An Estimation of Magmatic System Parameters From Eruptive Activity Dynamics

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Eruptive activity dynamics characterizes the changes in eruptive regime over time. Eruptive activity can be characterized by: the relation between eruptions and repose periods, the mass flow rate of eruption, the type and structure of the erupted products, and their velocity at the conduit exit. These characteristics and their evolution over time depend on both the structure of the magmatic system and on some external factors. These factors define the boundary conditions and include the eruptive prehistory. This study deals with the inverse problem: reconstruction of the structure of the magmatic system using the eruptive activity dynamics. The critical role of the sharp jump-like changes in eruption regime and intensity described theoretically in [*Slezin*, 1983, 1984, 1998, 2003a] is emphasized and the additional information needed to obtain a unique solution is discussed. Using this inverse approach in conjunction with a "chamber-conduit" model, some geometrical parameters of the following magma systems were estimated: Shiveluch, Mt St Helens, and Bezymianny.

1. GENERAL CHARACTERISTICS OF THE MAGMATIC SYSTEM OF AN ERUPTING VOLCANO.

1.1. The Substance

1.1.1. Magma. Magma is a silicate melt in the depth of the Earth, which contains dissolved volatile components (mostly water). When the ambient pressure is reduced or crystallization occurs, volatiles are exsolved. Magma almost always has some crystal content, which is usually not taken into account *directly* in the description of magma flow, although some models consider crystal content as a factor influencing magma rheology [Papale, 1999; Melnik and Sparks, 2005]. Magma is assumed to be in a liquid state with a given density and viscosity and, in certain cases, with a given yield stress. During an eruption, magma loses its volatiles and is transformed into volcanic products, which appear on the surface.

1.1.2. Volcanic products. The eruptive products result from the magma separation into volatile and nonvolatile components: i.e. a gas and a condensed phase. The latter can be lava or pyroclastics. The type and structure of the volcanic products depends on the composition of the initial magma as well as on the eruption dynamics. Lava is a viscous liquid; pyroclasts are the magma fragments dispersed in gas flow and usually described as solid particles. The transformation of magma into volcanic products occur during eruption in a volcanic conduit, where melt with bubbles and gas-pyroclastic mixture can flow.

1.2. The Magma System Geometry

The mass flow rate of erupting volcanic products averaged over a time interval, which includes several successive eruptions of a volcano treated as "events", is nearly constant [Kovalev, 1971; Tokarev, 1977]. This fact and the observed proportionality between a single erupted mass of magma to the duration of the repose interval, preceding that eruption [Tokarev, 1977; Simkin, T., Siebert, L., 1984], implies the

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existence of some holding capacity, where the magma is stored during the repose intervals [Kovalev, 1971; Kovalev and Slezin, 1974]. This capacity is often referred to as a peripheral magma chamber, which is fed from deeper parts of the magma system. The existence of the peripheral magma chambers under volcanoes (later referred as "magma chambers") has been demonstrated by geological and geophysical studies [Luchitsky, 1971; Farberov, 1974].

Because of the high intensity of eruptions and the short duration of them with respect to the duration of the repose intervals one can assume, as a first order model of an erupting volcano, a "chamber-conduit" system being isolated in all directions except the conduit exit to atmosphere. More complicated models can include a magma chamber feeding from the depth during an eruption and some heat and mass (volatile components mostly) exchange with the external medium.

1.2.1. Magma chamber. This is an approximately isometric capacity filled with magma on the order of a few to thousands of cubic kilometers. In models, the magma chamber is usually described as a vertical cylinder which height is less than the diameter. The upper boundary of a magma chamber is situated at a depth varying from a few kilometers to a few tens of kilometers from the Earth surface.

1.2.2. Volcanic conduit. In the solid crust the conduit appears initially as a fissure, which later can transform to a cylinder. Such a transformation proceeds very rapidly near the surface at the conditions of a very intense gas-pyroclastic flow. The cross-sectional area, as well as the volume of a conduit, is significantly less than those of a chamber. In existing models a vertical conduit with a constant cross-sectional area is usually assumed.

