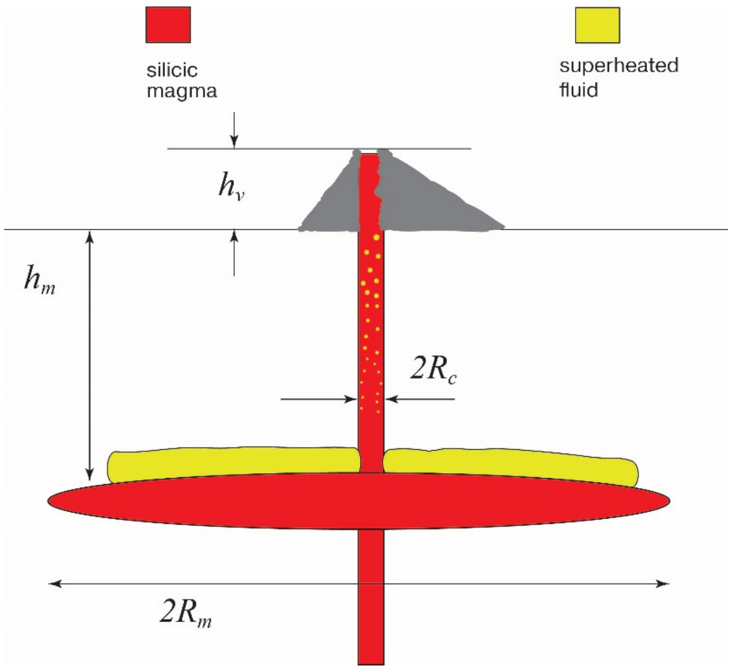

Figure 3. Magma chamber with a "collar" of endogenous fluid.

Cross-section of the channel is $S = \pi R_c^2$

Increasing the pressure in the chamber the fluid will contribute to the formation of fractures and dikes which enable magma to reach the surface. The maximum possible volume V_f of the gaseous phase in the chamber will depend on the percentage of fluid in the melt $k(h)$ and the depth of magma chamber h_m.

Taking into account (2) and the initial equality of pressure of magmatic column and fluid in the contact zone $\rho_m g(h_m + h_v) = \rho_f RT_m$, we obtain:

$$V_f = \frac{M_f}{\rho_f} = \frac{(k_0 - k_m)M_m}{\rho_f} = \frac{(k_0 - k_m)\rho_m V_m RT_m}{\rho_m g(h_m + h_v)} = \frac{(k_0 - k_m)V_m RT_m}{g(h_m + h_v)} \tag{6}$$

where M_m, V_m are mass and volume of the magma chamber; $(k_0 - k_m)$ is the proportion of the fluid which has passed into the gaseous phase at the rise of magma at the level h_m of the magma chamber. Critical volume in the case of Figure 3 is equal $\gamma(h_m + h_v)S$, and the condition of the eruption in accordance with (1) and (6):

$$V_m > \frac{\gamma g S(h_m + h_v)^2}{(k_0 - k_m)RT_m} \tag{7}$$

As follows from (7) the eruption condition for endogenous fluid is directly related to the volume of the magma chamber which must exceed a critical level depending on the magma chamber parameters: its depth, temperature and fluid content in the magma.

If there is a system of two or more magma chambers the eruption condition analogous to (7) can be written for each of these chambers. For example, for the magmatic system at Figure 4 the condition of the eruption of the lower chamber will be as follows:

$$V_{m2} > \frac{\gamma g S_2 (h_{m2})^2}{(k_0 - k_{m2})RT_m} \equiv V_{m2}^{cr} \tag{8}$$

