

Analysis of Magma Injection Beneath an Active Volcano Using a Hydromechanical Numerical Model

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ABSTRACT

A numerical model was used for a geomechanical analysis of dike formation beneath the Koryaksky Volcano, which was active during 2008 through 2009. We investigated whether seismicity associated with the volcanic activity may have been influenced by flow of magma into preexisting fault structures. In our conceptual model, magma flowed into a 2 km (along dip) by 2 km (along strike) fracture located at a depth of 6000 m (-3000 m abs.) with a dip angle of 60°. In the model, magma was injected into the fracture over the period of one day at a rate of 2000 kg/s and a maximum pressure of 200 MPa. The initial fluid pressure in the fault was 50 MPa. The magma density was 2800 kg/m³. We tested various magma viscosities ranging from 200 Pa s (andesitic magma) to 2 Pa s (basaltic magma). The state of stress in the study area was determined in a previous study.

The numerical model was used to calculate distributions of fluid pressure distribution, normal stress, fracture opening, shear displacement, and sliding velocity in the fracture. The behavior was characterized by fluid pressure of 60 to 65 MPa (overpressure of 10 to 15 MPa) within a 500 m radius of the location of magma injection. We observed opening displacements of 0.02 m in the periphery to 0.3 m at center. The volume of dyke formed by magma injection corresponded to magma flow rate and was 60.8 x 10³ m³. As magma injection occurred into the fracture, a reduction in the effective normal stress caused the fracture to slip. Slip occurred in a normal faulting mechanism. The cumulative shear slip discontinuity was roughly 1 m near the fracture periphery and roughly 3 m near the location where magma injection occurred. The maximum velocities of shear displacement of the fracture walls was observed to be 2 x 10⁻³ m/s (for the case with reduced viscosity basaltic magma), which corresponds to the hypocentral zones of plane-oriented earthquake clusters.

1. INTRODUCTION

In this work, we treat the emplacement of magma in a fractured medium beneath the active volcanoes by analogy to the injection of fluids into wells with subsequent hydraulic fracturing and fractures generation in the host formations. This is to some extent based on V.V. Ivanov's ideas (Ivanov, 2015) on the origin of microseismicity during magma emplacements and Gudmundsson (2015) review of the magma injection processes in active volcanic areas. This approach to the problem is also motivated by the observations reported by Sigmundsson et al. (2015), who described the injection of magma from the magma chamber beneath the Bárðarbunga central-type volcano, Iceland, which occurred in August 2014 and was accompanied by a dike that propagated for a distance of 50 km. This dyke system with a volume of 0.6 km³ was created during 22 days, it was segmented into 11 plane-oriented earthquake clusters zones (the number of earthquakes in each cluster is from 57 to 1181 with magnitudes of some earthquakes exceeding 5).

We used local seismicity data from KB GS RAS (Kamchatka Branch Geophysical Survey Russia Academy of Sciences) during the 2008–2009 burst of activity in the Koryaksky Volcano in Kamchatka to define hydromechanical conceptual model of magma injection beneath the volcano. A previous analysis of the seismic activity at the Koryaksky Volcano (Fig. 1) revealed the following geomechanical features (Kiryukhin et al., 2016): 1. The 2008–2009 summit steam–gas eruption of Koryaksky Volcano was accompanied by 153 plane-oriented earthquake clusters that are interpreted here as zones where dikes and sills were emplaced during magma injection; 2. The precursory period of this eruption began with magma filling the crustal chamber (the top is at an absolute depth of -3 km and the chamber is 2.5 km across) near the southwestern base of Koryaksky Volcano (July 2008 to January 2009); 3. Magma was injected into a nearly north–south zone (7.5 by 2.5 km, the main range of absolute depths was between -2 and -5 km) in the northern sector of Koryaksky Volcano simultaneously with the most intense period of the summit steam–gas eruption (February 2009 to March 2010). The magma injection at a magma pressure of 53 MPa (at a depth of 6 km) (this value was derived from Mohr diagram analysis (Kiryukhin et al, 2016, p. 287)) was accompanied predominantly by north-east striking dykes with dip angles larger than 50° (Fig. 2).

