ISSN 0742-0463, Journal of Volcanology and Seismology, 2017, Vol. 11, No. 6, pp. 419–433. © Pleiades Publishing, Ltd., 2017.
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# The Tolud Burst of Seismicity and the Earthquake of November 30, 2012 ($M_C$ = 5.4, $M_W$ = 4.8) that Accompanied the Start of the 2012–2013 Tolbachik Eruption

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Received May 12, 2016

**Abstract**—This paper reports a study of the Tolud earthquake sequence; the sequence was a burst of shallow seismicity between November 28 and December 7, 2012; it accompanied the initial phase in the Tolbachik Fissure Eruption of 2012–2013. The largest earthquake (the Tolud earthquake of November 30, 2012, to be referred to as the Tolud Earthquake in what follows, with $K_S$ = 11.3, $M_L$ = 4.9, $M_C$ = 5.4, and $M_W$ = 4.8) is one of the five larger seismic events that have been recorded at depths shallower than 10 km beneath the entire Klyuchevskoi Volcanic Cluster in 1961–2015. It was found that the Tolud earthquake sequence was the foreshock–aftershock process of the Tolud Earthquake. This is one of the larger seismicity episodes ever to have occurred in the volcanic areas of Kamchatka. Data of the Kamchatka seismic stations were used to compute some parameters for the Tolud Earthquake and its largest ($M_L$ = 4.3) aftershock; the parameters include the source parameters and mechanisms, and the moment magnitudes, since no information on these is available at the world seismological data centers. The focal mechanisms for the Tolud Earthquake and for its aftershock are consistent with seismic ruptures at a tension fault in the rift zone. Instrumental data were used to estimate the intensity of shaking due to the Tolud Earthquake. We discuss the sequence of events that was a signature of the time-dependent seismic and volcanic activity that took place in the Tolbachik zone in late November 2012 and terminated in the Tolud burst of seismicity. Based on the current ideas of the tectonics and magma sources for the Tolbachik volcanic zone, we discuss possible causes of these earthquakes.

**DOI:** 10.1134/S0742046317060033

## INTRODUCTION

This paper discusses the sequence of shallow earthquakes that was recorded between November 28 and December 7, 2012 in the southwestern sector of the Klyuchevskoi Volcanic Cluster (KVC), which was simultaneous with the initial phase (a few days) of the Tolbachik Fissure Eruption of 2012–2013 (TFE) (Gordeev et al., 2013; Belousov et al., 2015; among others). The epicenters concentrated in the area of the Tolud River; for this reason we will refer to this sequence of seismic events as the Tolud cloud or the Tolud earthquake sequence (Fig. 1). An $M_L$ = 4.9 earthquake occurred at a depth of ~6 km on November 30, 2012 (the Tolud Earthquake (TE), Fig. 2, Table 1). The subsequent seismic activization generally came to an end on December 6–7, 2012. The energy released by the Tolud earthquake cloud was ~50 times that released in 2012 in the area of Ploskii Tolbachik Volcano, both during the precursory period and immediately during the TFE occurrence. That seismic episode was so sudden, short-lived, and had such a high intensity that one can call it a burst of seismicity.

The seismicity of the Tolud River valley has repeatedly drawn the attention of researchers. The first mention of the Tolud epicenter zone[1] was in the studies of the 1975–1976 Great Tolbachik Fissure Eruption (GTFE), and its seismic activity was thought to be due to an outflow of basalt at shallow depths from under Ploskii Tolbachik Volcano during the eruption (*Bol'shoe ...,* 1984). However, large earthquakes such as the TE have never occurred in the Tolud epicenter zone.

The Tolud Earthquake is one of the five largest seismic events to have been recorded at depths shallower than 10 km beneath the entire KVC for all years of detailed seismological observation (1961–2015). Such were the earthquakes that preceded (in 1975) the North Vent eruption during the GTFE (*Bol'shoe ...,* 1984). The TE made the level of seismic activity in the Tolud epicenter zone *extremely high* according to the SOUS'09 scale (Saltykov, 2011) in time windows lon-

[1] A much larger area was understood as the Tolud epicenter zone in (*Bol'shoe ...,* 1984).

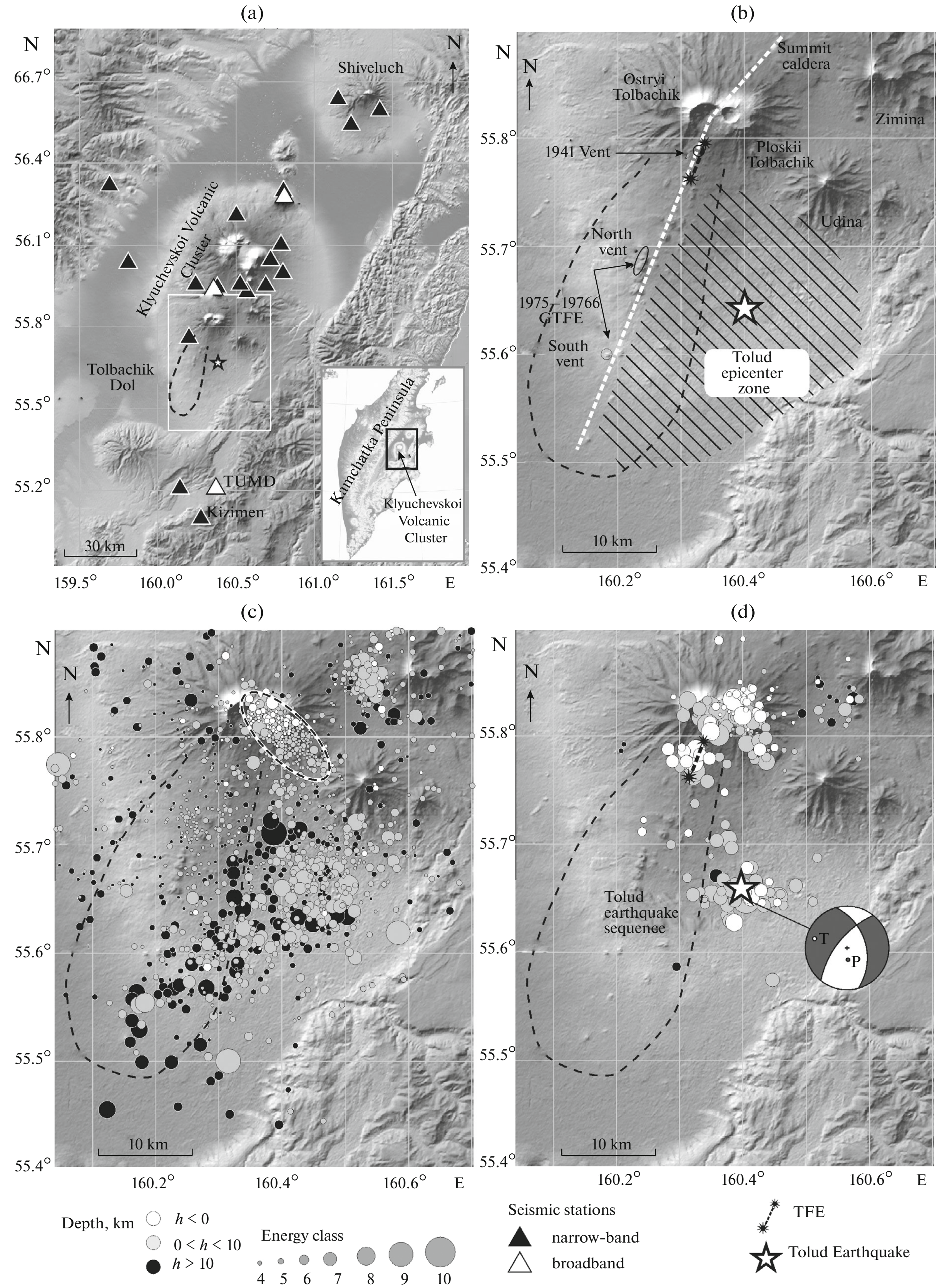

(a)
(b)
(c)
(d)
N
Shiveluch
Klyuchevskoi Volcanic Cluster
Tolbachik Dol
TUMD
Kizimen
30 km
Kamchatka Peninsula
Klyuchevskoi Volcanic Cluster
66.7°
56.4°
56.1°
55.8°
55.5°
55.2°
159.5°
160.0°
160.5°
161.0°
161.5°
E
Summit caldera
Ostryi Tolbachik
Zimina
1941 Vent
Ploskii Tolbachik
Udina
North vent
1975–19766 GTFE
South vent
Tolud epicenter zone
10 km
55.8°
55.7°
55.6°
55.5°
55.4°
160.2°
160.4°
160.6°
Tolud earthquake sequence
T
P
Depth, km
h < 0
0 < h < 10
h > 10
Energy class
4 5 6 7 8 9 10
Seismic stations
narrow-band
broadband
TFE
Tolud Earthquake