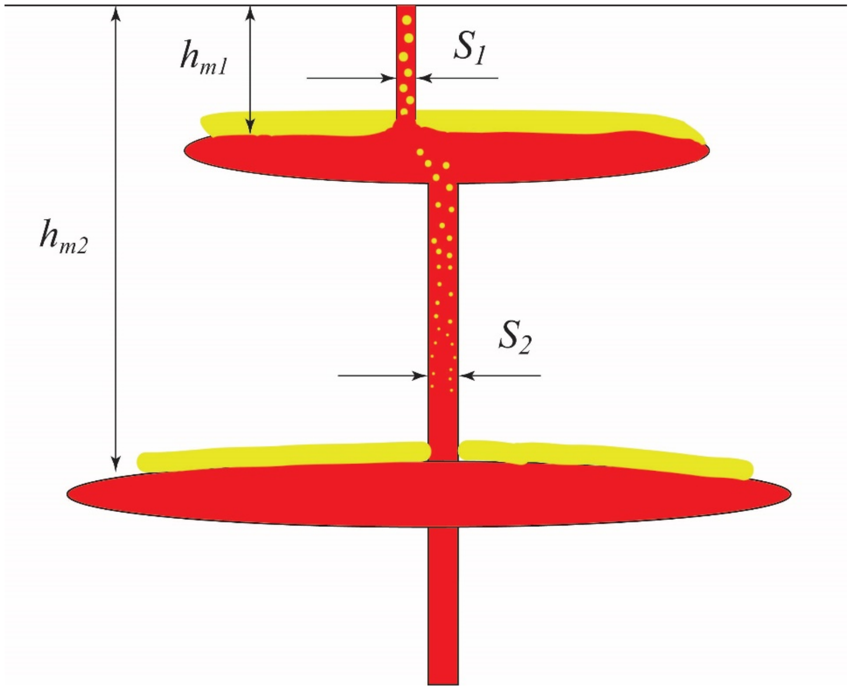

Figure 4. Magmatic system with two magmatic chambers

Here we take into account that the model in Figure 4 has no volcanic cone, so the height of the magma column is equal to h_{m2}. It is clear that for the upper chamber the condition of eruption will be similar to (8), only the magma chamber critical volume will be much less since the chamber lies at a shallower depth. Eruption of the upper chamber will be strombolian type with the release of the material in the output channel. After this eruption magma from the lower chamber, if it has the overpressure, will go upward where it forms a new gas "collar" of the fluid isolated from magma during its ascent to the next level. The volume of fluid in the lower "collar" after the eruption may rise due to supply of new magma. Obviously, the "upper" eruption should happen more often. After each "upper" eruption the lower chamber can receive an additional portion of the fluid and it can obtain a critical volume. The corresponding eruption may begin only after N «upper» eruptions took place according to the condition:

$$V_{m2} + NV_{m1} > V_{m2}^{cr} \tag{9}$$

Excessive fluid pressure will push magma to the surface. As soon as a slight collapse of the magma column occurs, the eruption begins for the chamber which already has a critical volume of superheated fluid. The eruption can devastate entire system above the lower magma chamber including the upper chamber and cause the caldera formation. In the future, the upper chamber can be filled with magma again and renew its eruptions which lead to the formation of a new stratovolcano within the caldera.

3. Types of Eruptions.

3.1 Strombolian

This type of eruption is characterized by relatively frequent, not very powerful explosions, emission of ash, gases, volcanic bombs, short-spouting lava that does not represent, as a rule, a serious risk to humans. In our view, this type of eruption can occur if the fluid layer is located above the peripheral chamber and crosses the output conduit: Figure 3 or Figure 5. In this case, the critical volume equal to $\gamma(h_f + h_v)\pi R_c^2$ is relatively small and does not require a large amount of superheated fluid.

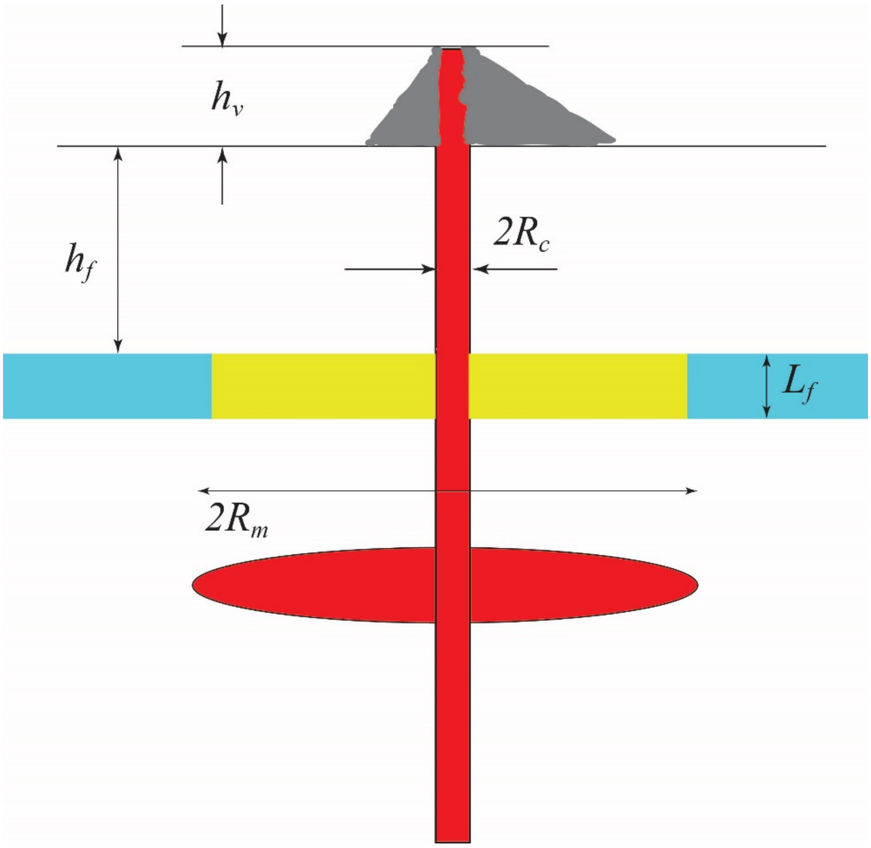

Figure 5. Fluid-magmatic system with exogenous Fluid layer corresponding to Strombolian type eruptions

In the upper part of the conduit gas bubbles will float and burst (if magma is liquid) or form a gas plug when the mouth conduit is closed, until the volume of superheated fluid reaches a critical level due to the inflow, for example, of meteor water coming from the surface or sea water (as, likely, in case of Stromboli). During the eruption all the contents of the conduit above the level of the fluid layer can be thrown including the small magma chamber if it exists between the fluid layer and the volcano crater.