The seismological observations were used to constrain our conceptual model of the hydromechanical processes that may have occurred at depth beneath the volcano. We assumed a simplified model geometry consisting of a single preexisting fracture to host the dike, and performed our investigation using the CFRAC numerical modeling framework (McClure, 2012; Norbeck, 2016). Based on the focal mechanisms of the seismicity, we assumed a normal faulting stress regime beneath Koryaksky Volcano (Fig. 3), such that the vertical

stress, S_v , is the maximum principal stress, the maximum horizontal stress, SH_{max} , is acting in a south-north direction, and the minimum horizontal stress, Sh_{min} , is acting in a west-east direction (Zoback, 2007).

Based on above, effective stress tensor below Koryaksky in a depth range from -5000 masl to 1000 masl is defined in a geographical coordinate system $X1, Y1, Z1$ ($X1$ – east direction, $Y1$ – north direction, $Z1$ – upward direction) in a following way:

$$S_g = \begin{pmatrix} Sh_{min} - Pf & 0 & 0 \\ 0 & SH_{max} - Pf & 0 \\ 0 & 0 & S_v - Pf \end{pmatrix} \quad (1)$$

- where Pf – is a fluid (magma) pressure.

At a depth of $z_0=6000$ m (≈ -3000 masl) S_v can be estimated as $S_v = \int_0^{z_0} \rho \cdot g \cdot dz = (2200 \cdot 9.81 \cdot 4000 + 2700 \cdot 9.81 \cdot 2000) = 139$ MPa (where ρ – rock density is assumed 2200 kg/m³ for the upper part of geological section (volcanogenic basin) and 2700 kg/m³ for volcano basement; $Sh_{min} = S_v/3.1 = 44.8$ MPa; SH_{max} was assumed to be roughly equal $(S_v + Sh_{min})/2 = 92$ MPa; $Pf = 45$ MPa.

2. HYDROMECHANICAL MODELING OF MAGMA INJECTION INTO AN INCLINED FRACTURE

2.1 Description of the Numerical Model of the Hydromechanical Processes During Fluid Injection into Fractures

The CFRAC model performs solution of the coupled system of hydromechanical equations for flow and deformation in discrete fracture networks (McClure, 2012, 2014; McClure and Horne, 2013; Norbeck et al., 2016; Norbeck, 2016). Fracture elements in a single two-dimensional fracture may open and slide, and stresses caused by those deformations are calculated using a boundary element method for quasistatic equilibrium conditions. The matrix rock surrounding the fractures was assumed to be impermeable, hence all fluid flow occurred in the fracture void space only. Radiation damping was used to approximate inertial effects during slip at high sliding velocity. Appropriate boundary conditions are applied to the open and sliding elements, and inequality constraints are applied to ensure that fracture walls cannot interpenetrate or slide backwards against the direction of shear stress. A static/dynamic description of fracture friction was used to simulate the earthquake nucleation, rupture, and arrest processes.

2.2 Conceptual Model and Input Data

We considered dyke injection in a fracture with a dip angle of 60° and that was 2 km (dip direction) by 2 km (strike direction) centered at a depth of 6000 m (or -3000 masl) beneath Koryaksky Volcano (see Fig. 3, size determined from the seismicity data). We assumed the following conditions: magma injection in the fracture took place within 1 day, the magma injection rate was 2000 kg/s, and the maximum injection pressure was 200 MPa. The magma density was 2800 kg/m³. We tested a range of magma viscosity between 200 Pa s (andesitic magma) and 2 Pa s (basaltic magma). The initial magma pressure was 45 MPa. See Table 1 listing the model parameters.

Table 1 Model parameters and their values. Note: Stresses are in geographical coordinate system at depth of -3000 masl.