**Fig. 1.** A schematic map of the area where the Tolud earthquake sequence and the Tolud Earthquake occurred. (a) epicenter of Tolud Earthquake (star) in the map of seismic stations installed in the Klyuchevskoi Volcanic Cluster area; the light-line rectangle encloses the area that is shown in more detail in Figs. 1b, 1c, and 1d; (b) a map of the GTFE and TFE area; the light-colored dashed line shows the axial line of the deep-seated magma-conducting fault (rift); hatching highlights the Tolud epicenter zone; (c) epicenters in the Tolbachik volcanic zone between January 1, 1999 and November 26, 2012, before the TFE began; the ellipse encloses the area of the August–November 2012 seismic activization that was precursory to the TFE; (d) the seismicity that accompanied the first few weeks of the TFE, between November 27, 2012 and January 1, 2013; the epicenter of the Tolud Earthquake is marked by a star, and its focal mechanism is presented in a lower-hemisphere stereographic projection based on broadband seismic records (T is the tension axis and P the compression axis). The black dashed line shows the approximate boundary of the Tolbachik Dol.

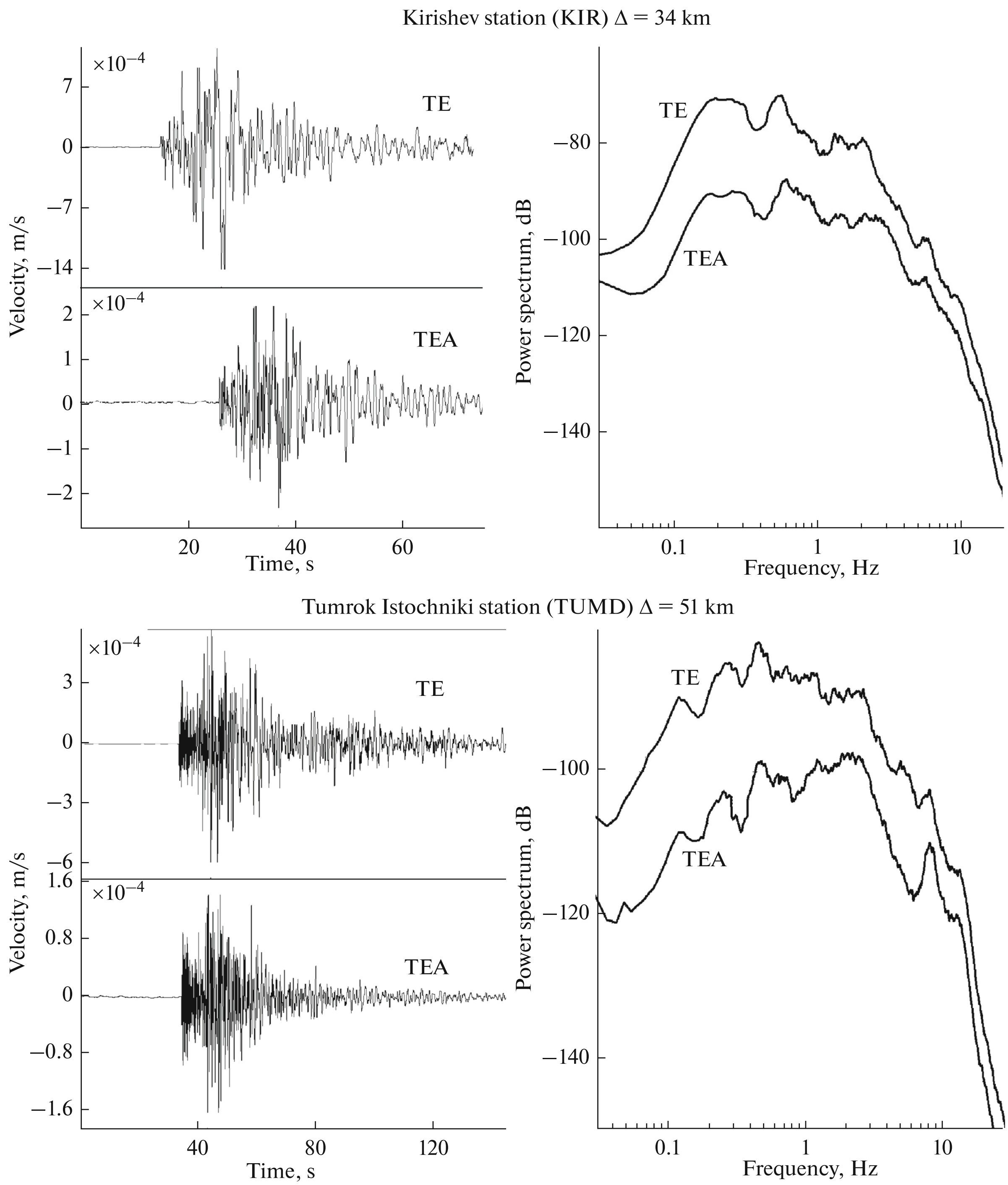



**Fig. 2.** Sample seismograms of the Tolud Earthquake (TE) and of its largest aftershock (TEA) as recorded by broadband seismic stations, and their spectra (vertical component).

**Table 1.** The parameters of the Tolud Earthquake (TE) and of its largest aftershock (TEA)

| Basic earthquake parameters, as reported by the KB FRC UGS RAS | | | | | | | |
|---|---|---|---|---|---|---|---|
| Event | Date and time[1)] dd.mm.yyyy hh:mm:SS | | Hypocenter location[2)] φ (°), λ (°), $h$ (km) | | | $K$[3)] | $M_l/M_C/m_b$[4)] |
| TE | Nov. 30, 2012 11:00:31.3 | | 55.66 | 160.41 | 6 ± 6 | 11.3 | 4.9/5.4/4.8 |
| TEA | Nov. 30, 2012 12:49:33.1 | | 55.65 | 160.42 | 5 ± 6 | 10.0 | 4.3/4.6/4.2 |
| Earthquake parameters based on broadband records | | | | | | | |
| Event | $M_0$ $10^{15}$ Nm | $M_W$ | $H$, km | $S$, km$^2$ | $D$, km | τ, s | σ, % |
| TE | 19.1 | 4.8 | 5 | 5 | 2.6 | 2 | 28 |
| TEA | 2.9 | 4.2 | 5 | 1.26 | 1.2 | 0 | 44 |

Abbreviations: KB Kamchatka Branch, FRC Federal Research Center, UGS Unified Geophysical Survey, RAS Russian Academy of Sciences

[1)]The uncertainty of the origin time is 0.3 s for both events; [2)]The uncertainty of the epicenter location is 6 km for both events; [3)]This paper uses $K = K_S$ following S.A. Fedotov's energy classification scheme (Fedotov, 1972); [4)]The magnitude $m_b$ was determined at the FRC UGS RAS, town of Obninsk (http://www.gsras.ru). $M_0$ is the scalar seismic moment; $M_W$ is the moment magnitude; $S$ is the rupture plane area; $H$ is the depth of the equivalent point source; $D$ is the linear size of the rupture zone; τ is rupture duration (the source for the aftershock is assumed to be instantaneous); and σ is the residual discrepancy (the sum of squares of deviations between the values of synthetic and observed seismograms as normalized by the sum of squares of the observed values).

ger than 11 days (Saltykov et al., 2012; Kugaenko et al., 2015).

