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Geomechanical Interpretation of Local Seismicity During 2012 Tolbachik Volcano Eruption

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ABSTRACT

Local seismic activity during 2012 eruption of Tolbachik volcano is considered as a result of the injection of magma forming plane-oriented zones: dykes and sills with associated fractures. In order to identify these zones - the plane-oriented clusters of earthquakes were distinguished with the catalogs of Kamchatka Branch of Geophysical Survey RAS, their subsequent spatial-temporal analysis allows the following interpretation. 27.11.2012 Tolbachik volcano eruption was preceded by the injection of magma with the introduction of a series of dykes of west-north-west striking in the depth range -4 - +3 km abs. in the area to the southeast of the Plosky Tolbachik volcano structure. The indicated fractures dissection of a subhorizontal permeable zone at an altitude near zero lead to the formation of sills and a magma discharge injection dike (dip angle of 50°, dip azimuth 300^o) at 5.5 km from the epicenter of the initial magma injection. The presence of shallow clusters with dip angles less than 30^o, which does not belong to the activated shear fracture zone of Mohr's diagram, indicates a possible existence of local melted magma chambers and (or) permeable stratiform reservoirs within the structure of Tolbachik volcanoes.

1. INTRODUCTION

Volcanoes and crustal magma chambers are the products of magma injection of the primary magma reservoirs located in the Kuril-Kamchatka volcanic zone at depths of 150-200 km. Crustal magma chambers are fed by magma from the primary magma reservoirs (magma accumulation zones) and are a source for the formation of inclined dikes, sills and dikes, including feeder dikes providing the eruption of magma to the surface and the formation of volcanic structures themselves. Many dikes "freeze" in host rocks without reaching out to the surface, some change their orientation during propagation and transform into sills. Change of dike orientation and dikes being transformed into sills often occur in stratiform reservoirs, complicated by faults (normal faults). The review of paleo-volcanic data and the existing thermohydrodynamic models of magma chambers shows the following [Gudmundsson, 2012]: (1) Many of crustal magma chambers are formed from the sills; (2) active crustal magma chambers facilitate magma injection to their related volcanoes, most of the chambers are of partially molten (pore) condition; (3) The ellipsoid is a thermally stable form of magma chambers; (4) During fracturing and dike injection we must take into account the excessive pressure of magma (fracture strength of host rocks, 1-6 MPa), the absolute pressure of magma and a total lithostatic pressure (stress); (5) During the eruption the excessive pressure decreases exponentially until the dike loses its hydraulic connection with the chamber; (6) During the periods of rest magma pressure in the chamber should be equal to the total lithostatic pressure; (7) The condition of hydraulic fracturing on the surface of magma chamber is achieved in two ways: increase in the absolute pressure of magma in the chamber as a result of the injection from the feeding magma reservoir or decrease in horizontal stress as a result of regional extension; (8) The local stress field in the vicinity of magma chamber depends on the shape of the chamber, its depth, geomechanical properties and characteristics of host rock stratification.

The above mentioned shows that the injection of magma from crustal magma chambers followed by the forming of dikes and sills as a result of magma fracturing are largely analogous to the process of injection (recharge) of fluids into the wells with hydraulic fracturing and formation of cracks in host formations. Thus in our further analysis with regard to magma injection we will use the term of magma fracturing with reference to the process of forming plane-oriented structures (dikes, sloping dikes, sills, large cracks and faults) during the activation of volcanic crustal magma chambers.

Formation of new hydraulic fractures and activation of the existing faults is accompanied with microseismicity associated with the formation of shear cracks in the main aseismic zone adjacent to the hydraulic fracture zone (trigger seismicity). Therefore, we may assume that the orientation of planes approximating the clusters of micro-earthquakes coincides with hydraulic fractures during magma injection (intrusion). Earthquake magnitudes for changes with amplitudes of 0.1 mm - 1 cm with the length of cracks in the first hundred meters are estimated to range from 1 to 2 (Ks From 3.5 to 5.5), which corresponds to the sensitivity of local seismic networks operating in the area of Tolbachik volcano.

In recent years the seismicity caused by injection (injection triggered seismicity), has attracted considerable attention with regard to the realization of EGS projects (Enhanced Geothermal Systems) and the operation of geothermal fields. Scientific study of the above problem is a theme of regular discussion during workshops on engineering of geothermal reservoirs at Stanford University (Proceedings, Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA, USA), the same topic was also highlighted at the World Geothermal Congress (World Geothermal Congress, Melbourne, Australia, 2015).

Less available are the data on seismicity induced by magma injection with the intrusion of dikes and the subsequent effusive eruptions since such events are rare and unexpected. The paper [Sigmundsson et al, 2015] describes magma injection from the magma chamber of Bartarbunga (Iceland), the volcano of central type, which continued over 14 days in August 2014 and was accompanied by the spread of the dike at a distance of 45 km and effusive eruptions at its end. The process was accompanied by plane-oriented clusters of seismic events, the visualization of these clusters allows one to clearly see dike segmentation into 8 components in the band of 3 km width [Sigmundsson et al, 2015]. We would like to note V.V. Ivanov's study [2015] as a domestic development, which discusses the nature of microseismicity at magma intrusion in the earth's fragile crust, which causes the heating of water with a consequent increase in pore pressure.