Parameter	Value	Unit
S_v	139	MPa
SH_{max}	92	MPa
Sh_{min}	44.8	MPa
Shear modulus	15000	MPa
Poisson's ratio	0.25	
Stiffness constants	10	MPa
Magma viscosity	2 to 200	Pa s
Magma density	2800	kg/m ³
Initial magma pressure	45	MPa
Maximum injection pressure	200	MPa
Magma flowrate	2000	kg/s
Duration	1	day

Effective stress tensor S_f in a fracture plane coordinates ($X2$ – dip direction, $Y2$ – azimuth direction, $Z2$ – normal to fracture plane) was calculated (in units of MPa) from known effective stress tensor in a geographic coordinate system (1) using the following coordinate conversion matrix:

$$A = \begin{pmatrix} \cos(\beta) \cdot \cos(\alpha) & -\cos(\beta) \cdot \sin(\alpha) & -\sin(\beta) \\ \sin(\alpha) & \cos(\alpha) & 0 \\ \sin(\beta) \cdot \cos(\alpha) & -\sin(\beta) \cdot \sin(\alpha) & \cos(\beta) \end{pmatrix} \quad (2)$$

-where α is a strike azimuth, β is a dip angle. Accordingly:

$$S_f = A \cdot S_g \cdot A^T \quad (3)$$

- where A^T is a transposed matrix of A.

Thus Sf is defined:

$$Sf = \begin{pmatrix} 70.5 & 0 & -40.7 \\ 0 & 47.0 & 0 \\ -40.7 & 0 & 23.5 \end{pmatrix} \quad (4)$$

Hence, remote stresses were resolved onto the fracture surface for the geomechanical calculations, e.g. stress conditions in fracture related coordinate system in terms of CFRAC code are defined as: $sxx_bc = 70.5$ MPa, $sxx_z_trend = 18.0$ MPa/km, $syy_bc = 47$ MPa, $syy_z_trend = 14.3$ MPa/km, $sxy_bc = -40.7$ MPa, $sxy_z_trend = 0.0$ MPa/km, $szz_bc = 23.5$ MPa, $szz_z_trend = 10.6$ MPa/km (stress gradients calculated numerically based on Equation (1) using dX, dY, and dZ derivatives). The shear modulus of the rock was $G = 15000$ MPa, the Poisson's ratio of the rock was $\nu = 0.25$, stiffness constants $esnref$ and $Esnref$ (which influence the hydraulic properties of the fracture) were 10 MPa. In the model, it was necessary to specify the initial hydraulic and void apertures of the preexisting fracture (reference fracture aperture $E0 = 0.0005$ m, hydraulic reference fracture aperture $e0 = 0.00005$ m).

2.3 CFRAC Modeling Results (Andesitic Magma Viscosity)

Figures 4 through 5 show the following distributions of fracture properties one day after injection started: fluid pressure and normal effective stress distributions (Fig. 4), sliding vectors and the fracture sliding velocity, and fracture aperture distributions (Fig. 5). The internal part of the fracture (limited by radii of ≈ 500 m) is characterized by fluid pressure of 60 to 90 MPa (overpressure of 15 to 45 MPa), fracture opening from 0.02 m (in peripheral parts) to 0.3 m in central part. The effective normal stress was reduced to zero in this area. The volume of the created dyke corresponds to the rate of magma injection and was calculated to be 60.8×10^3 m³. The upper fracture wall is sliding down relative to the lower fracture wall (normal fault type). Figure 4 shows the cumulative displacement in the fracture plane. Up to 3 m of slip occurred in the central part (near the magma injection location), and up to 1 m of slip occurred at the periphery of the fracture. Shear displacement velocities in the upper part of the fracture was estimated to be 7.8×10^{-6} m/s (1 day after magma injection started), maximum shear displacement velocities achieved in the initial stage of fracture opening, thus by 570 s they reach 2.9×10^{-4} m/s. Fig. 5 shows areas of maximum displacement velocities, which corresponds to hypocenters of the plane oriented earthquakes clusters above mentioned.