We used data from the Kamchatka seismic stations to calculate parameters for the TE and its largest aftershock ($M_L = 4.3$, this aftershock will be abbreviated to TEA); the parameters include the scalar seismic moment, the depth of the equivalent point source and dimensions of the rupture plane; as well, focal mechanisms and moment magnitudes were found. The mechanisms of these events were computed using two methods: first motions and complete waveforms of displacement records. The second method also yields the moment magnitude. No information on these parameters is available for the Tolud earthquakes at the world seismological data centers.

We used the catalogs and seismic records acquired at the Kamchatka Branch of the Unified Geophysical Survey of the Russian Academy of Sciences Federal Research Center (KB UGS RAS FRC).

## THE TOLUD EARTHQUAKE SEQUENCE AS A SEISMIC ACTIVIZATION IN THE VOLCANIC AREAS OF KAMCHATKA

We will compare the Tolud earthquake sequence with the larger seismic activizations in the volcanic areas of Kamchatka. Shallow earthquakes that occur at distances of 10–15 km from active volcanoes that generate seismic events are classified as volcano-tectonic earthquakes (Tokarev, 1981; Gorel'chik et al., 1987; Gordeev et al., 2006, among others). It is commonly supposed that such seismic events can be caused by the emplacement and movements of magma melts. The seismicity around active volcanoes mostly occurs in Kamchatka in the form of swarm sequences, which means the absence of a main shock that would have its seismic energy significantly above the other earthquakes, and a nearly constant rate of seismicity in the swarm. Only seven volcano-tectonic sequences have been recorded in the volcanic areas of Kamchatka for the entire period of detailed seismological observation (1961–2015) where the largest earthquakes had $K_{max} > 11.0$ (here and below we are using the energy class after Fedotov (1972)):

The swarm of November 11, 1964 ($K_{max} = 12.3$, $M = 5.5$), which preceded the catastrophic eruption of November 12, 1964 on Shiveluch Volcano (Tokarev, 1967; Gordeev et al., 1998);

The swarm of June 27 through July 5, 1975 ($K_{max} = 11.3$, $M_{LH} = 5$), which preceded the GTFE North Vent eruption (*Bol'shoe ...,* 1984);

The Karymskii swarm of January 25 through February 23, 1978 ($K_{max} = 12.7$, $M = 5.4$) occurred during the active phase of the 1976–1982 eruption on Karymskii Volcano (Zobin et al., 1983; Tokarev, 1989; Gordeev et al., 1998);

The Asacha swarm of March 7 through April 8, 1983 ($K_{max} = 11.8$, $M = 4.6$) beneath the Asacha inactive volcano; this swarm sequence came to an end without any volcanic activity (Tokarev, 1984);

The seismic events of January 1 through February 20, 1996 in the Karymskii seismo-volcanic crisis (Fedotov, 1997); these have frequently been called a swarm, but an analysis of this seismic activization by Gordeev et al. (1998) showed them to be the foreshock–aftershock process of the January 1, 1996 Karymskii earthquake, which is the largest crustal earthquake ($K_S = 14.3$, $M_S = 7.0$, $M_W = 6.3$) ever to have been recorded beneath continental Kamchatka during the period of detailed seismological observation (Levina et al., 2002; Pavlov, 2010);

The swarm of 2009–2010 ($K_{max}$ = 11.9, $M_C$ = 5.3), which preceded the 2010–2013 eruption of Kizimen Volcano (Senyukov et al., 2011);

The Tolud earthquake sequence of November 28 through December 7, 2012, including the November 30, 2012 TE with $K_S$ = 11.3, $M_L$ = 4.9, $M_C$ = 5.4, the sequence that is the subject of the present study.

Nevertheless, we must note that one of the larger shallow Kamchatka earthquake swarms, the Shchapino swarm of 1963 ($K_{max}$ = 11.9, $M$ = 6.0), which covered the area of the Shchapina River graben and Kizimen Volcano as far as the northern Kronotskii Peninsula (Gordeev et al., 1991, 1998), occurred in one of the better-pronounced zones of crustal tectonic earthquakes of Kamchatka and is not considered to have been related to the activity of Kizimen Volcano, but is thought to be a result of local tectonic activity.

To sum up, the above list of sets of major volcano-tectonic earthquakes classifies the Tolud earthquakes of November 28 through December 7, 2012 as belonging to the largest seismic activizations that have been recorded in the volcanic areas of Kamchatka during the period of detailed seismological observation (1961–2015). Of these, only the Asacha swarm of 1983 and the Tolud earthquake sequence did not precede an eruption.

## THE AFTERSHOCKS OF THE TOLUD EARTHQUAKE

Seen on a map, the Tolud earthquake cloud is unrelated either to the precursory seismic activization before the eruption (see Fig. 1c) or to the area of earthquakes that occurred in the eruptive zone (see Fig. 1d). It tends toward the eastern edge of the long, NNE trending rift that traverses the summit of Ploskii Tolbachik Volcano and the zone of monogenic volcanoes in the Tolbachik Dol, and which supplies magma to the eruptive centers of Holocene eruptions (see Fig. 1b). The epicenters of the Tolud earthquake cloud make a compact ~5 × 10-km area that extends east–west (Fig. 3) 20 km to the south from Ploskii Tolbachik Volcano (see Fig. 1d). Approximately 70 seismic events with $K_S$ = 5.2–11.3 occurring between November 28, 2012 and December 7, 2012 have been located, with the total seismic energy released being $\Sigma E \sim 2.1 \times 10^{11}$ J. The focal depths are mostly within 10 km. The bulk of the aftershocks are above the main-shock hypocenter. The residuals from the location of the Tolud earthquakes are 4 km for the epicenters with a rms deviation of $\sigma$ = 1 km, and 5 km for depth with $\sigma$ = 2 km (this uncertainty is the rms deviation).

The frequency–size curve plotted for the Tolud earthquakes (Fig. 4) shows that the lowest level of complete reporting (under intensive volcanic tremor during the initial phase of the TFE) was determined to be $K_S$ = 6.2.

The behavior of the aftershock process over time is a characteristic instance of the empirical Omori law, which states that the activity of an aftershock sequence decays over time according to the power-law relationship $\frac{dN}{dt} \sim \frac{1}{t^p}$, where $N$ is the rate of aftershocks, $t$ is the time, and $p$ is the Omori parameter.

An analysis of the Tolud cloud showed that the TE was followed by an aftershock sequence of earthquakes during ~3 days (see Fig. 4) whose intensity decay followed a hyperbolic law (the Omori law with the parameter $p$ = 1). We must note that the two largest aftershocks with $K_S$ = 9.6 and $K_S$ = 10.0 occurred on November 30, 2012 during 2 hours after the main shock. That phase gave way to an episode of lower seismicity (between 7:30 December 3, 2012 and 3:09 December 5, 2012 ($K_S$ = 5.7–7.9), which had the character of a swarm with a nearly constant rate of seismicity; after that, the seismic activity of the Tolud cloud ceased. The three earthquakes that were recorded on November 28–29, 2012 before the TE seem to have been its foreshocks ($K_S$ = 6.4–6.8).

Examples of seismic records for the TE and for its largest aftershock (TEA, $K_S$ = 10.0, $M_L$ = 4.3, $M_C$ = 4.6) are shown in Fig. 2, with their basic parameters being listed in Table 1. Both events have impulsive onsets of P and S waves, which is in agreement with the characteristic record of a tectonic earthquake.

Summing up this discussion, we can say that the Tolud cloud was not a *swarm* of earthquakes as ordinarily defined. Taken on the whole, this set of seismic events can be regarded as a large earthquake that was preceded by a few distinctly recorded foreshocks, its decaying aftershock process, and a phase like a swarm, which mainly terminated this burst of seismicity.