3.2 Eruptive Cycles and Paroxysms

This type of volcanic activity is characteristic of many volcanoes. For example, of Mount Etna and Stromboli (Italy) and Klyuchevskoi in Kamchatka (Russia). Alternation of eruptive and effusive eruptions is in good accordance with the scheme of GLI-mechanism discussed above for the assumed case of two magma chambers (Figure 4). Fresh magma supplies the lower chamber coming, probably, directly from the mantle, which in the case of Etna is shallow: Moho is only about 15 km (Behncke & Neri, 2003). Perhaps magma injection periods are subjected to the peculiarities of mantle convection. Filling the lower chamber, magma releases a certain amount of fluid that occupies a volume in the apical part of the chamber and create a positive overpressure, which move magma to the upper chamber and to the crater of the volcano. Reducing of the pressure in the upper chamber $\rho_m g(h_{m2} - h_{m1})$ releases from the melt an additional amount of dissolved fluid. If the volume of magma in the upper chamber exceeds a critical value (7), the volume of fluid will exceed $\gamma S h_{m1}$ and will give the first condition of the eruption. The second condition is the collapse of the magma column when magma overflow the crater. Summit eruption ends with release of all content of the output conduit above the upper chamber. As the fluid pressure in the lower chamber is maintained, it must refill the magmatic system with melt from the lower chamber by updating the magma in the upper chamber and in the conduit up to the top of the volcano. Thus, the summit eruptions will be repeated until the excess pressure in the apical volume of the lower chamber will be enough to fill the entire upper part of the magmatic system (Figure 4), and the fluid content in magma will be enough to have in the upper chamber the fluid volume exceeding critical one. With each new summit eruption the volume of magma in the lower chamber will decrease (injection of magma from the mantle is not yet happening), respectively, the volume of fluid will increase and its pressure will decrease. The latter circumstance will cause the magma will not be able to reach the top of the volcano, it will stand in the conduit and find weaknesses in the side slope of the volcano for a breakthrough. As the critical conditions for the upper chamber all the time are fulfilled, and the magma column in a side breakout gets collapse, the eruptions take place on the slopes of the volcano. A series of flank eruptions can lead to the fact that the volume of fluid in the lower chamber, increasing after each eruption, exceeds the critical level, thus the new eruption begins, and it will free all the magmatic system above the lower chamber including its gas "collar". Naturally, this eruption will be the last and most powerful in the eruptive cycle as the fluid of lower chamber will be exhausted. This sequence of events was recorded in numerous observations of the volcano Etna (Behncke & Neri, 2003). Pause in a series of eruptions must end with the update of the magma in the lower chamber.

Stromboli activity cycle may also begin with the filling of the lower (deeper) chamber by "fresh" magma that isolate a certain amount of fluid (mainly carbon dioxide), which accumulates at the roof of the chamber and occupies the initial volume V_f . Assume that this volume is much less than the volume of the magma chamber and has no contact with the magma conduit. Because of its overpressure the fluid starts to squeeze out magma from the chamber and move it to the top of the volcano. In the area between two chambers the decompressed magma will release carbon dioxide and water vapor in the form of bubbles rising up and accumulating in the upper part of the upper chamber which unlike the Etna supposedly has a volume less than the critical one. Another part of fluid released during the ascent of magma through the conduit rises directly to the crater of the volcano and "provide" the routine activity of Stromboli. When fluid penetrates from the upper chamber into the conduit the eruption does not occur since the volume of fluid is always less than the critical value. Fluid penetrates into the conduit in the form of a bubble having a large linear dimensions and the pressure corresponding to its depth. Further motion of a bubble to the surface and its burst may follow the mechanism analyzed in (Del Bello et al., 2012), so the bubbles from the upper chamber may serve as the source of "major explosions". Thus, the cause of the weak and relatively strong explosions of Stromboli, as researchers believe may be the rise of gas bubbles through the magmatic conduit and their destruction near the surface with the release of gas and magma clots. Explosive force must obviously depend on the value of the overpressure acquired by bubble at the corresponding depth. As for the paroxysms, their mechanism, in our opinion, has a different origin, although supporters of the "bubbles" theories explain such eruptions by non-standard sizes of bubble-slug (Del Bello et al., 2012). The nontrivial fact characteristic for paroxysms was found by Calvari et al., 2011: it is the existence of a "cumulative" amount of lava, which must be erupted before paroxysmal events. Critical volume of lava was equal to $4 \cdot 10^6$ m^3. It was found for two paroxysms occurred April 5, 2003 and March 15, 2007 during the corresponding effusive eruptions (Calvari et al., 2011).