2. THE DYNAMICS OF THE ERUPTIVE ACTIVITY OF A VOLCANO: GENERAL CHARACTERISTICS

The principal feature of the eruptive activity of a volcano is its intermittence, which usually includes overlapped periods of approximate periodicity. The main rhythm is alternation of the eruptions-events and repose intervals. The larger periods are called cycles of activity, every one of which includes several eruptions with regularly varying characteristics. Every individual eruption is a non-uniform process with regularly changing successive stages including paroxysms and pauses. There is no objective true criterion to distinguish a repose interval between eruptions from a pause in an eruption. Kovalev et al. [1971] proposed to define eruption as a process, not as an event.

In the course of every cycle of activity, and often during every individual eruption, not only variation of the magma mass flow rate is observed, but also variation of the eruption regime. Sometimes very large and sharp changes in the type and velocity of the erupting volcanic products are related to a large and sharp change of the magma mass flow rate. These sharp changes from one steady (quasi-steady) regime to another may provide us with important information about the structure of the magma system.

2.1. The Principal Eruption Regimes and the Types of Volcanic Products

The regime of a volcanic eruption depends on the continuous phase (gas, magma) in the eruption flow at the exit of the conduit.

The volatile component of magma as a rule is composed of at least 95% water [Fedotov (ed.), 1984; Yirabayashi et al., 1984; Menyailov et al., 1985, 1988]. In mechanical models of magma flow, the volatile component is usually treated as 100% water. The exsolved gas phase appears in the form of bubbles. Initial dissolved mass fraction and solubility of water in magma are of such values that at the atmospheric pressure at the conduit exit, the volume flow rate of gas is tens or hundreds times that of the condensed phase. The volume relation between phases in the flow depends on the relative velocities. Consequently, the condensed phase can keep its continuity only if its velocity at the conduit exit is much less than that of the gas phase.

Extensive escape of gas from magma can be provided by two mechanisms: 1) fast uplift of bubbles through the liquid and 2) continuous leakage of gas through a system of channels in condensed phase. This results in three basic regimes of eruption and three corresponding types of volcanic products: 1) effusive regime: there is a bubbly flow in the conduit; the excessive amount of gas escapes with floating bubbles; the eruption produces lava flows; 2) extrusive regime: the excessive amount of gas escapes through the permeable system of interconnected bubbles; the eruption of a very viscous lava forms an extrusive dome; 3) explosive regime: the eruption of the gas-pyroclastic flow, in which gas is a continuous phase and pyroclastics is the dispersed phase. The conditions of realization of any of these regimes were found by the author [Slezin, 1979, 1995b, 2003a].

2.2. The Types of Eruptions and the Evolution of the Flow Structure in a Volcanic Conduit

An eruption-event usually includes several successive regimes. The most complete succession of regimes is demonstrated by so called "catastrophic explosive eruptions" (CEE). The most thoroughly investigated eruption of that type is the eruption of Mount St. Helens in 1980 [Lipman and Mullineaux, 1981]. In this case a moderate “intrusive-explosive” regime changed to a gas-pyroclastic flow of high intensity (catastrophic phase), then to the extrusive regime of low intensity. There was a repose interval between catastrophic and extrusive phases. All the regime changes were very sharp.

During a gas-pyroclastic eruption, all types of the flow take place in the conduit: homogeneous liquid, bubbly liquid, partly destroyed foam and gas-pyroclastic mixture, which is observed at the surface. In the starting and finishing stages of an eruption of this type a steady flow of the gas-pyroclastic mixture is absent in the conduit, and bubbly liquid or partly destroyed foam [*Slezin*, 1980, 1995b, 2003a] is instead erupted. In the final stage an extrusive regime (eruption of partly destroyed foam) takes place [*Slezin*, 1995a].

2.3. Theoretical Basis

2.3.1. Eruption. The sharp transitions from a moderate stage of an eruption to a catastrophic and vice versa are results of a smooth change of the governing parameters of the magma system [*Slezin,* 1984, 1991, 2003a]. They also can be initiated by external factors (such as landslides) if these external factors change the governing parameters in a due direction.