CFRAC code identify the threshold value of shear displacement velocity to trigger earthquake as $1e-3$ m/s, in that moment model element where this condition achieved is interpreted as an initial point of the earthquake rupture, which is closed when shear displacement velocities drop down to threshold value above mentioned. Parameters of earthquakes identified in such a way in CFRAC (times, hypocenters coordinates, seismic moments and magnitudes, earthquake rupture areas) are saved in output files. CFRAC shows that duration time of earthquakes is an order of seconds, while time intervals between earthquakes may achieve days or months. Seismic moment M_0 is estimated in relation to shear displacement case as: $M_0 = G \cdot \int slip \, dA$, where G – shear modulus, A – area of displacement. Then magnitude M_w is estimated as: $M_w = \lg(M_0)/1.5 - 6.06$ (where M_0 is expressed in N*m). For areas with high shear displacement velocities shown in Fig. 4, seismic moments estimates yield range of values $M_0 = 5.7e15 - 6.8e15$ N*m, which corresponds to earthquake magnitudes range of 4.4 – 4.5 ($K_s = 7.4 - 7.6$).

2.4 CFRAC Modeling Results (Basaltic Magma Viscosity)

Modeling magma injection with lower viscosity in the range of 2 Pa s (basaltic magma) shows more asymmetric upward fracture propagation, significant increase of shear displacement velocities up to $2e-3$ m/s, thus injection of less viscous magmas are characterized by more pronounced seismicity (Fig. 6).

3. DISCUSSION & CONCLUSIONS

CFRAC modeling of magma injection into the fracture, characterized by conditions of Koryaksky volcano basement (normal fault, dip angle 60° , sizes 2×2 km², depth – 4 km below sea level) was performed. Modeling shows that magma injection rate of 2000 kg/s during 1 day will cause: fracture opening with aperture up to 0.3 m and shear displacement velocities up to $2e-3$ m/s (that is corresponds to earthquakes with magnitude M_w up to 4.5). Thus, it is feasible, that plane oriented clusters of earthquakes beneath the active volcanoes may be pointed out on magma-fracking or dyke formation processes.

Empirical approaches (Nicolas et al, 2011) to link a volume of fluid injected with a maximum magnitude of triggered earthquakes may be a subject of a future CFRAC modeling study in case of magma injection beneath active volcanoes.

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REFERENCES

Gudmundsson, A.: Magma chambers: Formation, local stresses, excess pressures, and compartments, *J. of Volcanol. and Geotherm. Res.*, **237-238**, (2012), 19-41.

Earthquakes in Russia in the year 2013, Obninsk: GS RAN, (2015), 224 p.

Earthquakes in Russia in the year 2014, Obninsk: GS RAN, (2016), 204 p.

- Ivanov, V.V.: A burst of activity on Koryakskii Volcano, Kamchatka in late 2008 and early 2009: Estimates of heat release, aqueous fluid discharge, a conceptual model for magma ascent, and a forecast of the evolution of the eruption, *Proceedings, Conference Devoted to Volcanologist's Day, March 30–31, 2009, Petropavlovsk-Kamchatskii: IViS DVO RAN*, (2010), 24–39.
- Ivanov, V.V.: The role of fluids in the generation of microearthquakes on volcanoes and in hydrothermal systems, *Abstracts, Reports at the 18th Annual Conference Devoted to Volcanologist's Day "Volcanism and Related Processes", March 1 to April 1, 2015, Petropavlovsk-Kamchatskii: IViS DVO RAN*, (2015), 164–169.
- Kiryukhin A., Manukhin Y., Fedotov S., Lavrushin V., Rychkova T., Ryabinin G., Polyakov A., Voronin P.: Geofluids of Avachinsky-Koryaksky Volcanogenic Basin, Kamchatka, Russia, *Proceedings, World Geothermal Congress, Melbourne, Australia, 19-25 April (2015)*, 1-12.
- Kiryukhin A.V., Fedotov S.A., and Kiryukhin P.A.: A Geomechanical Interpretation of the Local Seismicity Related to Eruptions and Renewed Activity on Tolbachik, Koryakskii, and Avacha Volcanoes, Kamchatka, in 2008–2012, *Journal of Volcanology and Seismology*, **10**(5), (2016), 275–291.
- McClure, M.W., and Horne, R.N.: *Discrete Fracture Network Modeling of Hydraulic Stimulation: Coupling Flow and Geomechanics*, Springer, (2013), doi:10.1007/978-3-319-00383-2.
- McClure, M.W.: Modeling and characterization of hydraulic stimulation and induced seismicity in geothermal and shale gas reservoirs, PhD thesis, Stanford University, Stanford, California, USA (2012).
- McClure, M.W.: CFRAC (version 1.2) Complex Fracturing Research Code User's Guide (version 20), December, (2014).
- Nicolas, C., Michel, F., Catherine, D., and Marco, C.: Induced Microseismic Activity During Recent Circulation Tests at The EGS Site of Soultz-Sous-Forest (France), *Proceedings, Thirty-Sixth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, January 31 - February 2 (2011)*, SGP-TR-191.
- Norbeck, J.H.: Hydromechanical and frictional faulting behavior of fluid-injection-induced earthquakes, PhD thesis, Stanford University, Stanford, California, USA (2016).
- Norbeck, J.H., McClure, M.W., Lo, J.W., and Horne, R.N.: Simulation of hydraulic fracturing and shear stimulation within an embedded fracture modeling framework, *Computational Geosciences*, **20**(1), (2016), 1-18, doi: 10.1007/s10596-015-9543-2.
- Norbeck, J.H., and Horne, R.N.: A numerical method for fractured reservoir poromechanics using a mixed-continuum embedded fracture model, *Geothermal Resources Council Transactions*, **40**, 23-26 October, Sacramento, California, USA (2016).
- Sigmundsson, F., Hooper, A., Hreinsdóttir, S., et al., Segmented lateral dyke growth in a rifting event at Barrparbunga volcanic system, Iceland, *Nature*, 2015, vol. 517, pp. 191–194. doi 10.1038/nature14.
- Zoback M.D.: *Reservoir Geomechanics*, Cambridge University Press, (2007), 448 p.