The process taking place in the lower chamber has, in our view, fundamentally different physics. The overpressure in the volume V_f must be sufficient for magma rising to the top of the volcano, for breaking through the volcano slope to organize the effusive eruption. Magma gradually leaves the lower chamber, so the volume of fluid V_f accordingly increases. The fluid pressure, of course, falls but it can be maintained by bubbles emerging from deep horizons of the magmatic system. Magma is squeezed from the chamber, the volume of gaseous fluid increases. Once fluid will penetrate into the conduit, it may trigger the GLI- mechanism as the critical volume $\gamma S h_{m2}$ can be surpassed. In accordance with the GLI-mechanism the critical volume of erupted lava that precedes the "paroxysm" must be equal to the volume increase, which obtain the fluid in the lower chamber during effusive eruptions before the moment of penetrating the magma conduit. From this the paroxysmal eruption of the melt located in the conduit above h_{m2} depth must begin.

What could be the real magnitude of the critical volume? Let us evaluate it. For the lower chamber of the above supposed magmatic system of Stromboli (Figure 4) it should be equal $\gamma S h_{m2}$. Taking the conduit diameter as 4 m (at April 5, 2003 paroxysm (Calvari et al., 2005) a video camera fixed the glowing object with a diameter of 4 m above the crater), the depth as 6 km and carbon dioxide as the fluid ($\gamma = 1,3$), we obtain the critical volume equal to 10^5 m^3. If we assume that the fluid is distributed uniformly along the roof of the magma chamber, then for a typical chamber radius of 1 km we obtain the average thickness of the fluid "collar" just only 0.03 m! It is clear that the fluid under the roof will accumulate non-uniformly, but from the above calculation it is evident that the geophysical methods can't fix such fluid accumulation even it exceed this amount hundreds of times.

Critical volume "works" only when the fluid penetrates the magma conduit. The greater the excess of the actual volume of fluid above the critical one, the more intense eruption develops. Amount of magma erupted before the paroxysm of Stromboli in 2003 was equal to $4 \cdot 10^6$m^3 , and it gives a minimum evaluation of the expansion volume of the fluid in the lower chamber. So this volume could exceed the critical value of at least an order of magnitude. The entire volume of erupted magma during the paroxysm was 84 000 m^3 (Calvari et al., 2005), which corresponds to the "idealized" channel depth of 6 km and a diameter of 4 m.

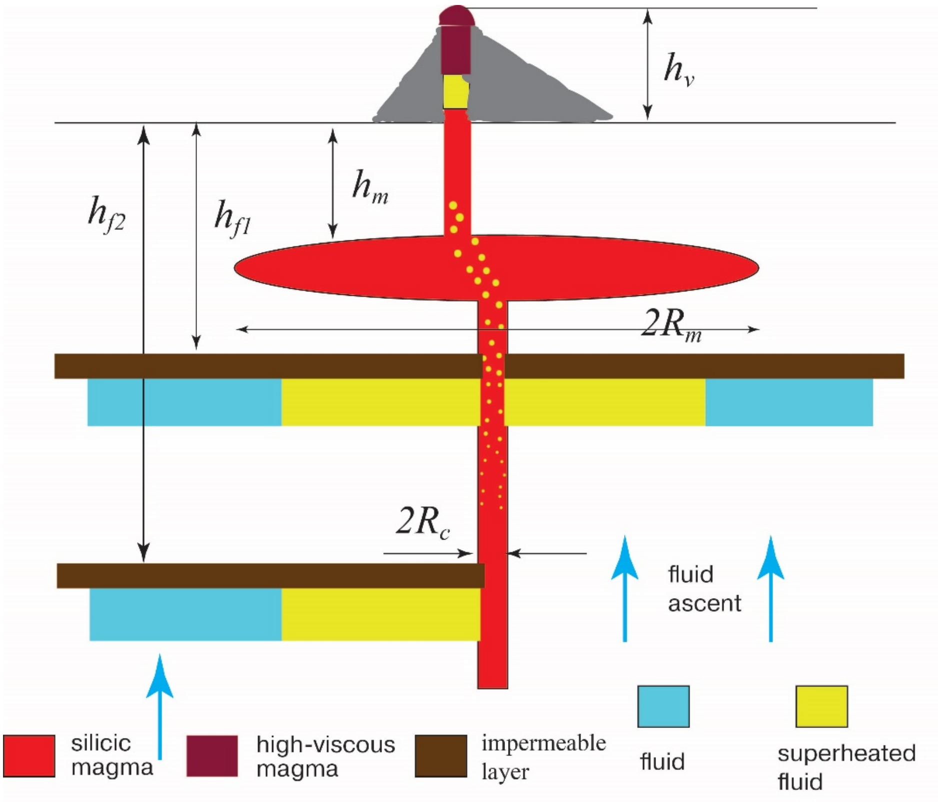

Figure 6. Magmatic system with two fluid layers: the "upper" and "lower". Fluid layers are formed and recovered by the ascent of fluid bodies from the upper mantle. The location of the fluid layer is determined by impermeable layers. The asymmetry of the lower layer emphasizes that the configuration of fluid layers may be arbitrary

3.3 Caldera Forming

These are rare types of eruption, during which cubic kilometers of rock are erupted on the Earth's surface. Peripheral magma chamber is emptied whole or in part, rocks over it come down, forming a characteristic ring structure, the Caldera. Tradition eruption mechanisms, based on the idea of boiling "volatile" during the magma lifting, "retreats" in front of these grandiose disasters. We show that the GLI-mechanism in the presence of two or more layers of fluid below the magma chamber, easily and naturally explains the features of the formation of the caldera.