The basic features of the magma system outlined above allow us, as a first approximation, to reduce the problem of eruption dynamics to the description of the quasi-steady flow of degassing magma in a vertical conduit with nearly constant (slowly varying) geometry under a given (slowly varying) pressure difference between conduit ends. The behavior of such flow, including jump-like changes of regimes, is described using equations of hydrodynamics for a steady-state two-phase two-component flow with relevant boundary conditions for the conduit ends and for the boundaries between zones [*Slezin*, 1983, 1998, 2003a].

The recent development of numerical models allowed taking into account additional parameters such as time dependence, variation of magma rheology, heat and mass transfer through the chamber and conduit walls, viscous dissipation, variation of magma properties in two spatial dimensions and in time [e.g. *Papale*, 1999; *Melnik* and *Sparks*, 2005; *Vedeneeva* et al.,2005]. These models provide more accurate solutions for specific aspects of an eruption, and are in a good agreement with the results of this study.

For the analysis of effects the following three basic governing parameters were selected: 1) depth of the magma chamber (length of the conduit), H; 2) excess pressure in the magma chamber, p_{ex}, (equal to total pressure minus static pressure of overlying conduit magma column without bubbles); 3) “conductivity parameter of the conduit” $\sigma = b^2/\eta$, where b is a characteristic cross sectional dimension of the conduit, and η is viscosity. It has been demonstrated, that the dependence of the flow rate on any pair of basic governing parameters has a “cusp singularity” and in a certain area every point in a plane of the arguments has three images on the folded plane of the function. This is a standard "catastrophe" of two-parameter sets of functions [*Poston* and *Stewart*, 1980] (Figure), which describes jumps of a function under smooth changes of the arguments.

This explains abrupt changes in eruption regime: the transition from moderate to catastrophic explosive regime is a result of the conductivity parameter increase (Figure) or the conduit length decrease (e.g. due to a volcano summit destruction by explosions or landslide). Conversely, the transition from catastrophic to extrusive regime is a result of decreasing excess chamber pressure and/or conduit

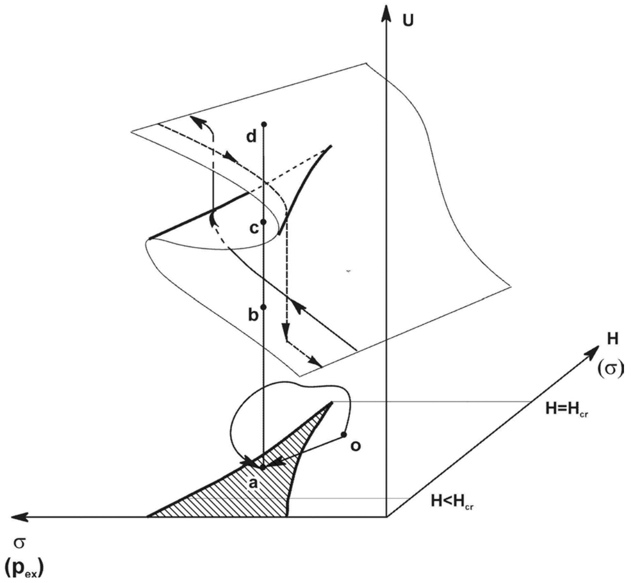

Figure. Magma ascent velocity U as a function of conduit conductivity parameter σ and conduit length H. Note that analytical solution for U as a function of excess pressure in the magma chamber p_{ex} and σ has the same form. Vertical scale is logarithmic. The hatched cusp on the plane of arguments encompasses parameters σ, H, and p_{ex} at which the “catastrophe” scenario is possible. For example, at point a the magma ascent velocity can be b, c, and d corresponding to three eruption regimes with different magma flow rates. The jump-like changes of the magma ascent velocity can be caused by increase of conduit conductivity or by decrease of the excess pressure in magma chamber (indicated by arrows). The straight trajectory leading from point o to point a on the plane of arguments intersects the cusp boundary and leads the function to the catastrophe scenario, whereas the trajectory going from o to a around the cusp leads the function to the point d without any sharp changes of magma velocity. The later case is rather exotic, as it requires a gradual change of H or c_0. Please refer to the text for discussion.

conductivity. The flow velocity jump can be seen as the result of the positive feedback when positive effect of the decrease of the liquid flow region length and average flow density in the conduit prevails over the negative effect of the viscous friction increase. This may become possible due to a several orders of magnitude difference of friction coefficients between zones of liquid and gaseous flow in case when the conduit length is not very large.