2. INITIAL DATA AND SELECTION ALGORITHM OF PLANE-ORIENTED EARTHQUAKE CLUSTERS

2.1 Initial data

In 2012-2013 to register local earthquakes in the area of Tolbachik volcanoes we used Kluchevskaya network of KB GS RAS radio telemetry stations, which consists of 12 stations. Five of them (Fig. 1) can detect earthquakes with magnitudes of -1 or 2 of the volcano Plosky Tolbachik.

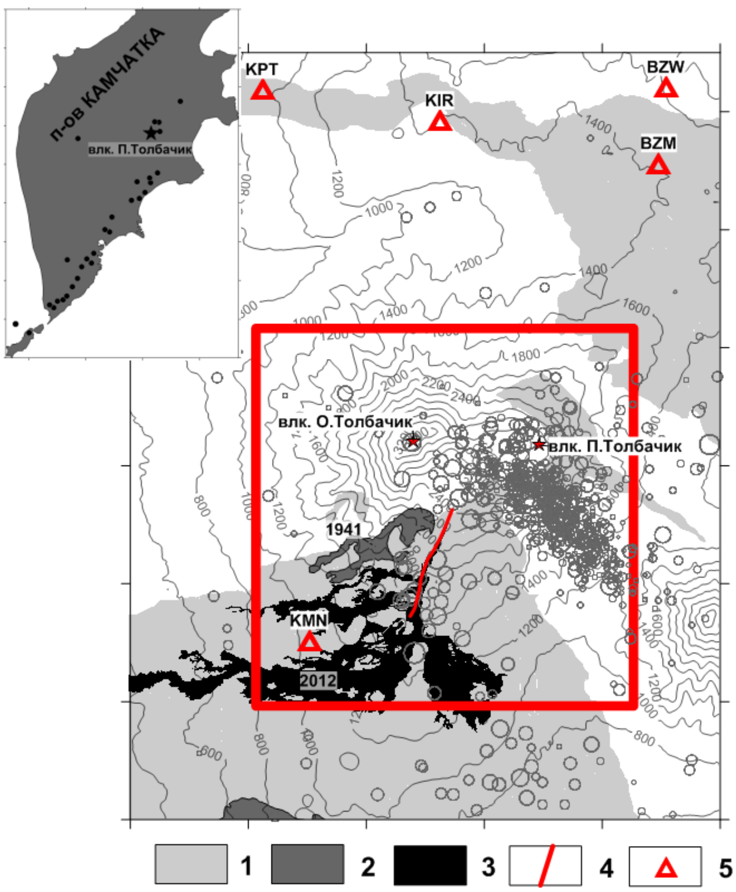

Figure 1: Diagram of the district of Tolbachik volcano. 1 - Holocene lava; 2 – lavas of historical eruptions (1941 breakthrough and Northern breakthrough); 3 – lavas of 2012-2013 eruption; 4 – projection of eruptive fissure 27.11.2012 on the surface; 5 – seismic stations of KB GS RAS with acronyms of seismic stations. 2012-2013 Earthquake epicenters (KB GS RAS data) are shown with circles (in proportion to Ks energy class from 2.6 to 11.3), the inner rectangle shapes the borders of a 3D model in Fig. 5. Isolines show topographic surface, axle markings – 5 km.

The study [Fedotov et al., 2014] builds and analyzes vertical geophysical sections of the subject area with the application of the hypocenters of registered earthquakes. The absolute accuracy of the calculation of the coordinates of hypocenters and epicenters of micro-earthquakes at the considered time of 2012 Tolbachik volcano eruption is estimated at 3 km [Earthquakes …, 2014]. The study [Kugaenko et al., 2014] identifies the stages of seismic activity and its spatial distribution in the vicinity of the volcano Plosky Tolbachik before the eruption of 27.11.2012, at the same time there is a statistically significant seismic activity from July to October 2012 (Ks = 4-6), the level of seismicity becoming extremely high three weeks before the start, and the strongest earthquakes (Ks = 7-9) occur in the final hours before its start. After the eruption (30.11 - 07.12.2012) seismic activity moved 10 km to the south, to the Tolud earthquake zone (Ks = 5.2-11.3).

The catalogs also show that earthquakes close in time and place have similar error in determining the time, i.e. shift in the same direction – this suggests that the relative accuracy in coordinate positioning of the considered earthquakes is considerably less for the clusters of events which are close in time and space. For example, VLN127128-VLN127172 events [Earthquakes ... 2014], corresponding to cluster 40 (Table 1), show considerably less standard deviation of error in the determination of time than all the events from the catalog analyzed below. From this we can assume that at clustering of earthquakes close in time and space, the relative error in the determination of their coordinates would be acceptable for the identification of plane-oriented objects with sizes in the first kilometers. It is also clear that at a random shift of coordinates the event is much more likely not to get in a plane-oriented cluster than to get there, consequently if the events are arranged geometrically in spite of the errors of measurement of their coordinates - this must have a definite physical meaning.