## SOURCE PARAMETER DETERMINATION

No source parameters of the TE and TEA are available at the world seismological data centers. They were determined at the KB FRC UGS RAS based on records of Kamchatka seismic stations along with data from the worldwide network. The response curves for the Kamchatka system of seismic monitoring can be found in (Chebrov et al., 2013; *Sil'nye ...,* 2014); the seismic stations that monitor the KVC are shown in Fig. 1a.

The source mechanisms of the TE and TEA were obtained using two methods: from the first motions of body waves (Vvedenskaya, 1969) using Lander's software called FA2011[2] and from broadband digital seis-

[2] Lander, A.V., *Kompleks program opredeleniya mekhanizmov ochagov zemletryasenii i ikh graficheskogo predstavleniya* (A Set of Programs for Determining Earthquake Source Mechanisms and for Their Visualization), a report of the Kamchatka Seismological Technique Testing Team of the RAS Geophysical Survey entitled *Kompleksnye seismologicheskie i geofizicheskie issledovaniya Kamchatki i Komandorskikh ostrovov v 2003 g.* (Multidisciplinary Seismological and Geophysical Studies of Kamchatka and the Commander Islands in 2003). Archived at KB FRC UGS RAS, pp. 359–380.

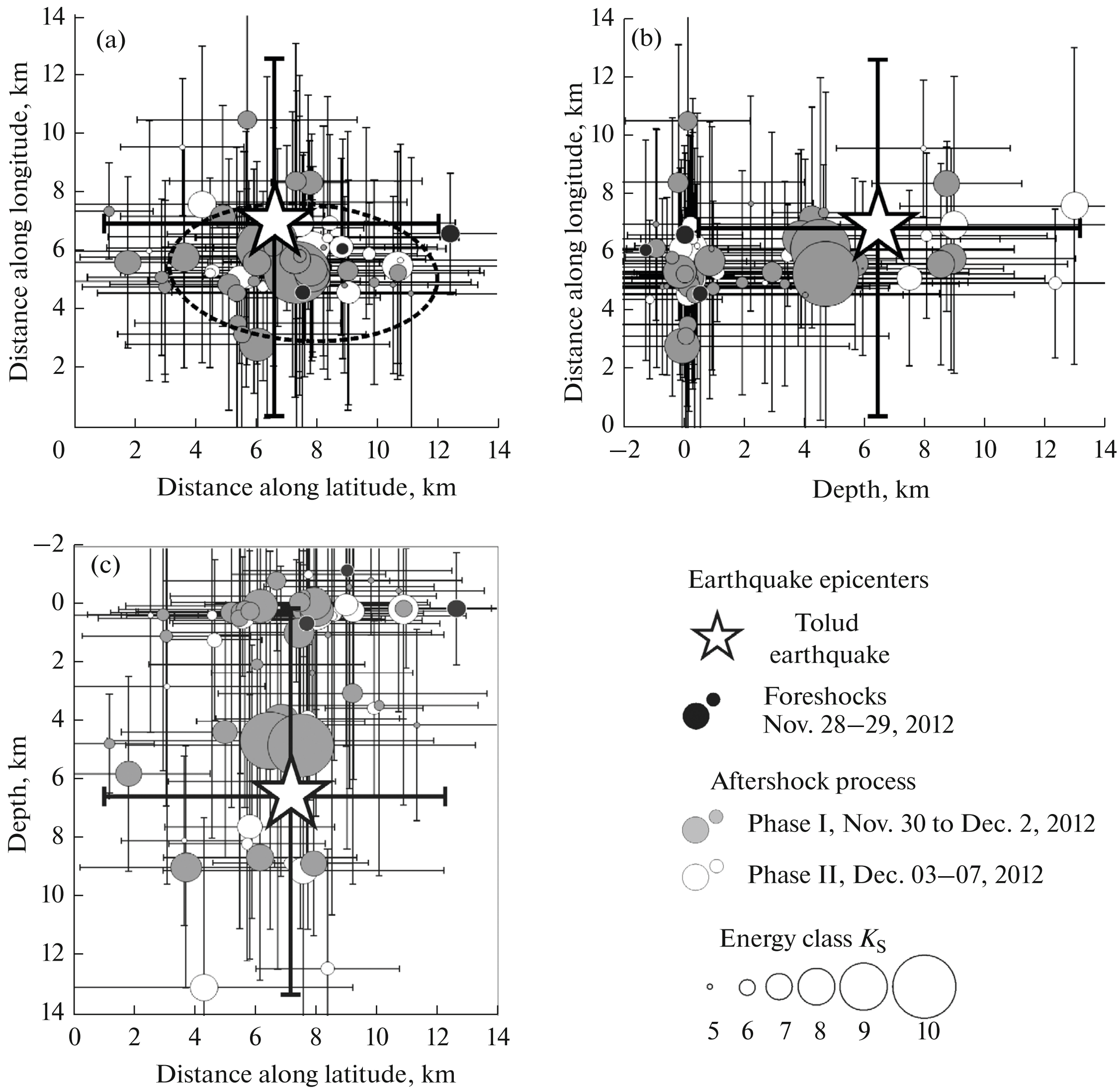



**Fig. 3.** The foreshocks and aftershocks of the Tolud Earthquake. A map of epicenters (a) and vertical cross sections (nearly east–west (b) and nearly north–south (c)). The ellipse encloses 90% of the epicenters. The different shading styles refer to the phases in the evolution of the foreshock–aftershock process as described in text. The bars show residuals in earthquake location (those for the TE are more solid).

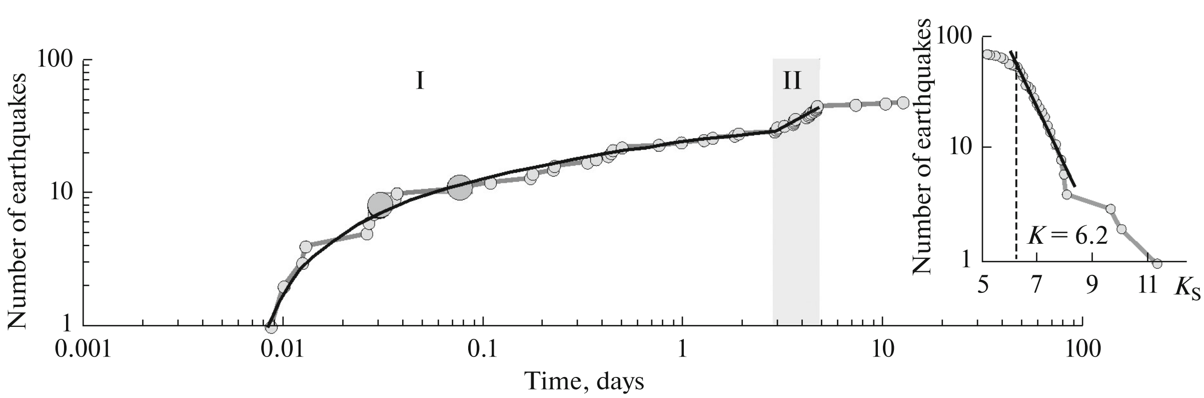
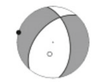
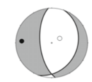



**Fig. 4.** Characteristic phases in the evolution of the aftershock process for the Tolud Earthquake. The time origin is the occurrence time of the main event. Time boundaries are marked for the identified phases: the aftershock sequence (I) and the swarm (II). The plot shows the two largest aftershocks. The inset shows a cumulative frequency–size curve for the Tolud earthquake cloud.