Consider one of the possible scenarios in the case of exogenous fluid (Figure 6). Assume that stratovolcano already formed due to the activation of the upper fluid layer at depth h_{f1}.

Volcano is "mature", the eruptions from the central crater are already rare, the mouth is clogged by lava "plug". Fluid layer is warmed up to the maximum temperature, and excess pressure in the magma chamber is only enough for the side breakouts. Meanwhile, at the relatively large depth the second, lower, fluid layer is warming. Its initial pressure is equal to the pressure of the magma column $\rho g(h_{f2}+h_v)$, but the supercritical temperatures can be obtained tens of thousands of years after the formation of a stratovolcano. If the volume of superheated fluid exceeds the critical value $\gamma(h_{f2}+h_v)\pi R_c^2$, one slight increase of pressure that release the mouth of a volcano could trigger an eruption. Its capacity will be determined by the difference in the depth levels of the fluid layer and the magma chamber, since the maximum excess pressure will be $\rho g(h_{f2}-h_m-h_v)$, and it will be supported the longer, the greater the volume of superheated fluid. Penetrating into the magma chamber and mixing with the melt which (due to the age of stratovolcano) could already be andesitic, the fluid throws out the magma in form of cubic kilometers of pumice and tuff. Thus, the deep-lying fluid layer warmed to the critical temperature is able to empty magma chamber of commensurate volume.

If the chamber is located right under the volcano and its dimensions are within the foothill, collapse can occur inside the volcano cone and Somme is forming. If the upper fluid layer is absent, the formation of the caldera can occur without the formation of a stratovolcano. The collapse of the roof of the magma chamber during the formation of the caldera does not preclude accumulation of new magma in the same place. Both fluid layer (Figure 6) after the disaster can be restored, and, therefore, a cycle with new caldera and new stratovolcano forming is possible.

Caldera may form in the case of endogenous fluid in the system with two magma chambers (Figure 4). For this it is necessary that "gas collar" in the lower chamber obtain a critical volume. Then, any expansion of the "collar" in the conduit, leading to the slightest collapse of the magma column, will trigger the eruption. The scale of this eruption will be determined by the ratio of the volume of superheat fluid in the lower chamber and the critical volume $\gamma S h_{m2}$.

3.4 Plinian

If the pressure and the volume of superheated fluid are so great that all magma in the conduit and magma chamber above the fluid layer is erupted, Fluid get freedom and pass into the atmosphere. He brings everything possible to break from the conduit walls: shreds of fresh magma, fragments of older rocks, ash. The velocity of the heated stream may be supersonic, and the temperature up to 1000 C. From this scorching cloud a "rain of fire" falls on the ground turning into a kind of sintered rock, ignimbrite. The collapsed roof of the devastated magma chamber can squeeze through the mouth of crater the remains of viscous lava in the form of an obelisk as happened at the famous eruption of Mont Pele in 1902.

3.5 Hawaiian.

The GLI-mechanism allows to interpret the eruption of Hawaiian volcanoes located on the islands above “hot spots” (Figure 7). Exogenous fluid in this case may be located in the bottom sediments saturated with water and overlapped by basaltic layers in process of forming of oceanic crust. Magma chamber warms up a nearby sedimentary layer which becomes a source of Superheated fluid.