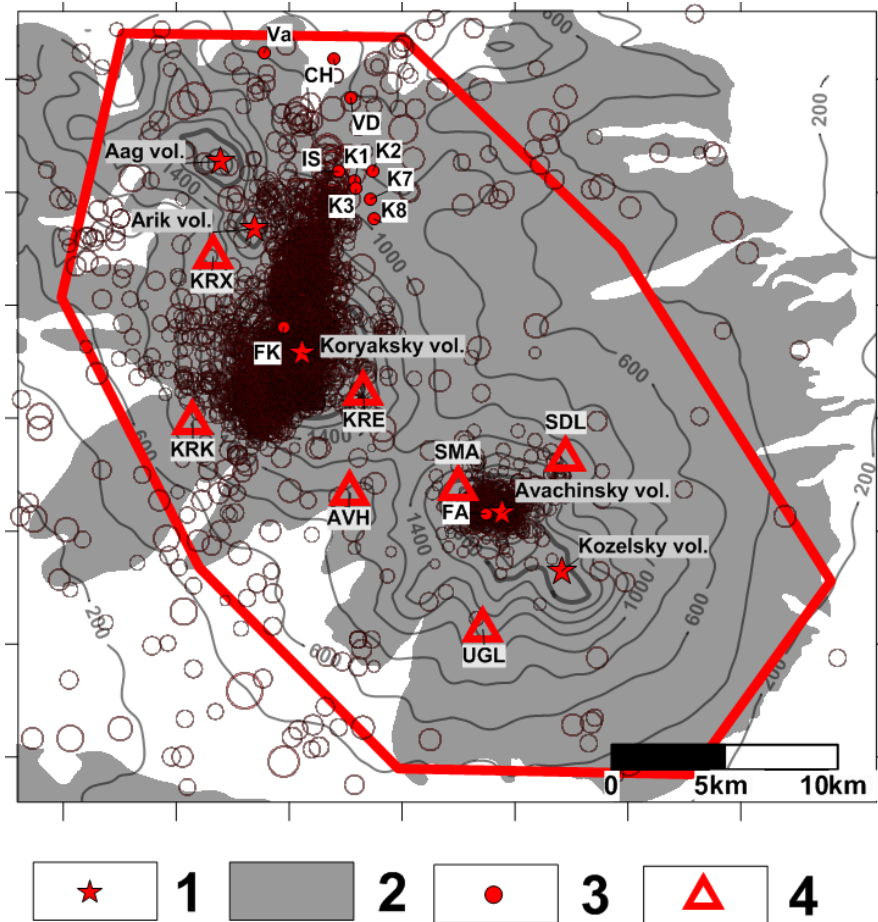


Figure 1 A map of the Koryakskii–Avacha volcanogenic basin. (1) the summits of the Avacha, Koryakskii, Kozel’skii, Arik, and Aag volcanoes; (2) ejecta of volcanic eruptions indicated above; (3) thermal occurrences: FA, fumaroles on Avacha Volcano, FK fumaroles on Koryakskii Volcano; thermal mineral springs: K1, K2, K3, K7, K8 are Koryakskii Narzany; IS, Izotov; VD, Vodopadnyi; CH, Chistinskii; Va, Vakinskii; (4) the