**Table 2.** The source mechanisms for the Tolud Earthquake and its largest aftershock

| Data used | Principal axes[1] | | | | | | Source mechanism[2] | | | | | | Beachball diagram[3] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | T | | N | | P | | *NP1* (°) | | | *NP2* (°) | | | |
| | *pl* | *azm* | *pl* | *azm* | *pl* | *azm* | *stk* | *dip* | *slip* | *stk* | *dip* | *slip* | |
| Tolud Earthquake | | | | | | | | | | | | | |
| Broadband seismograms | 11 | 289 | 37 | 27 | 50 | 185 | 342 | 47 | −146 | 227 | 66 | −49 |  |
| Signs of *P* first motions | 0 | 286 | 28 | 16 | 62 | 196 | 351 | 51 | −126 | 221 | 51 | −53 |  |
| The lyargest aftershock of the Tolud Earthquake | | | | | | | | | | | | | |
| Broadband seismograms | 11 | 286 | 28 | 23 | 59 | 175 | 345 | 41 | −136 | 219 | 63 | −58 |  |
| Signs of *P* first motions | 18 | 273 | 11 | 180 | 69 | 60 | 20 | 28 | −67 | 174 | 63 | −102 |  |

1) Axis orientation is given by two angles: plunge angle, pl and azimuth, azm; 2) The orientation of a nodal plane is given by two angles, strike, stk and the dip angle, dip. The angle of slip (slip) is the angle in the fault plane between the strike and the slip vector measured counterclockwise from the strike direction); 3) An equal-area projection of the lower hemisphere was used.

mograms by computing the seismic moment tensor (Pavlov and Abubakirov, 2012). We note that the mechanism based on first motions mostly supplies information on the initial phase of the earthquake rupture, while the mechanism derived from long period waveforms is relevant to the source as a whole. Both of these earthquakes show rather impulsive P onsets (see Fig. 2). Owing to this, we have succeeded in using the P displacement signs in the first case as recorded at 37 regional Kamchatka stations and at 14 worldwide stations in the range of epicentral distance $\Delta$ below ~8000 km. In the second case we also estimated the depth of an equivalent point source, its duration $\tau$, the moment magnitude $M_W$ , and the size of the rupture plane (see Table 1).

The procedure that is used to estimate the mechanism from waveforms was described in (Pavlov and Abubakirov, 2012). Properly speaking, the mechanism (a pair of P waves nodal planes having matched normals) is found from the seismic moment tensor (SMT). The components of the SMT are found by minimizing a normalized function of residuals between observed and synthetic displacement waveforms. The resulting components are used to calculate the principal values and principal vectors of the SMT, which give the nodal planes and the scalar seismic moment $M_0$. This last determines the value of the moment magnitude $M_W = 2/3(\log(M_0[\text{N m}]) - 9.1)$ (Hanks and Kanamori, 1979).

The procedure begins by reconstructing the "true" displacements from instrumental records. The synthetic seismograms were computed using a modified variant of the AK135 global earth model (Kennett et al., 1995). Both the observed and the synthetic waveforms were filtered in the band of periods 16–25 s. The filter bandpass was chosen so as to make the records of "true" displacements dominant compared with the noise. The assumption was that the SMT is of the "double couple without moment" type. The source time function for the TE is a symmetrical triangle, while that for the TEA is a delta function (an instantaneous pulse). For both events the optimal mechanism is for a depth of 5 km. The results of this calculation for the main shock and its aftershock are shown in Fig. 5 and in Table 2. Figure 6 presents waveforms of observed displacements and the displacements that were calculated using the optimal SMTs.

The value of the moment magnitude was used to estimate the source lengths for the Tolud earthquakes. We begin by estimating the fault plane area using the correlative relationship $\log(S[\text{km}^2]) = M_W - 4.1$ following (Gusev and Mel'nikova, 1990). If the fault plane is a circle of radius $R$, then $R = (S/\pi)^{1/2}$. In that case we obtain, for the main shock of magnitude $M_W$ = 4.8, the value of radius equal to $R$ = 1.3 km; for the aftershock of magnitude $M_W$ = 4.2 we get $R$ = 0.6 km. Summing up, we conclude that, assuming a circular fault plane, the dimensions of the TE and TEA can be

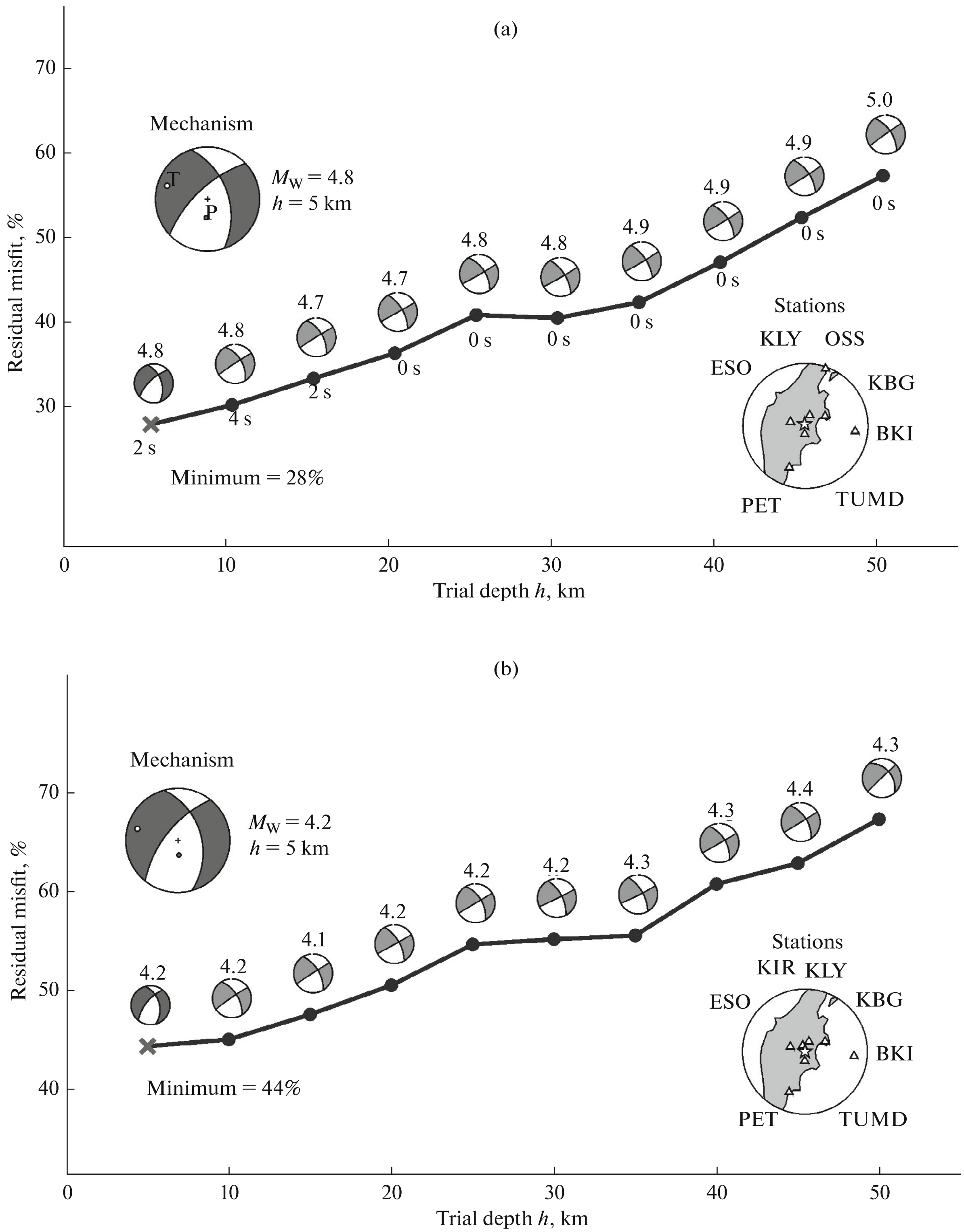



**Fig. 5.** The results of calculations of the SMT of the double couple without moment type for the Tolud Earthquake (a) and its largest aftershock (b). One can see remaining residuals ε as a function of trial depth (at steps of 5 km), where the remaining residuals are equal to the sum of squares of the differences between synthetic and observed seismograms normalized by the sum of squares of observed seismograms. For each trial depth we give the relevant mechanism, the moment magnitude, and rupture duration at the source τ (the source for the aftershock is instantaneous, τ = 0; the time step is 2 seconds). Both figures show the optimal solution in the top left corner, while the right bottom corner contains the locations of the broadband stations (triangles) around the epicenter (star) that we used. The mechanisms are shown in the equal-area projection of the lower hemisphere.