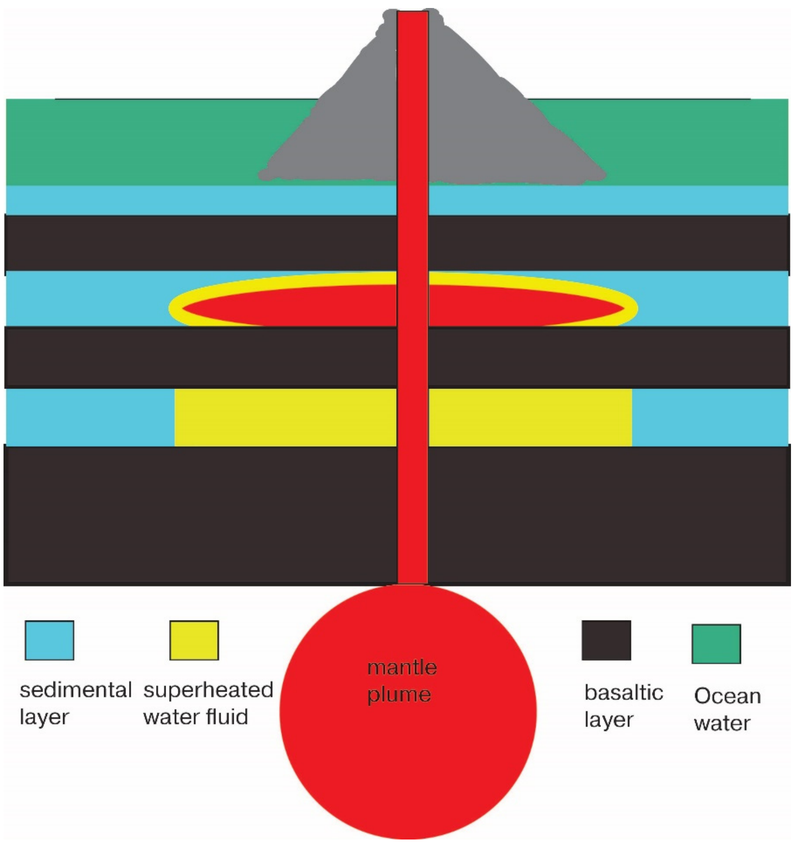

Figure 7. Assumed magmatic system of the volcano of Hawaiian type

Since the distance between the chamber and fluid layer is rather small, the overpressure reaches relatively low values what is conformable with the height of the basaltic lava fountains (hundreds of feet).

3.6 Areal

This type of volcanic eruption leads to the formation of one or more cinder cones of the same type, occupying a certain area (Figure 8).

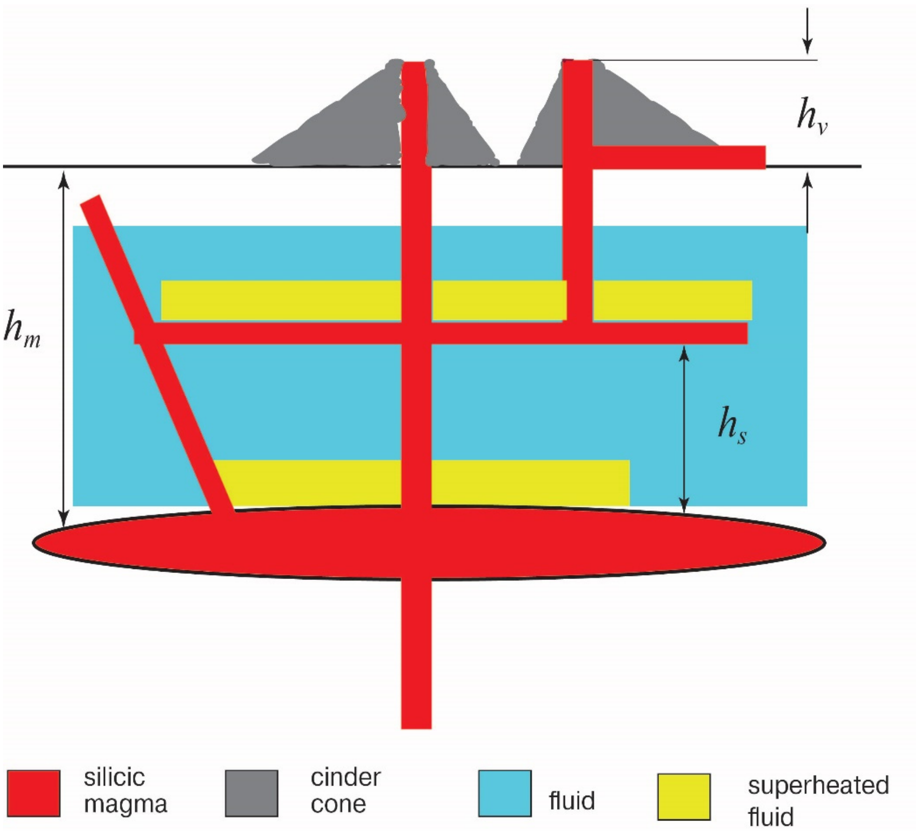

Figure 8. Assumed magmatic system at areal eruption. Active zone is formed by the "grid" of dikes and sills.