KB GS RAS seismograph stations. Epicenters of the 2000–2013 earthquakes (data from the KB GS RAS) are shown as circles (proportionally to energy class K_s from 1.1 to 8.5, $M = 0.5K_s - 0.75$). The isolines show the topographic surface, the ticks along the axes stand at intervals of 5 km.

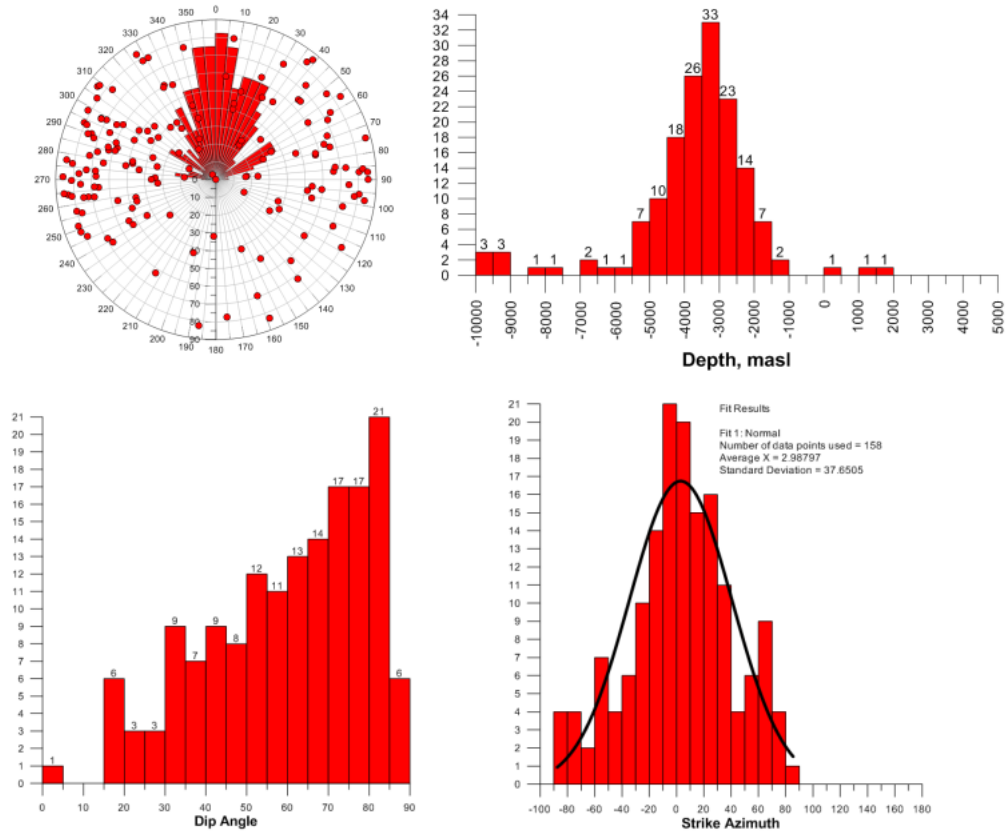


Figure 2 Dykes swarm stereogram (upper left) and histograms (depth, dip angle and strike azimuth) below Koryaksky volcano.