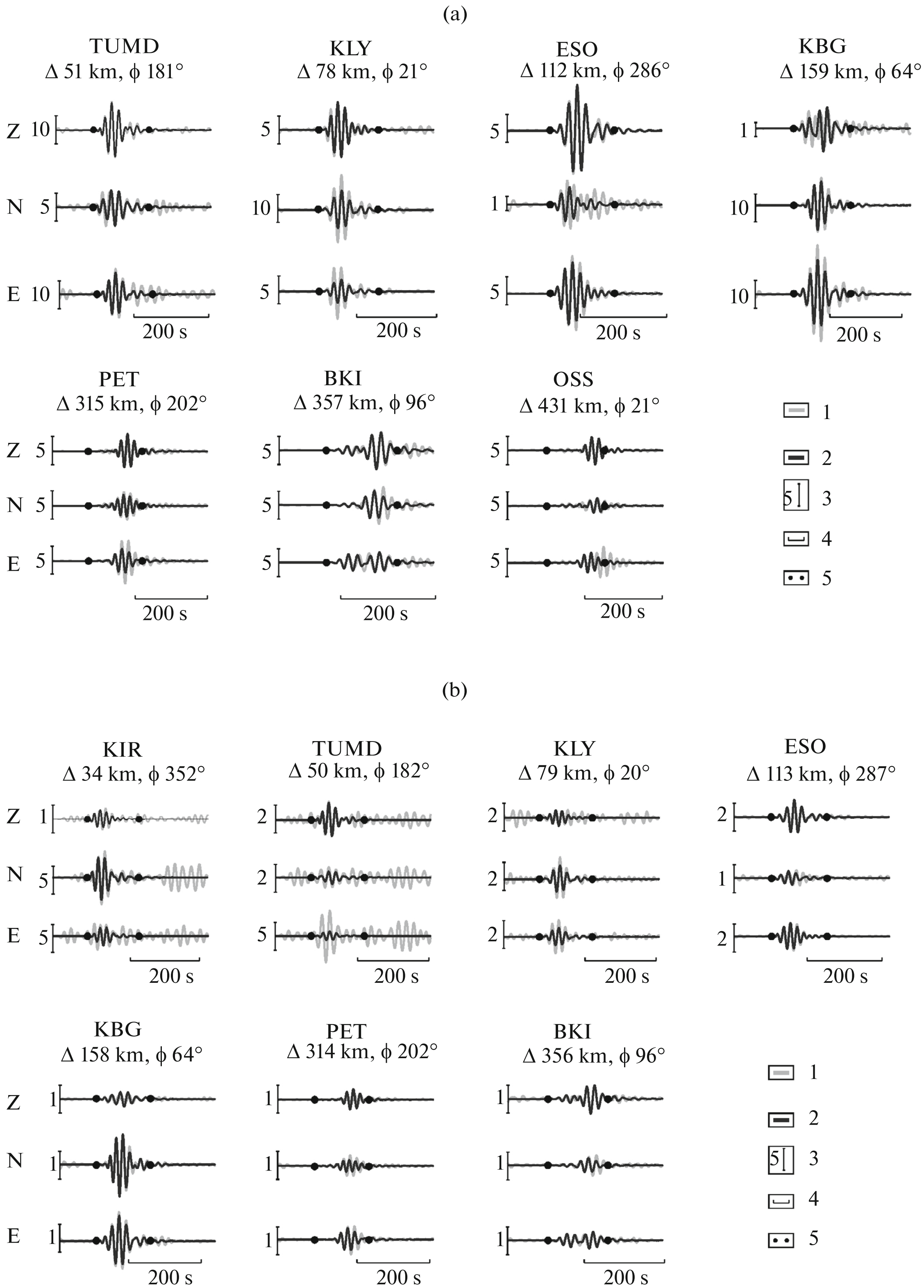



**Fig. 6.** Comparing the waveforms of observed (1) and synthetic (2) displacements due to the Tolud Earthquake (a) and to its largest aftershock (b) as calculated for the optimal mechanisms and a depth of 5 km. The amplitude scale (3) is given in units of $10^{-4}$ cm. For each station we mark the epicentral distance Δ and azimuth φ; the 200-s interval is marked (4). The dots (5) enclose the end-points of the interval of fitting.

estimated as $D = 2R = 2.6$ km and $D = 1.2$ km, respectively.

The source mechanisms for the TE and the TEA as given by the two methods are quite mutually consistent for the main shock and show mostly the normal type of slip for the aftershock (see Table 2). The earthquakes were caused by a prevailing east–west tensional stress. Both nodal planes had normal displacement combined with a strike-slip component. We note that the configuration of the Tolud burst area (see Fig. 3) does not fit either of the two possible rupture planes, while the linear dimensions of the aftershock area are comparable with the uncertainty of hypocenter location; hence, it would be difficult to estimate its real spatial parameters. We would be even less justified to discuss any fine structure of the aftershock cloud (e.g., clustering, see Figs. 3b and 3c), since such clustering can turn out to be an artifact. We thus do not interpret the spatial hypocenter distribution and do not try to find relationships between the TE source mechanism and its aftershock process, because the aftershock cloud is spread out due to errors. In accordance with the tectonics of the Tolbachik volcanic zone (a NNE rift, see Fig. 1b), our choice of the fault plane prefers the NNE-striking nodal plane (NP2, see Table 2).

## ESTIMATING THE INTENSITY OF GROUND MOTION

The historical eruptions of Kamchatka volcanoes (Klyuchevskoi, Tolbachik, Shiveluch, Avacha, Kizimen, and Zheltovskii, and others) were frequently accompanied by felt earthquakes, with the intensity of shaking at population centers reaching ~7 grades on the MSK–64 scale (Fedotov and Shumilina, 1971; Tokarev, 1981; Gusev and Shumilina, 2004; Gordeev et al., 2006; *Svodka ...,* 2010; Krasheninnikov, 2013, among others).

The TE occurred in a remote unpopulated area, so that there is no information on felt effects. However, one can estimate the intensity from instrumental observations (Aptikaev, 2012). We will use the scale of seismic intensity from (*Zemletryaseniya ...,* 2015), which gives estimates of seismic intensity that are identical with those on the MSK-64 scale to within the error of determination.

The KLY (village of Klyuchi, $\Delta \sim 78$ km) and TUMD (the Tumrok Turbaza, $\Delta \sim 50$ km) seismic stations are also equipped with digital accelerometers, in addition to velocity meters. Peak ground accelerations (PGA) at these sites were (for the east–west, north–south, and vertical channels, respectively) 4.5 cm/s$^2$, 9.3 cm/s$^2$ , and 3.6 cm/s$^2$ for the KLY station and 8.9 cm/s$^2$, 6.1 cm/s$^2$ , and 9.4 cm/s$^2$ for TUMD; the peak ground velocities (PGV) were 0.05 cm/s, 0.07 cm/s, and 0.04 cm/s for KLY, and 0.12 cm/s, 0.09 cm/s, and 0.07 cm/s for TUMD.