2.2 Selection algorithm of plane-oriented clusters of microearthquakes and estimation of parameters of the corresponding planes

To find the clusters we have developed a program using Java SE Development Kit 8 (jdk-8u40-windows-x64). The criteria for the comparison to include a new object in the cluster were selected: 1) the proximity in time (Δt = 1 day); 2) the proximity of the distance in the horizontal plane (ΔR <6 km); 3. the proximity to plane orientation (the distance from the object to the plane ΔZ is no more than 200 m). Further we analyzed only the clusters with a number of elements N> 5.

Selection of clusters. In performing the program to check the above 3 conditions we previewed all initial earthquakes from the main list in the cycle. If the result obtained in the size of cluster N > 5 elements, the cluster is considered generated and that is to be added to the list of clusters. The procedure is repeated until the basic list of elements becomes empty.

Calculation of parameters of a plane-oriented cluster. Data-in is the list of cluster elements. Each element i contains the coordinates (x_i, y_i, z_i). For n (the number of elements in the cluster) points with coordinates (xi, yi, zi) the approximating plane equation z = ax + by + c which we calculate by a method of minimum squares. Thus, the solution is reduced to solving a system of linear equations (SLE):

$$\begin{bmatrix} \sum x_i^2 & \sum x_i y_i & \sum x_i \\ \sum x_i y_i & \sum y_i^2 & \sum y_i \\ \sum x_i & \sum y_i & n \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} = \begin{bmatrix} \sum x_i z_i \\ \sum y_i z_i \\ \sum z_i \end{bmatrix} \qquad (4)$$

SLE is solved by Cramer's method.

Thus, we get coefficients a, b, c for the equation of plane z = a x + by + c. Further, we calculate a single normal vector to the approximating plane **n** = (a /Δ, b /Δ, -1/Δ), where Δ - is a SLE determinant. Then we calculate the geological characteristics: the dip angle β = arcos (1/Δ) * 180 /3.142 and dip azimuth arctg (a / b) * 180 / 3.142.
Sensitivity analysis of the selection algorithm of plane-oriented clusters with respect to time and spatial proximity indicates that the above criteria provide physically and geologically acceptable identification results.

According to KB GS RAS catalog of local earthquakes (1262 events for the period (1.01.2012-31.12.2013) in the area of Tolbachik volcanoes are distinguished 310 events, that form 22 plane-oriented clusters of earthquakes preceding 27.11.2012 volcano eruption. The table shows the results of identifying plane-oriented clusters of earthquakes with the criteria set out above, as well as structural and geological characteristics of the respective planes (the dip angle, dip azimuth, coordinates of the centers of clusters, implementation time and the number of earthquakes). We would also like to note that after 27.11.2012 eruption until the end of 2013 we identified only 4 plane-oriented clusters corresponding to the Tolud cloud of earthquakes (30.11.2012 - 04.12.2012), 10 km south to the center of the eruption. One of these clusters is interpreted as a sill on the abs. elevation. -260 m that may indicate its hydraulic connection with the system of magma discharge sills of 27.11.2012 eruption (clusters 38 and 40, Table 1).

Table 1. Plane-oriented clusters of earthquakes derived from KB GS RAS catalog of seismic events (for 2012-2014), prior to 27.11.2012 eruption of the Tolbachik volcano and the parameters of the planes that approximate them.

## cluster	Dip Angle, degree	Dip azimuth, degree	X м	Y м	Z м abs	Start of cluster DD/MM/YY HH:MM	Number of earthquakes in a cluster	Cluster area, km^2
19	80	137	588041	6185570	-2369	25.11.12 10:56	8	8.8
20	25	230	589355	6185175	-3256	25.11.12 20:29	27	6.6

21	44	148	588412	6185393	-2422	25.11.12 22:00	19	0.7
22	32	250	588749	6185321	-2893	26.11.12 1:12	28	0.6
23	58	74	588183	6185916	-1727	26.11.12 6:06	27	8.8
24	77	209	587489	6186380	-1887	26.11.12 6:59	31	1.6
25	62	6	588037	6185744	-2536	26.11.12 9:29	17	17.9
26	42	112	587506	6185373	-3030	26.11.12 15:12	9	15.3
27	46	233	587490	6186646	-1162	26.11.12 17:02	11	10.5
28	52	138	588833	6185808	-1454	26.11.12 18:50	20	16.1
29	27	245	589936	6184132	-3135	26.11.12 19:51	17	3.7
30	61	53	587366	6185779	-263	26.11.12 20:58	12	1.8
31	59	20	586981	6185946	-818	26.11.12 23:04	12	9.7
32	62	208	589346	6185416	-1780	26.11.12 23:16	13	21.2
33	63	18	587227	6186504	-797	26.11.12 23:45	7	10.4
34	60	197	588391	6186634	-2127	27.11.12 0:19	7	7.5
35	75	192	585967	6186785	-2147	27.11.12 0:38	6	21.2
36	74	213	591075	6183134	-1053	27.11.12 2:26	6	5.7
37	83	98	589811	6184397	-1122	27.11.12 3:16	6	1.5
38	**3**	**135**	**589307**	**6183391**	**-177**	**27.11.12 3:55**	**9**	13.1
39	**55**	**300**	**583378**	**6183079**	**302**	**27.11.12 5:35**	**6**	4.0
40	**7**	**196**	**583269**	**6181414**	**-35**	**27.11.12 7:09**	**12**	8.9

Footnote. X, Y, Z – coordinates of cluster centers (UTM WGC-84 coordinate system).