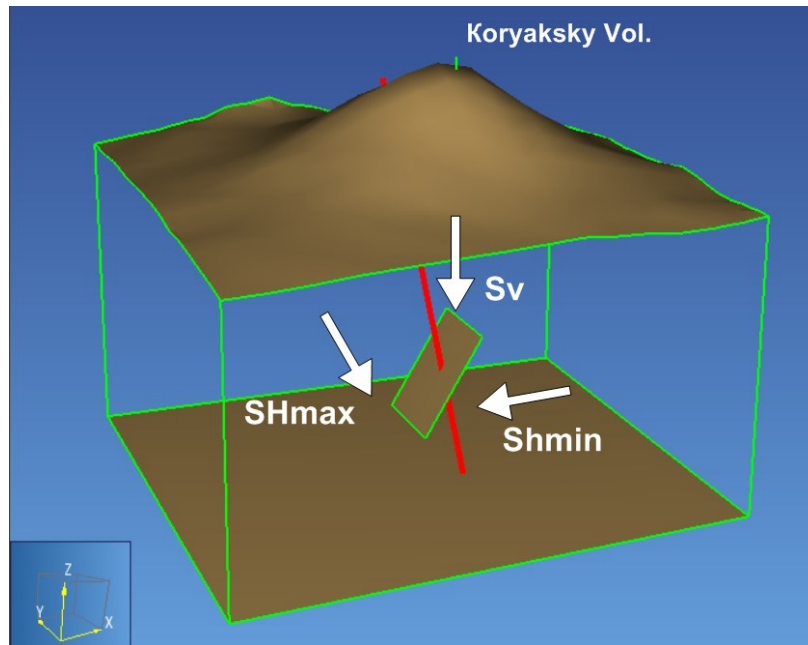


Figure 3 Conceptual model of the dyke formation during magma injection beneath active volcano. S_v – vertical stress, SH_{max} – maximum horizontal stress, Sh_{min} – minimum horizontal stress.

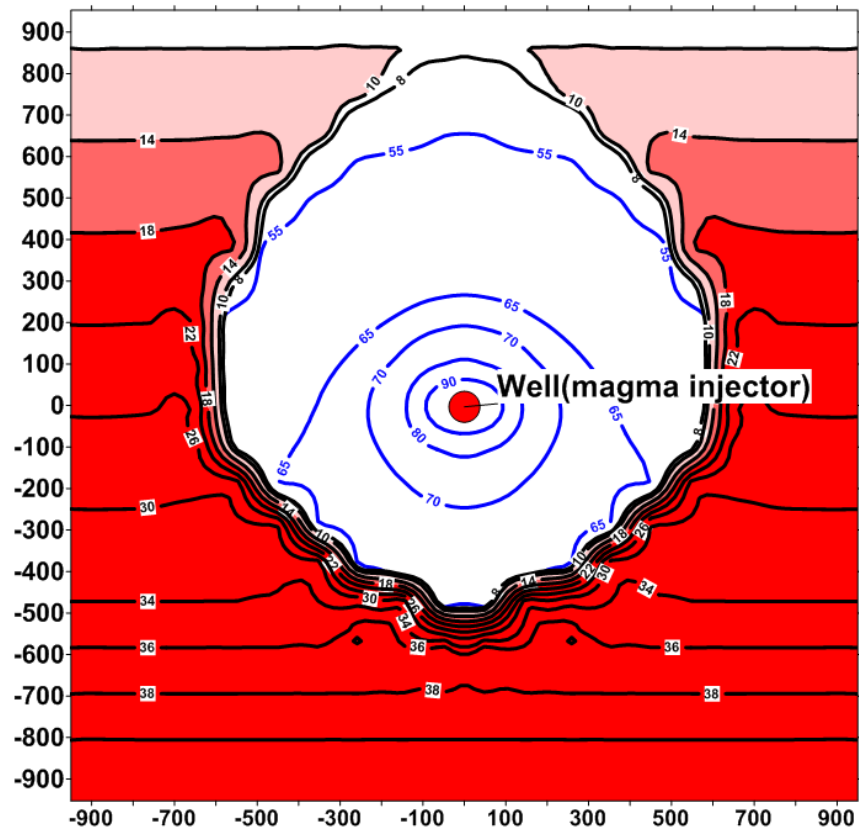


Figure 4 Magma pressure distribution in a fracture plane (blue isolines, MPa) and effective normal stress (black isolines, MPa) one day after magma injection started.