2.3.2. An approach to the inverse problem. It appeared that sharp jump-like changes of the eruptive regime could be realized only in a narrow range of parameters of a volcanic system, which is helpful for solving the inverse problem. The very fact of the sharp change of regime applies strict limits on the values of the parameters. The additional quantities such as magma mass flow rate values before and after the jump, duration of the certain stages of eruption, flow velocity, total mass erupted during a certain stage of eruption, and the magma properties, obtained by studying of the erupted volcanic products, give information, which in nearly all cases, is sufficient to allow full reconstruction of the magma chamber and conduit parameters.

Because the system of hydrodynamic equations for the two-component two-phased flow can be solved only by numerical methods, in practice a series of direct problems were solved and the proper structure of the magma system boundary conditions and prehistory chosen.

3. ESTIMATING OF THE PARAMETERS AND EXAMPLES

3.1. Magma Chamber Parameters

3.1.1. The depth of the upper boundary (conduit length). In the most cases after a repose period, a new eruption is started by breaking a new conduit in the shape of a fissure in the solid rocks overlying the chamber, or in a plug sealing up the upper part of the conduit after a previous eruption. The normal evolution of eruption after such a start is connected with widening of the new conduit (destruction of the plug) by the flow. Sometimes this process is very sharp and catastrophic. An increase in magma mass flow rate as well as magma velocity, leads to the transformation from an effusive or extrusive regime to a gas-pyroclastic regime with mass flow rate increase by two or more orders of magnitude [*Slezin,* 1984, 1998, 2003a]. At the end of eruption the reverse sharp transformation with a corresponding mass flow rate decrease (usually with a bigger amplitude than at the start) is probable [*Slezin*, 1991*,* 2003a].

It was found that the sharp jump-like increase of magma mass rate can take place only if the magma chamber depth (conduit length) is less than some critical value H_{cr}, which depends at a first approximation on the initial content of the water dissolved in magma c_0 only [*Slezin*, 1994]. In the cited paper the empirical formula for the H_{cr} is given:

$$H_{cr} = 356(c_0 - 0.01), \tag{1}$$

where H is in km and c_0 is a wt. fraction.

One can conclude that if the jump-like transition took place the water content must be not less than 0.01 and that if the water content is known the chamber depth must be less than it is given by expression (1). One can estimate the low limit of the possible water content in magma if the magma chamber depth is known.

Additional data allow a more accurate estimation of magma chamber depth. If a magma chamber depth is large enough that the fragmentation level has not reached it, only the conduit is effectively evacuated and the loss of magma is not very large. As a result, the time interval between the end of the gas-pyroclastic stage and the beginning of the extrusive stage must be small. The closer a chamber is located to the surface, the deeper its relative evacuation and the longer the time interval between catastrophic and extrusive stages. This dependence is confirmed qualitatively by observations of the eruptions of Bezymyanny in 1956 (magma chamber depth is 12 km and the interval no more than a few days) and Mt. St. Helens in 1980 (magma chamber depth is 7.2 km and the interval 3 weeks) [Lipman and Mullineaux, 1981; Rutherford et al, 1985]. After the catastrophic eruption of Shiveluch in 1964 the repose interval before the start of the extrusive stage was 16 years, and the author suggested that magma chamber depth must be less than that of the Mount St. Helens (i.e. less than 7 km) [*Slezin*, 1995a]. Recently the depth was estimated to be between 5 and 6 km based on the pressure at which melt inclusions in phenocrysts of the erupted products were entrapped [*Dirksen et al.,* 2006].

3.1.2. Magma chamber diameter. Estimation of the horizontal dimensions of a magma chamber is possible for shallow chambers which are deeply evacuated during a large catastrophic eruption. In this case the evacuated volume of the conduit as a first approximation can be neglected relative to the chamber evacuated volume, and all the magma erupted can be assumed to have been transported from the chamber.