These "single use" cones, so-called monogenetic, never grows a real volcano. Their height is usually not more than 500 m. Eruptions through the same cone is not repeated. It can be assumed that the mechanism of areal eruptions is associated with the interaction of a shallow magma chamber and fluid layer located above the chamber on a slight distance from it. Formation of this layer can be closely linked to groundwater discharge zone. It is known that geophysical surveys of the Big Tolbachik Fissure Eruption 1975-76 (Large Tolbachik, 1984) gave the base for the assumption of the existence of extensivly flooded underground area whose lower level, according to seismic sounding, coincides with the upper level of the extended magma chamber at a depth of 2 km (V. Yermakov & A. Yermakov, 2006). There is also a reasonable geological hypothesis (Erlund et al., 2009) that the underground area of the monogenetic volcano Parícutin (1943-1952), similarly to Tolbachik volcanoes, was entirely formed by dikes and sills connecting the peripheral magma chamber. In the case of the above-mentioned Tolbachik eruption the water-saturated layer, possibly, was penetrated by dykes and sills forming a kind of "grid" (Figure 8), in which the cells of the superheated fluid formed area with volume exceeding critical one for some dikes that is connected to the surface. The height of the first cone was 300m which should not exceed the size of the "cell" (this may be the distance between sills), and after its formation the eruption has moved to a new fracture. The height of the second cone was less (200m), as fluid, apparently, has begun to expand in the corresponding sill and the pressure therein has fallen. The third cone was even less, but fluid pressure was still enough for the gushing lava and pyroclastic material. Eruption of the fourth cone (Southern Breakthrough) has already been effusive since the overpressure in the conduit decreased as a result of expansion of the fluid into the system of dikes and sills and could provide only laminar outflow of lava. The principal difference between areal, monogenetic, eruption and the eruption, forming a stratovolcano, is likely that the supply of magma through dikes and sills is not renewed after the eruption and the fluid can’t be restored too. The appearance of zones of the areal volcanism near stratovolcanoes (Flat Tolbachik and Krasheninnikov volcano in Kamchatka) may mean that the excess pressure in the main magma chamber of a volcano is not enough to raise magma to the crater. But it is enough to form an extended sill-chamber outside the volcanic edifice at a relatively shallow depth. This sill "gropes" a fluid-saturated region and heats it up to supercritical temperatures using dikes and sills. Then warmed area contacts the dike, and the moment when magma finds a way to the surface, GLI- mechanism runs and the eruption begins which will continue as long as the fluid conserves the resource of its overpressure.

3.6 High-Explosive

This type of eruption is typical for old volcanos completed the step of stratovolcano formation. It is known that mainly acidic rock is erupted as a result of explosive eruptions, i.e. magmatic substance contains a high percentage of silica, which makes it more viscous than the magma of young basalt volcanoes. The presence of dissolved fluid in the silicic magma and its moving upward is inevitable as in basaltic magma, but the mobility of the "volatile" should be considerably lower. In any case, fluid bubbles formed in the melt at a certain depth, will rise up together or independently with magma (their density is always less than the density of the magma) and are wearing their high pressure. Consider the magmatic system with two chamber, one of which has an andesitic magma, which has the ability to freeze rising to the surface, so a solid plug do form in the crater of the volcano between the eruptions (Figure 9). Let's apply to this case the same approach that gave the result in the previous section for an explanation of the eruptive cycle of Mount Etna. Suppose that in the lower chamber the excess fluid pressure in the gas "collar" is retained and it push the magma to the surface in the form of andesite dome.