2.3 Sensitivity analysis of the selection algorithm of plane-oriented clusters

Sensitivity analysis of definition of the number and parameters of plane-oriented clusters during micro-earthquakes (dip angle and dip azimuth) in the case of a random component of errors in determining earthquake coordinates was done on the example of the earthquake data catalog in the Tolbachik volcano area (2012-2013) in the following way. Earthquake coordinates were shifted to software-generated random variables distributed by normal distribution (Gaussian distribution) with a variety of standard deviations σ (125 m - 3000 m). After that, according to the algorithm described in Section 2.2, we selected plane-oriented clusters of earthquakes and assessed the characteristics of clusters (dip angle and dip azimuth), which were then presented in a graphical form in polar coordinate system with different values of σ. The analysis results show that the preservation of the characteristics of a sequence of plane-oriented clusters is achieved by a random component σ of up to 125 m. It was also revealed that the weakening of criterion of the vicinity of cluster components to the plane enables the unification of spatially close clusters. The greater change in the time interval Δt at identifying plane-oriented clusters on the one hand increases the number of the identified plane-oriented clusters, on the other hand - combines clusters with similar orientation, while the overall picture of dike and sill intrusion remains fundamentally unchanged (see Appenidix, Figs. A1 and A2).

3. GEOMECHANICAL INTERPRETATION: STAGES OF 25.11 – 27.11.2012 MAGMA INJECTION PRIOR TO THE TOLBACHIC VOLCANO ERUPTION

3.1 Interpretation of satellite, geospatial data and field measurements of fracture

The latest fissure eruption on the southern slope of the Tolbachik volcano began 27.11.2012 and lasted for 9 months, the total amount of volcanic products is estimated at 0.55 km^3 with the area of 36 km^2, the flow of magma reached 440 m^3/s at the beginning of the eruption, during the eruption it gradually decreased from 140 to 18 m^3/s [Belousov et al, 2015]. This eruption significantly renewed the volcano landscape after 1975-1976 Great Fissure Tolbachik Eruption [Fedotov et al., 1991].

Geodeformation changes during 2012-2013 eruption were assessed with repeated radar satellite imagery (interferometric synthetic aperture radar (InSAR)), with the data from Canadian Space Agency's RADARSAT-2 and the Italian Space Agency's COSMO-SkyMed [Lundgren et al, 2015]. According to climatic conditions (snow), it is only possible to compare interferograms when surveying was performed in August-September of 2012 and 2013. 3D geomechanical model describes deformations which are observed during specific time interval (year) as a result of horizontal stretching from the intrusion of a radial dike of Tolbachik volcano (80 ° dip angle in the west-north-west direction).

According to GPS observations [Kugaenko et al., 2015], the monitoring of geodeformation mode shows that the beginning of 27.11.2012 eruption was synchronized with the dramatic sinking of 30-40 mm and a shift toward the center of the eruption (azimuth $\approx 210^o$) in the area of Klyuchevskaya volcano group at a distance of 45-70 km. These observations point to the hydraulic connection between magma feeding systems of Klyuchevskaya volcano group and Tolbachik volcanoes.

We made field measurements of open fracture parameters in the area in September 2013. Analysis of these data came to the following conclusions: 1. Strike of the main magma discharge fracture 25^o; 2. Prevalence of open (up to 0.5 - 1.0 m) fractures of the north-north-west-trending, 340^o to the east of the main magma discharge fracture; 3. Spreading of polygon open (up to 0.5 - 1.0 m) fractures on the slopes of Kleshnya cone (to the south of the main eruptive center). Open linear fractures at an angle of 45 ° to the main crack magma discharge fracture indicate its shear character. Polygonal open cracks indicate the conditions of radial expansion, possible with a substantial excess of the vertical stress above the horizontal one (Sv> Shmax = Shmin, [Zoback, 2010, p.9], which can occur with the intrusion of sills.

Thus, although the geomechanical model of one dike (Lundgren et al.,2015) might explain the total geodeformation effect, it is unlikely to adequately describe the order of the intrusion of magmatic bodies prior to 27.11.2012 eruption. In which connection let us consider the possibility of using the data on local seismicity to restore the sequence of magma injection prior to the eruption of the Tolbachik volcano.

3.2 Geomechanical interpretation of local seismicity

The identified plane-oriented clusters of earthquakes (Table 1) are interpreted as sills and dikes, formed at magma injection. If this assumption is correct, then the eruption of Tolbachik volcano was preceded by about twenty intrusions of dikes during magma injection (mainly of west-north-west trending) in the depth range -4 - +3 km abs. in the area to the southeast from the Plosky Tolbachik volcano structure (see Table 1, clusters of earthquakes 19-37; Fig. 2A). This led to the opening of subhorizontal permeable reservoirs and formation of conditions for the injection of two sills (0 km abs.) and a magma discharge dike of north-east-north trending 30^o (see Table 1, 38-40 clusters of earthquakes; Fig. 2B), resulting in 27.11.2012 Tolbachik volcano eruption.