Our intensity estimates for these two sites were based on the following parameters of ground motion: PGA, PGV, as well as the product PGA · PGV (the power of the seismic wave), and PGA · $\tau^{0.5}$ (the Arias intensity, where the duration of motion is $\tau = 5$ s, following (*Zemletryaseniya ...,* 2015)). In accordance with the recommendations in (*Zemletryaseniya ...,* 2015), we used only the maximum values for the horizontal component of seismic records. The arithmetic means of PGA, PGV, PGA · $\tau^{0.5}$, PGA · PGV, the respective values of intensity $I$ and its standard deviation $\sigma(I)$, as well as the weight functions $f$, were given in (*Zemletryaseniya ...,* 2015). The intensity of shaking as estimated for the TE and averaged over all the above parameters, with due account for $f$ and $\sigma$, was $I = 4.0 \pm 0.8$ at TUMD and $I = 3.5 \pm 0.8$ at KLY. We wish to note that the functions of intensity versus distance given by Gusev and Shumilina (1999) as estimated for long rupture zones in the Kuril–Kamchatka–Japan region enable one to estimate the intensity for an $M_W \sim 5$ event as $I \sim 7.5$ at a distance of ~5 km from the center of the epicentral zone and $I \sim 3$–4 at distances of 50–80 km, which is acceptable (for the goals of the present study) and is consistent with the values derived above for the TE.

The intensity in the TE epicentral zone was estimated using the linear equation of the macroseismic field $I = aM - b \log h + c$, where $h$ is the depth of focus, and $a$, $в$, and $c$ are empirical constants (we have $a = 1.5$, $в = 2.6$, and $c = 2.5$ for Kamchatka), after (*Zemletryaseniya ...,* 2015). According to this relationship, $I$ is ~8 grades for an earthquake of magnitude $M \sim 5$ and the hypocentral depth $h \sim 6$ km. This intensity value can also be obtained by using the macroseismic field equation from (Fedotov and Shumilina, 1971), which was previously applied to shallow earthquakes in Kamchatka. Considering that the uncertainty of depth determination for the TE is ~6 km ($h = 6 \pm 6$ km), the intensity of ground shaking in its epicentral zone might exceed 8 with a shallower hypocenter, and could well be ~7 with a hypocentral depth equal to $h \sim 10$–12 km. Earthquakes that cause $I \geq 8$ produce cracks in the ground and still larger discontinuities. It is impossible either to confirm or reject such an effect due to the TE, because the epicentral zone has not been visited and surveyed.

## RESULTS AND DISCUSSION

We will discuss the Tolud earthquake cloud by examining the sequence of events that bear the imprint of the seismic and volcanic activity in the Tolbachik zone in late November 2012, at the start of the TFE (Fig. 7).

The TFE, its chronology, and results from comprehensive studies have been reported in numerous publications (Saltykov et al., 2012; Gordeev et al., 2013; Dvigalo et al., 2014; Ermakov et al., 2014; Fedotov

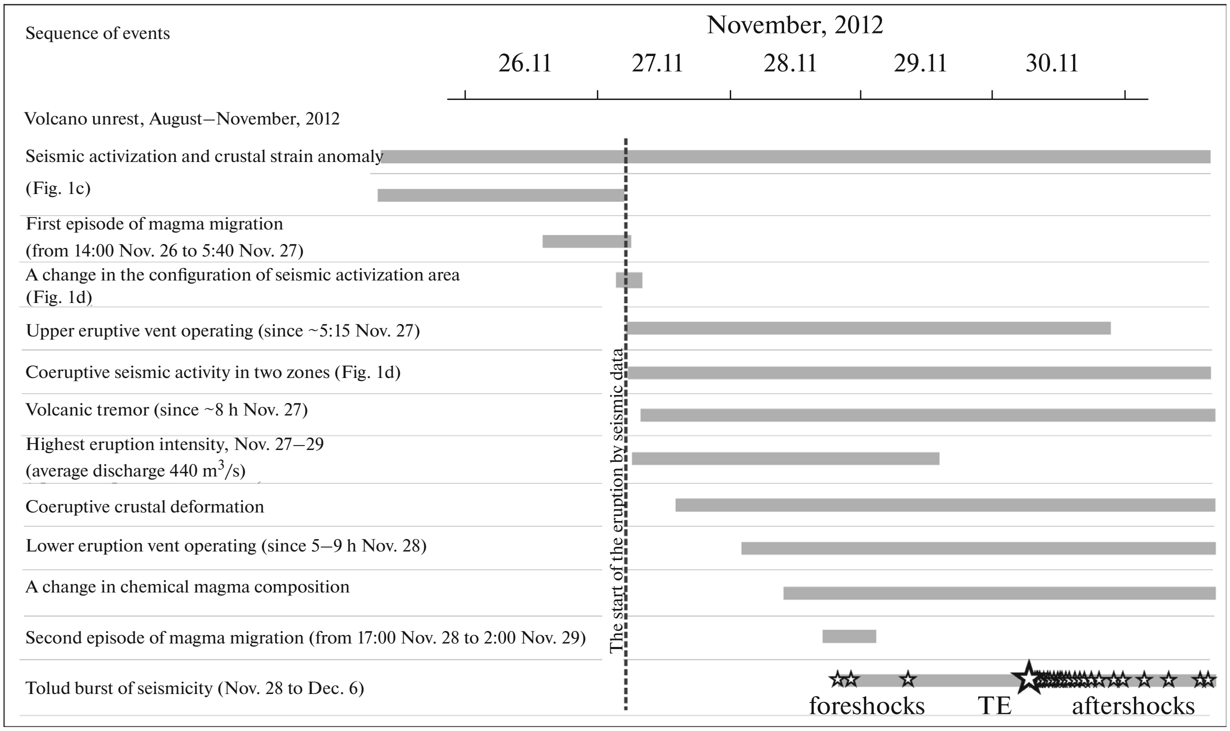



**Fig. 7.** The chronology of the main events related to the start of the TFE. Their description and the needed references are in the text.

et al., 2014; Kugaenko et al., 2015; Belousov et al., 2015, among many others). The eruption was treated at length in a special issue of the *Journal of Volcanology and Geothermal Research*, which appeared on December 1, 2015 with 17 articles by Russian and foreign researchers. The Tolud earthquakes were not considered in detail in these papers, although they were repeatedly and unjustifiably mentioned as the Tolud swarm.

The precursory period of the TFE was recorded by instrumental means as follows: the eruption was preceded by a long-term and shallow seismic activization at a low energy level (August through November 2012), which occurred synchronously with a developing anomaly of crustal deformation that was detected independently using GPS data (Saltykov et al., 2012; Kugaenko et al., 2015a, 2015b). The seismicity in the seismic volume under study here had been at an *extremely high level* on the SOUS'09 scale during the last 3 weeks before the TFE (Saltykov, 2011) and considerably increased on November 26, 2012. The deformation anomalies were observed throughout the entire middle part of the KVC: a radial (relative to the eruption) compression was recorded and an extension in a tangential direction (Kugaenko et al., 2015a). These processes were consequences of extra magma portions that were being emplaced into the magmatic plumbing system in the TFE area.

The start of the eruption was detected from seismic data, in the absence of direct visibility. It is thought to have occurred at 5:15 on November 27, 2012 (UTC is used here and below) (Senyukov et al., 2015).

During the same time, a fracture zone striking nearly north–south for a distance of ~6 km began to be formed on the southern slope of Ploskii Tolbachik Volcano and in the northern part of the adjacent Tolbachik Dol in the altitude range ~1740–2360 m (Dvigalo et al., 2014), with eruptive centers gradually concentrating along this zone. This can be clearly seen in a map of earthquake epicenters where two spatially separated sets of earthquakes were formed on November 27, 2012. One of these sets remained connected to Ploskii Tolbachik Volcano, while the other was formed in the zone of the incipient TFE (see Fig. 1d).

The eruptive process was dominated by the upper part of the fissured zone during the first 2 days; this part was the upper vent or the Menyailov Vent. The vent was only active until November 30, 2012. Approximately 24 hours after the start of the eruption a vent was formed in the lower part of the fissured zone, which was called the Naboko Vent; this vent concentrated the TFE eruptive activity until it came to an end in September 2013. The timing of the lower vent was determined, in the absence of direct visibility, by a multidisciplinary analysis of satellite and petrologic data: ~5–9 h November 28, 2012 (Melnikov and Volynets, 2015). The lower vent gave the first indication of a change in the chemical composition of erupted rocks during the TFE (Volynets et al., 2015).