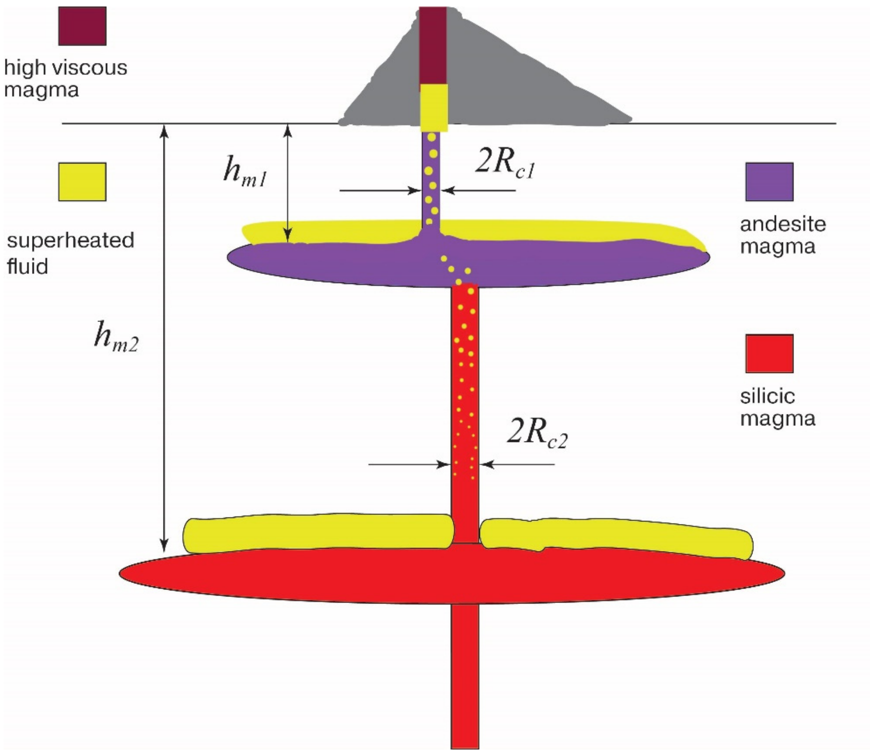

Figure 9. Assumed magmatic system with high-explosive eruption

Reducing the amount of magma in the lower chamber is accompanied by a corresponding expansion of the fluid "collar", but until its volume has not reached the critical value (Figure 9), the system is in stable equilibrium. Upward movement of magma releases a certain part of the fluid, which can rise on fractures and come out into the atmosphere in the form of fumaroles on the growing dome. Another part of the fluid can accumulate under the roof of the upper chamber if it exists. This fluid, gaining critical volume and squeezing "plug" in the conduit, can cause explosions with a relatively short period of repetition. But the real disaster is imminent when the Fluid "collar" of lower chamber gets its critical volume. Magmatic column will be squeezed out, and this process can be accelerated, as the column pressure is reduced and the fluid pressure remains practically unchanged. Since the upper part of the conduit is filled with extra-viscous magma its motion velocity will be very small, but it must grow, and it can serve as a precursor to an eruption (remember that before the explosion of Mount St. Helens in

1980, the growth rate of its dome markedly increased (Carson, 2015)). Thus, the "gas piston" that retains high pressure moves slowly up to the edifice of the volcano. The catastrophe occurs when the fluid pressure exceeds the pressure of the overlying rocks and the strength of their grip. The appearance of the slightest through crack lead to an explosion as the enormous pressure drop equal $(\rho g h_f - p_0)$ applied to the air gap will cause a shock wave.

4. Concluding Remarks

1). A volcanic eruption may be generated by the fundamental Imbalance (GLI-mechanism) between magma and gaseous fluid accumulated within the magmatic system and having contact with magma conduit. Uncontrolled eruption of magma evolves if the volume of fluid exceeds a certain critical value. The nature of the eruption (effusive or eruptive) depends on the amount of fluid, the depth of the magma chamber and magma viscosity.

2). To form a stratovolcano one magma chamber connected with a mantle and the Earth's surface is enough if its volume is greater than the critical one. Overpressure, providing magma rise to the surface, is created by fluid dissolved in the deep magma and passing into the gas phase during the formation of magma chamber. The presence of two or more magma chambers (at different levels) accelerates the formation of a stratovolcano and creates conditions for the caldera-forming eruptions.

3). Formation of calderas in the absence of a stratovolcano (Yellowstone, Toba) can be explained by GLI-mechanism interaction of two large magma chambers formed at different depths. Fluid accumulated under the arch of the lower chamber creates excessive pressure for a further rise of magma and the formation of the upper chamber. When the volume of this fluid exceeds the critical value (1) the main necessary condition for the eruption is implemented and it begins when magma finds a way to the surface. The time required to accumulate the critical volume (the interval between eruptions) the greater the higher the viscosity of magma in the lower chamber since it determines the rate of rising of fluid bubbles and its accumulation under the arch of the chamber. We note the recent work (Huang et al., 2015) in which strong evidence of the existence of a two Yellowstone magma reservoirs was demonstrated: the upper (volume of 10,000 km3) at a depth of 10 km and lower (volume of 45,000 km3) at a depth of 50 km. The amount of carbon dioxide daily released into Yellowstone system is more than 45 000 tons. It apparently is produced when magma rises to the upper chamber. Some part of its volume accumulated in traps under the arches of the lower chamber can reach a critical value which according to (1) is proportional to the product of the depth of lower chamber location at average cross section of dike (or system of dikes), connecting the upper and lower chambers.

4). GLI- mechanism can explain the formation of monogenetic volcanoes (cinder cones) by the interaction of magma chamber and exogenous fluid layer. These layers may consist of underground water flows or flooded areas that are heated by magma system (dikes and sills) to supercritical temperatures. During this eruption the fluid as well as magma in supplying conduits are expended completely, the likelihood of its recovery is small as well as the repetition of this type of eruptions.

5). Plinian type of eruption, in terms of GLI-mechanism, requires a significant excess of fluid volume over a critical one. In this case, the expansion of the fluid in the magma chamber does not lead to the fluid pressure decreasing and does not stop the eruption: it can go "to the end" until the chamber will be devastated and the fluid comes into the atmosphere in the form of scorching clouds.

6). In the case of highly explosive eruptions the lava dome formation occurs due to viscous magma squeezing under the excessive pressure of fluid accumulated in magma chamber. If the volume of the chamber exceeds a critical value (8), the gas "piston" with high pressure start to push magma to the top of the conduit in accordance with the GLI-mechanism. Once the strength of the surrounding rock will be less than the fluid pressure the destruction of the volcanic edifice begins followed by an explosion, whose power is determined by the depth of the corresponding magma chamber.

7). The popular CF and RSD-models of basaltic volcanic eruptions (Parfitt, 2004) probably represent the united chain with the above described GLI-mechanism: the formation of a big "bubble" from the gas foam in CF-model is a stage of the critical volume attainment, the collapse is the onset of instability and RSD-model with appropriate magma defragmentation joins GLI-mechanism at the time of dynamical motion and acceleration of the magma column.

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