We would like to note that the strike azimuth of a magma discharge dike 30^o (see. Table, cluster 38) estimated from seismic data is in good agreement with the results of field observations (25^o) and satellite geodeformation observations InSar [Lundgren et al, 2015], and clusters 38 and 40 (see Table 1) which are identified with sills - correspond to the observations of polygonal fractures.

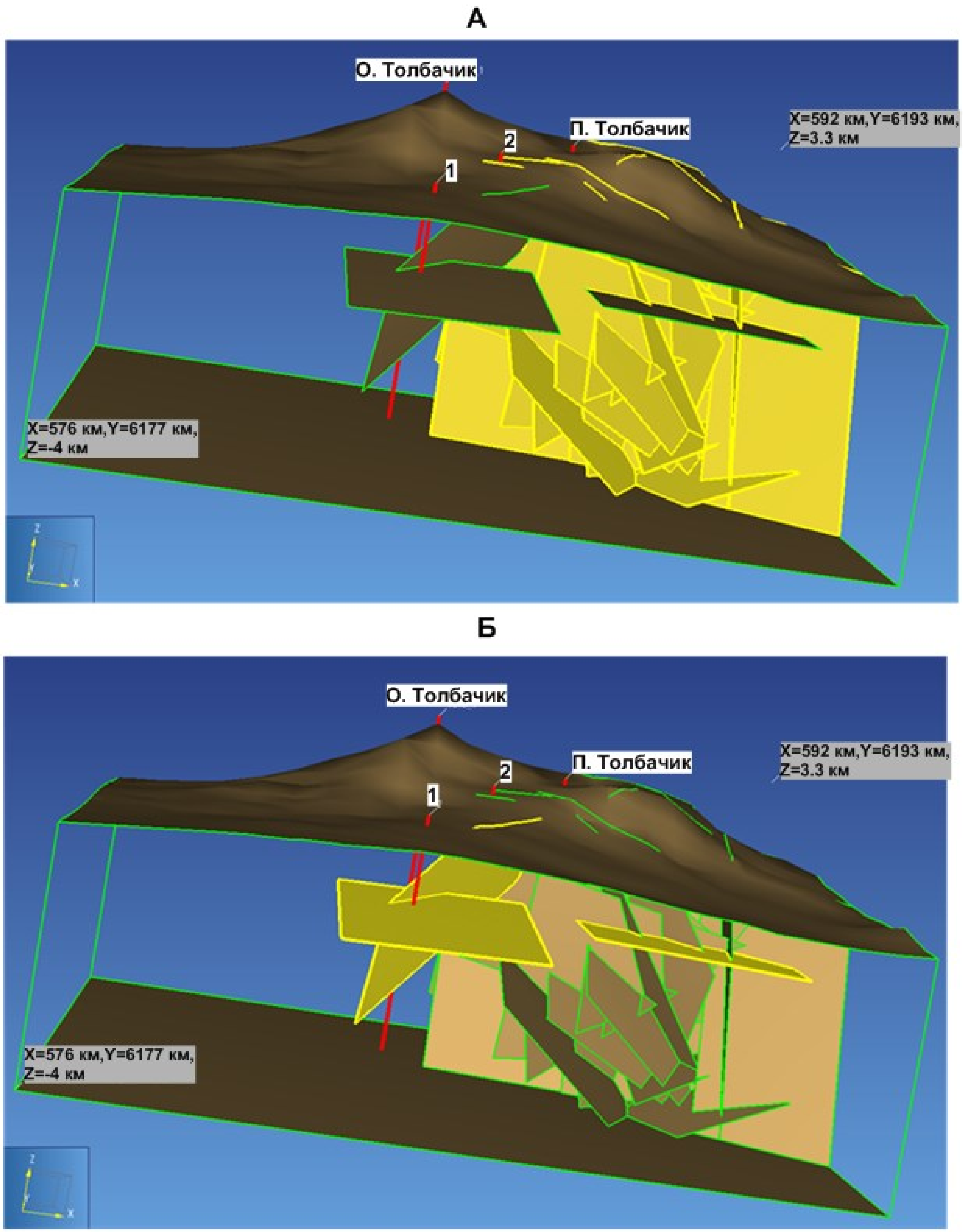

Figure 2: Geomechanical interpretation of local seismicity prior to 27.11.2012 Tolbachik volcano eruption. In the upper figure A we backlight dikes and sills formed at the initial stage with the dominance of vertical stress (geomechanical conditions NF: Sv > Shmax > Shmin). In the lower figure Б we backlight two sills and a magma discharge dike which was formed just before the eruption under the dominance of horizontal stress of north-east-north direction (geomechanical conditions: Shmax >> Sv=Shmin). 1 – Menyalov crater, 2 – Naboko crater.