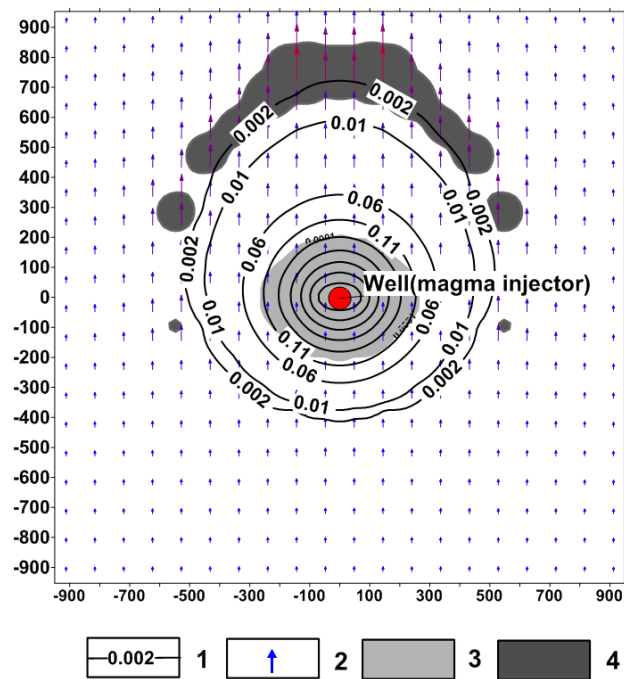


Figure 5 Fracture aperture distributions and vectors of sliding one day after magma injection and zones of potential hypocenters of the plane-oriented clusters of earthquakes. Legend: 1 – aperture isolines (m); 2 - vectors of sliding (laying block relatively to hanging block); 3 - zones of high displacement velocities more than $1e-4$ m/s in a 570 s after magma injection started; 4 - zones of high displacement velocities more than $3e-6$ m/s in a 1 day after magma injection started.

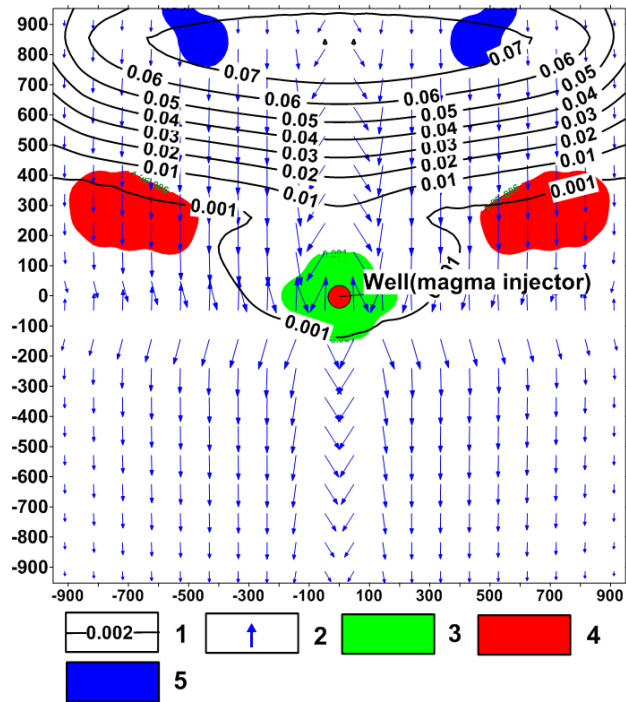


Figure 6 Fracture aperture distributions and vectors of sliding one day after magma injection and zones of potential hypocenters of the plane-oriented clusters of earthquakes. Legend: 1 – aperture isolines (m); 2 - vectors of sliding (hanging block relatively to laying block); 3 - zones of high displacement velocities more than $1\text{e-}3$ m/s in a 60 s after magma injection started; 4 - zones of high displacement velocities more than $3\text{e-}5$ m/s in a 7200 s after magma injection started; 5 - zones of high displacement velocities more than $1.2\text{e-}6$ m/s in a 1 day after magma injection started.