The degree of magma chamber evacuation ("magma drawdown" Δ [*Spera* and *Crisp*, 1981]) can be calculated using formulas given in [*Slezin*, 1987] if the volume fraction of a gas phase near the upper boundary of the magma chamber at the end of a catastrophic stage of eruption is known. This fraction can be calculated by the method of [*Slezin*, 1998, 2003a] if the magma chamber depth and the dissolved water content are known.

Magma chamber evacuation is a result of magma foaming and can proceed up until the start of foam destruction in the magma chamber (i.e. the fragmentation level enters the magma chamber), which causes stopping of the eruption of condensed material. A large negative value of the p_{ex} causes conduit wall and chamber ceiling destruction that may lead to conduit blocking. The beginning of disruption of the silicate foam in the chamber is taken as a condition of the catastrophic stage ceasing. This process starts approximately when the volume fraction of bubbles corresponds to the state of tight packing, and this last was taken as a formal condition in the model.

If the magma chamber depth and the dissolved water content are found independently, magma drawdown Δ can be calculated. The horizontal cross-sectional area of a cylindrical magma chamber can then be calculated by dividing the total volume of the erupted products reduced to the magma density in the chamber by the value of Δ. Using this method, this area was found by the author for the volcano Shiveluch [*Slezin,* 2005] to be little more than 0.5 km^2. For the volcano Mt. St. Helens, for which the chamber cross sectional area was known, the value of the coefficient *a* in the water solubility law in magma $c = ap^{1/2}$ was estimated [*Slezin*, 1987]. It appeared to be close to the value obtained using experimental data for the appropriate magma composition.

3.1.3. Vertical dimension. In some cases the vertical dimension of a magma chamber can also be estimated. For the shallow chamber, where the fragmentation level reached upper boundary of it, the value Δ can be calculated using formulas given in [*Slezin*, 1987, 2003a] if the dissolved water content of the magma is known and the lower boundary of the magma chamber is deeper than the level where bubble nucleation starts. The value of Δ in this case is about 3 km assuming an initial dissolved water content of about 5%. The value of Δ can also be calculated by dividing the total erupted volume reduced to the dense magma by the cross-sectional area of the chamber if this is known. The value of Δ was calculated using this last method for the 76 caldera-forming eruptions in [*Spera* and *Crisp*, 1981] and in most cases it was significantly less than the maximum (~3 km). This fact can be explained by the assumption that the lower boundary of the magma chamber is above the level of bubble nucleation. In this case Δ can be calculated by the same formulas from [*Slezin*, 1987, 2003a] substituting the vertical chamber dimension h_1 instead of the level of the bubble nucleation start z_1. The value h_1 is found iteratively provided that the calculated Δ is equal to Δ obtained from field data.

All of the calculations described above must be treated as estimates because the accuracy of data used is not quite high. For example, one of the main sources of uncertainty for the chamber evacuation model is the value of the coefficient *a* in the expression for water solubility. The result is very sensitive to this value, which is found experimentally for melts of similar, but not exactly the same composition, and under similar, but not exactly the same conditions.

3.2. Conduit Parameters

A volcanic conduit is characterized by its length, area and shape of cross-section. The first parameter was discussed in the previous section, whereas the last one is closely related to the conductivity parameter σ described in the first section:

$$\sigma = b^2/\eta \qquad (2)$$

Magma mass flow rate, which can be measured on every stage of an eruption, is proportional to the product of the conduit cross-sectional area, magma density and magma velocity. The total resistance of a volcanic conduit approximately equal to the resistance of the liquid flow zone. Magma velocity in the liquid flow zone is proportional to the product of the driving pressure difference and conductivity parameter. Conductivity parameter σ and magma velocity can be found by numerical calculations for the conditions of jump-like change of regime and the conditions before and after the jump. If the magma mass flow rate is known then the conduit cross-sectional area can be calculated. If the magma viscosity is known independently (using experimental data for melts of similar composition at similar thermodynamic conditions) the characteristic dimension b can be found and also the shape of the cross section and parameters of the fissure if the shape is fissure-like. If the viscosity varies along the conduit average value should be used.

Using this method the radius of the cylindrical conduit for the 1964 eruption of Shiveluch was estimated to be approximately 70 m. In this case the cylindrical shape of the conduit cross section corresponding to catastrophic stage was postulated as an independent assumption [*Slezin*, 2005].