4. DISCUSSION OF THE RESULTS OBTAINED WITH USING MOHR'S DIAGRAMS

The zone of Kamchatka active volcanoes is generally characterized by conditions of horizontal extension, dominated by graben structures (geomechanical state of NF (Normal Fault, vertical stresses exceed horizontal ones Sv> SHmax> SNmin). In transport of magma from the primary or crustal magma chambers the formation of magma fault fractures is carried out perpendicular to the direction of minimum stress Shmin, while the pressure of fluid Pf must exceed Shmin. Thus vertical dikes are the major primary fractures through which the transport of magma is performed. If the pressure of the fluid (magma) increase so that $\tau > \mu\cdot\sigma$ (where τ - shear stress, σ - normal stress, $\mu \approx 0.6$ coefficient of internal friction), this induces activization of critically compressed shear fractures. The dip angles of these fractures are most clearly defined by Mohr's diagram. Conversely, with the available data on the dip angles of active shear fractures one can estimate fluid pressure in magma fracturing zone.

Mohr's diagrams for the Tolbachik volcano (2012 condition) are used as a graphical illustration. Mohr's circles are a graphical representation of the state of stress in differently oriented sites with respect to the principal axes of stress. The coordinates of Mohr's circles on the diagrams are calculated by the formulas:

$$\tau = 0.5 \cdot (\mathrm{Sv} - \mathrm{SHmin}) \cdot \sin(2\beta) \qquad (5)$$

$$\sigma = 0.5 \cdot (\mathrm{Sv} + \mathrm{SHmin}) + 0.5 \cdot (\mathrm{Sv} - \mathrm{SHmin}) \cdot \cos(2\beta) - \mathrm{Pf} \qquad (6)$$

- where β – the dip angle of plane-oriented clusters (see Table 1).

$$\mathrm{SHmin} = \frac{\mathrm{Sv}}{[(\mu 2 + 1)0.5 + \mu]^2} \approx \frac{\mathrm{Sv}}{3.1} \qquad (6)$$

Vertical stresses Sv are defined in all cases as lithostatic pressure (Sv = ρgH, ρ = 2800 kg / m^3 (Gudmundsson, 2012)) at the point of magma injection (average depth H of the centers of plane-oriented clusters is identified with the center of magma chamber, in which is carried out magma injection), for the Tolbachik volcano - 4 km (2012), horizontal stress SHmin is determined for the conditions of extension (Normal Faults, NF) [Zoback, 2010, p.132]:

According to Mohr's diagram (see. Fig. 3), for the Tolbachik volcano, magma injection at a depth of 4 km was carried out at the pressure of magma 35 MPa and accompanied by the opening of fractures and the formation of steeply dipping dikes (see Table 1, clusters 19, 24, 25, 35, 36, 37) with dip angles 75-83^o. The activization of shear fractures occurred synchronously (clusters 19, 21-23, 25-28, 30-34) with dip angles 32-62^o, these fractures are indicated in Mohr's diagram in the failure zone above the line $\tau = \mu\cdot\sigma$. Two relatively flat fractures (clusters 20 and 29), with dip angles 25-27^o do not fall into the zone of active shear fracture in Mohr's diagram, probably they are initiated by the local stress on the surface of a melted magma chamber. Most likely, all of the above dikes and fractures were filled with magma and the formation / completion of a partially melted magma chamber had a size of 5 x 3.5 x 3 km^3 (≈50 km^3). The breakthrough of magma to the surface occurred when one of the shear fracturess "had found" a permeable sub-horizontal zone on the 0 m.a.s.l. (the base of the volcano, the contact of Neogene volcanogenic sediments and Quaternary volcanics), which led to the formation of two sills (clusters 38 and 40) and a magma discharge dike (cluster 39, angle of incidence 55^o with azimuth 300^o), 5.5 km from the initial magma injection.

We would like to note that strike of a magma discharge dike (see. Table 1, cluster 39) and the direction of its dipping is in line with the results of geomechanical interpretation of ground deformation according to the satellite data [Lundgren et al., 2015]. The fact that the dike is feathered from the south by open submeridional fractures (identified by the results of the field work in September 2013) indicates the presence of left-sided shear component. The presence of shallow sills (see Table 1, clusters 38 and 40) at the site of the eruption is consistent with the presence of polygonal fractures on the surface (also identified as a result of field research, 2013).

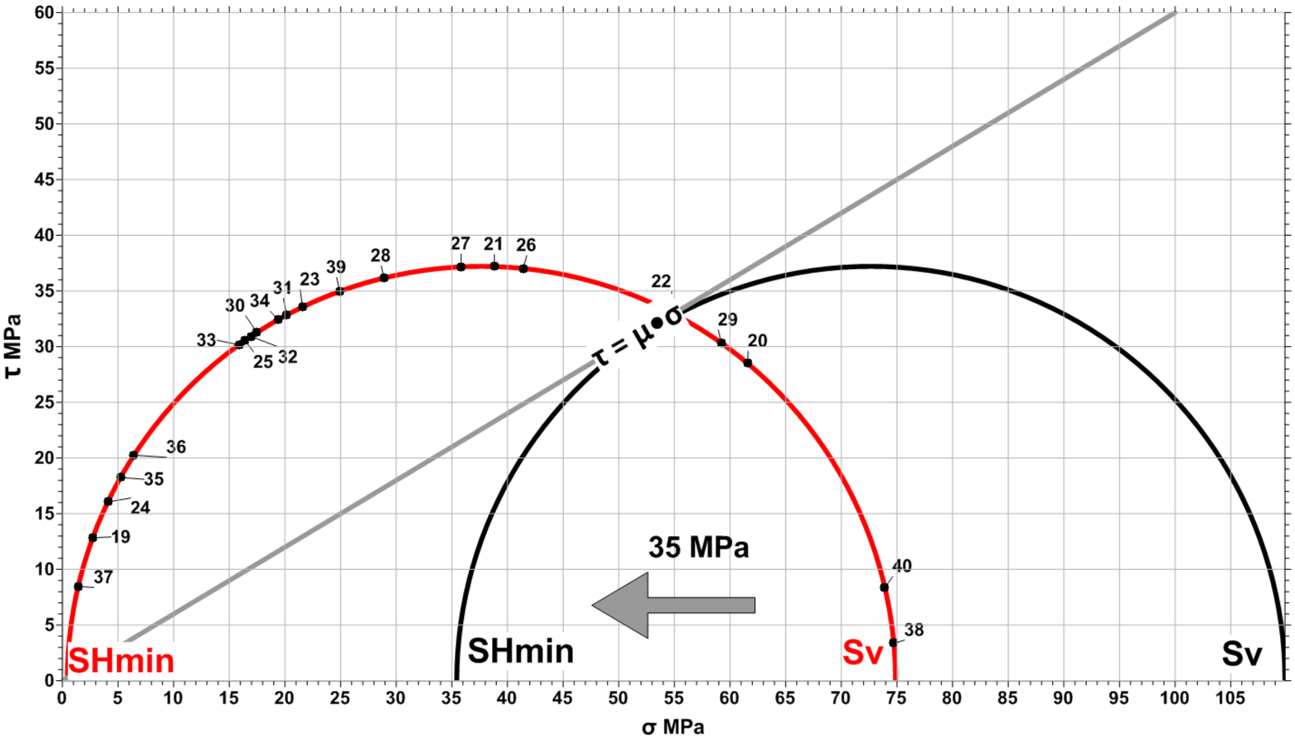

Figure 3: Mohr's diagrams showing the change in state of stress during the injection of magma, the circle to the right covers a range of normal and shear stresses prior to the injection of magma, the circle to the left - after the injection of magma; point numbers correspond to active fractures defined according to the seismic data in the area of the Tolbachik volcano (November 2012, at the depth of 4 km). Note: in order to position the point on the circle in the center we must set the angle 2β from the horizontal axis (where β - the angle of incidence of a plane-oriented cluster, column 2 in Table 1).

4. CONCLUSIONS

1. The example of 2012-2013 effusive Tolbachik volcano eruption shows that the catalogues of local seismic events include plane-oriented clusters, which can be interpreted as a zone of sill and dike formation as a result of magma fracturing of host rocks at magma injection. The results of sensitivity analysis with respect to random errors in determining earthquake coordinates show that the preservation of the characteristics of a sequence of plane-oriented clusters is achieved by the random component σ up to 0.125 km

2. In the area of Tolbachik volcanoes we distinguish 22 plane-oriented clusters of earthquakes that preceded 27.11.2012 volcano eruption. The identified planes are interpreted as zones of dike and sill intrusion during magma injection. Based on this interpretation, the eruption of the Tolbachik volcano was preceded by the intrusion of steeply dipping dikes of west-north-west trending with dip angles 32-62^o and magma pressure of 35 MPa (at a depth of 4 km) in the depth range -4 - +3 km abs. to the southeast of Plosky Tolbachik volcano structure in the area of 5 x 3.5 km^2. The breakthrough of magma to the surface occurred after opening of permeable subhorizontal zone at 0 m.a.s.l., which led to the formation of two sills and a magma discharge dike (dip angle 55 ° with azimuth 300^o), 7 km from the area of the primary magma injection. The identified mechanism of magma transport to the surface is in line with the results of field measurements of fracturing at the site of 2013 eruption and the interpretation results of ground deformation according to the satellite data [Lundgren et al., 2015] .

The authors realize that the quality and completeness of the available initial data, the accuracy of hypocenter coordinates, which determine the possibilities of this study depend on the catalogs provided by KB GS RAS, and the work to specify them and to relocate earthquakes is to be continued. Therefore, the results presented above are preliminary and can be revised when we obtain more complete and accurate data about the coordinates of earthquake centers.

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Appendix. **Sensitivity analysis of plane-oriented clusters estimates.**