For Mt. St. Helens with a deeper situated magma chamber and a less intensive eruption the magma velocity was estimated at $U \sim 0.5$ m/s and the conductivity parameter $\sigma \sim 10^{-4}$ $m^2\ Pa^{-1}\ s^{-1}$ [*Slezin*, 2003b]. Knowing the erupting magma volume rate reduced to dense magma (~8000 m^3/s [Lipman and Mullineaux, 1981]) the cross-sectional area can be found ($S = 16000\ m^2$) and the cross-sectional dimension b, or viscosity η for a given shape. If the cross section has a circular shape, the viscosity must be ~10^9 Pa s. At the same time the viscosity of a melt with the composition of Mt. St. Helens magma at the pressure and temperature corresponding to magma fragmentation in accordance to experimental data of [*Williams* and *McBirney*, 1979] must be about 10^6 Pa s. Taking this latter value and using formula (2) b is estimated to be approximately 10 m. So below the fragmentation level the conduit cross-section supposed to be a fissure with a width of 10 m and about 1600 m in length.

3.3. Other Characteristics of a Magma System

"Chamber-conduit" is the first approximation in volcanic magma system modeling. Peripheral chambers are fed from deeper situated magma-generating zones through some feeding channels. The last ones can include intermediate chambers and conduits. The deep part of a magma system also affects eruption dynamics, and some features of the latter bear some information about the former. Heat and mass transfer in the depth are much more inertial processes than at shallower depths. Consequently, the dynamic effects related to the deeper parts of the magma system must be connected with the longer time intervals. They may be connected with cycles of volcanic activity including several eruptions and repose periods and with the evolution of volcanic groups or volcanic centers composed of several individual volcanoes.

Little was made in this field for the time being. Only a constant flow or episodic impulses from the depth were taken into account as external affects, and cycles of activity were described only as a probable result of a deep zone dynamics (for example: [*Kovalev et al*., 1971; *Slezin*, 2005]). Recently the dynamics of extrusive eruptions were analyzed quantitatively in [*Melnik* and *Sparks*, 2005] with the help of a transient model, which incorporated many characteristics including the constant feeding of the chamber from depth, volatile diffusion in melt and decompression-induced crystallization. Such transient models should be very useful for solving the inverse problem.

4. CONCLUSION

It can be concluded that in most cases for volcanoes which erupt "in full cycle" including catastrophic explosive stage the geometrical structure of the upper part of magma system can be reconstructed with satisfactory accuracy using a very simple model. The model describes a "chamber-conduit" system, which geometrical parameters can be found for any individual volcano. The approach relies on using the conditions for eruption stability and sharp changes between main eruptive regimes. Quantitative results can be obtained using rather simple model and approximate data.

Catastrophic explosive eruptions and caldera-forming eruptions are common for andesitic volcanoes in subduction zones. The outlined approach can be used to reconstruct the structure of magma systems beneath volcanoes of Pacific subduction zones, particularly the Kurile-Kamchatka and Aleutian island arcs. The magma system structure must depend on the magma generation process, which, in its turn, depends on the local tectonic setting and on specific features of the local subduction process. Hence the studying and modeling of the volcanic activity dynamics and reconstruction of the magma systems structure of the volcanoes along Pacific Fire Ring may throw light on the total geodynamic situation and on specific features of the subduction process and magma generation in different parts of this global structure. In the North-West part of the Pacific Ring of Fire it would be interesting to compare Aleutian and Kurile-Kamchatka island arcs. It will be especially interesting to examine the specific tectonic features and magma generation process found at the junction of these Island Arcs, where the Shiveluch volcano and the Kliuchevskaya volcanic group are located.

Advanced numerical models, which appeared in recent time, take into account some additional factors such as variation of magma rheology, heat and mass transfer through the chamber and conduit walls, viscous dissipation, variation of magma properties in two spatial dimensions and in time [Papale, 1999; *Melnik* and *Sparks*, 2005; Vedeneeva et al., 2005]. These models combined with the described approach will likely yield more accurate quantitative results.

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