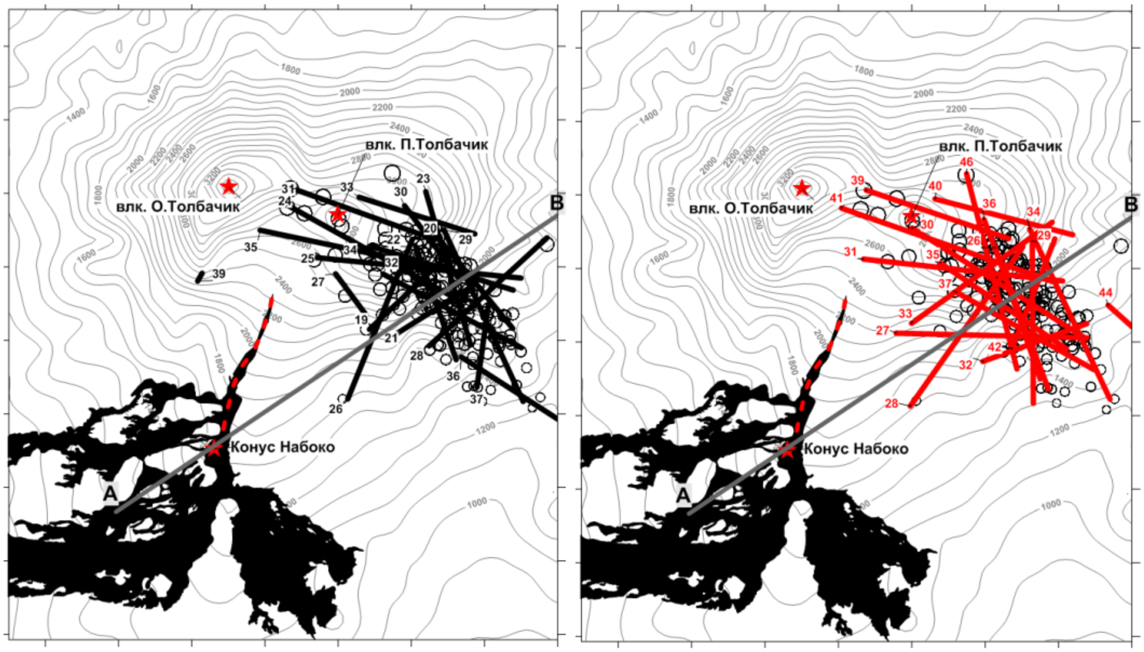

Figure A-1: Estimated zones of dikes and sills intrusion in the area of Plosky Tolbachik volcano 25-27.11.2012 г. in the horizontal slice (- 3 km abs.). Figure on the left - traces of plane-oriented clusters in the horizontal slice -3 km abs, the time interval at identifying plane-oriented clusters Δt = 1 day. Figure on the right - the same, but the time interval at identifying plane-oriented clusters Δt = 2 days. Black painted are lava flows (Volynets AO et al, 2013), the dashed line shows the eruptive fissure of 27.11.2012. Isolines show a topographic surface. Horizontal axis scale - 2 km.

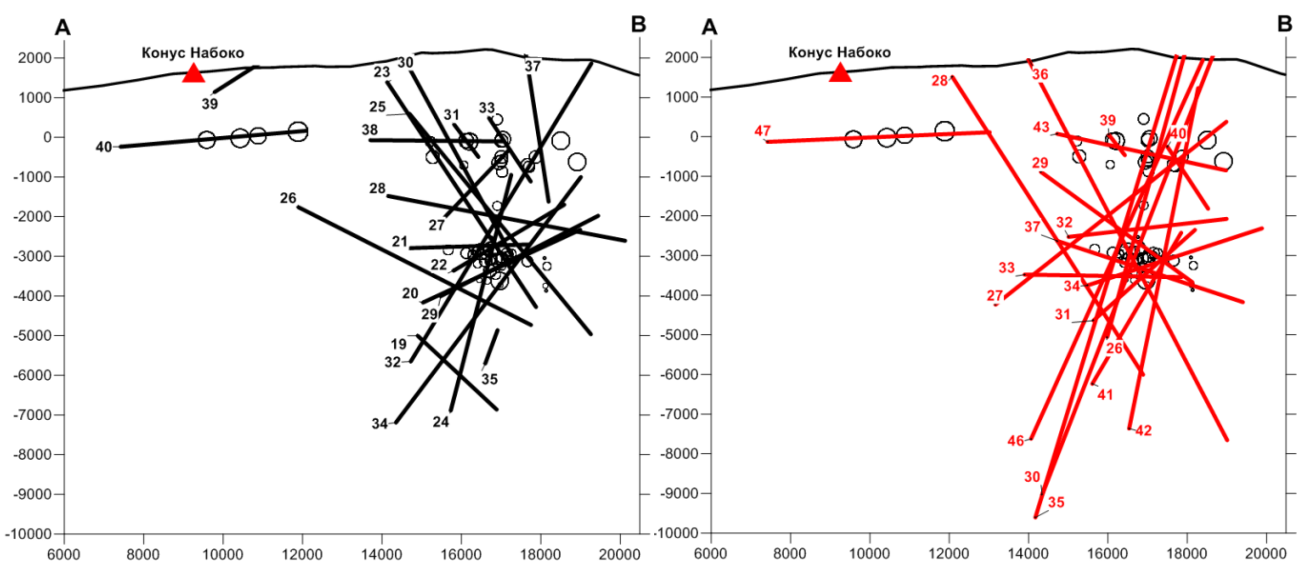

Figure A-2: Estimated traces of dikes and sills intrusion in the area of Plosky Tolbachik volcano 25-27.11.2012, in the vertical section AB (the line is shown in Fig. A-1). Figure on the left - traces of plane-oriented clusters, the time interval at identifying plane-oriented clusters Δt = 1 day. Figure on the right - the same, but the time interval at identifying plane-oriented clusters Δt = 2 days.