Giant movements of material occurred in the area of Ploskii Tolbachik Volcano during the initial period of the TFE. The magma discharge was 440 $m^3/s$ during November 27 through 29, 2012, with the volume of erupted material reaching 0.072 $km^3$ (Dvigalo et al., 2014). The first days of the eruption saw a change in the sign of the principal strains; some ground movements occurred within 60 km of the eruptive centers (Kugaenko et al., 2015a, 2015b), providing evidence of a rapid discharge in the magma chamber region.

However, the magma movements were not confined merely to discharge onto the ground surface. An analysis of seismic records for November 24 through 30, 2012 using the SARA technique (Seismic Amplitude Ratio Analysis, see Taisne et al., (2011)) revealed two episodes of hidden magma migration (Caudron et al., 2015). The first episode involved the replacement of an initial vertical migration with a horizontal movement starting approximately 15 h before the reported eruption time, at ~14 h on November 26, 2012. The episode came to an end at 5:40 on November 27, 2012, approximately corresponding to the hypothetical time when the TFE began. The second episode of southward magma migration (from ~17 h November 28, 2012 to ~2 h November 29, 2012) occurred in timing with the foreshocks of the Tolud Earthquake and the start of the Tolud earthquake sequence.

The "center of gravity" for the seismicity that accompanied the start of the TFE moved into the Tolud epicentral zone during November 28 through 30, 2012, signalling the start of the Tolud burst of seismicity.

It may be supposed to a high degree of probability that the TFE and the Tolud earthquakes were related paragenetically and had the same geodynamic cause.

Based on the current concepts of the tectonics and magma sources of the Tolbachik volcanic zone, we will discuss two possible scenarios for the sequence of events that might have led to the Tolud burst of seismicity.

### *The Tolud Burst of Seismicity as a Result of the Emplacement of a Nearly Vertical Intrusion in the Hanging Wall of an Inclined Magma-conducting Fault*

Ermakov et al. (2014) formulated a hypothesis purporting to explain the seismic activity of the Tolud epicentral zone, viz., that the asymmetrical locations of earthquake hypocenters relative to the axial line of a deep-seated fault is related to the fact that the fault (the main magma-conducting feature) dips steeply east, plunging under the Tolud epicenter zone (see Figs. 1b and 1c). Further argument invokes intrusions of magma (in the hanging wall of the fault, mostly shallower than 20 km) that comes along the fault from below; it was thought that these intrusions caused the earthquakes. Belousov et al. (2015) used V.A. Ermakov's ideas and perologic data to argue for the existence of an extensive region where magnesian basalts are being accumulated at a depth of ~20 km beneath the entire Tolud epicenter zone. These authors consider this region as a possible source of supply for the 1975 North Vent generation during the GTFE, for the 1941 eruption, and probably for several other Late Holocene eruptions in the Tolbachik Dol. The seismic activization before the start of the GTFE is treated by Belousov et al. (2015) as a result of upward movement of magma from under the Tolud epicenter zone rather than at any other location. Following this logic, we believe that an analogous situation might have occurred in 2012 as well: an intrusion or another vent might be formed during the TFE if the zone of magma storage beneath the Tolud epicenter zone experienced some triggering disturbance later than the TFE source did. In that case, the TE might be interpreted as a manifestation of local intrusive activity that has not reached the ground surface. The intrusion might activate a tension fissure and produce normal-slip earthquakes. In our opinion, the data are still insufficient to confirm and explain an almost simultaneous resumption of activity for the two zones of magmatic plumbing indicated above, with the two zones producing substantially different erupted rocks. This problem is outside the scope of the present paper.

### *The Tolud Burst of Seismicity as a Result of Lateral Migration of Basalt Along the Rift*

Bearing in mind the episodes of magma migration that have been identified to occur at the start of the TFE (Caudron et al., 2015), it might be hypothesized, proceeding by analogy with the 1975–1976 GTFE, that the Tolud epicenter zone had become a kind of reservoir to store the basalts that were coming to it from the north, from the area of the starting eruption. Here, we will note the events during the GTFE that are thought to have been related to sublateral migration of basalts. A collapse occurred in the summit caldera of Ploskii Tolbachik Volcano during the first few months of the eruption in 1975 as the GTFE North Vent was being generated, with the collapse being synchronous with the seismicity increase in the Tolud epicenter zone. The North Vent then stopped its activity and the seismicity began migrating southward where a new eruptive center, the GTFE South Vent, was formed at a distance of ~25 km from Ploskii Tolbachik 2 days afterwards. As its eruptive activity came to an end in late 1976, the seismicity continued to occur, but moved again some 10–15 km south of the Tolbachik Dol; however, magma did not reach the ground surface at that time. The history of the 1975–1976 eruption, as well as seismological, geodetic, and petrologic data, suggested the hypothesis that a large-scale shallow movement of basalt took place from under Ploskii Tolbachik in 1975, first to the Tolud zone, and afterward into the southern Tolbachik Dol (*Geologicheskie ...,* 1978; *Bol'shoe ...,* 1984; Gorel'chik and Zav'yalov, 1986; Fedotov et al., 1991; Magus'kin and Magus'kin, 2016, among many others). A substantial body of evidence has accumulated that supports the idea of analogous considerable lateral movements of magma, occasionally for distances of many kilometers, in the crust in volcanic areas (Sigmarsson et al., 2000; Ishizuka et al., 2008; Taisne et al., 2011; Grandin et al., 2012; Gonzalez et al., 2013; Sigmundsson et al., 2015; Tibaldi, 2015; Magee, 2016, among others). It can therefore be hypothesized that magma might come from the north during the initial phase of the TFE (November 27 through 30, 2012) along the rift to penetrate under the Tolud epicenter zone. This might open one of the preexisting fissures that run nearly parallel to the main magma-conducting fault in the Tolbachik Dol, resulting in the TE on November 30, 2012 accompanied by foreshocks and aftershocks. This sequence of events, similarly to the first scenario, is not inconsistent with the TE source mechanism, which involves normal slip under tension across the fissure. In our opinion, the second variant, which explains the Tolud burst of seismicity by magma moving along the rift, is more realistic and fits the sequence of events during the initial phase of the TFE.

We note that magma emplacement in both of these cases might be also accompanied by a lower seismicity ($K < 5.0$), which might not have been recorded by the seismic network due to intensive volcanic tremor. It may well be that further seismological and other research of the TFE would produce some more evidence to support or reject the above scenarios. In both of these cases the TE is a tectonic earthquake that was initiated by magma movement, that is, is a volcano-tectonic earthquake.

However, one can easily think of another possible cause of the Tolud earthquakes, which is a rearrangement of the stress field due to the deformation during the precursory period of the TFE and during the intensive magma effusion of November 27 through 29, 2012. The hypothesis calls for substantiation and several simulation studies. However, such simulation will be impeded by difficulties due to imperfections of the GPS network in the area of Ploskii Tolbachik Volcano.

## CONCLUSIONS

This study was concerned with the Tolud earthquake sequence of November 28 through December 7, 2012. This sequence was a burst of seismicity that accompanied the start of the 2012–2013 Tolbachik Fissure Eruption and occurred ~20 km to the south of the eruption zone. We studied the two largest earthquakes from this sequence of seismic events, viz., the Tolud Earthquake with $M_L = 4.9$ and its largest aftershock with $M_L = 4.3$. We used seismic records to compute the scalar seismic moment, the focal mechanism, the moment magnitude $M_W$, the depth of an equivalent point source and the dimensions of the rupture plane. The aftershock process of the Tolud Earthquake was analyzed.

The intensity of shaking in the epicentral zone of the Tolud earthquake might reach ~8 on the MSK-64 scale, with the intensity at the nearest population centers, 50–80 km from the epicenter, being estimated to have been 3–4 grades as derived from instrumental data.

The following results have been obtained:

—The Tolud sequence of seismic events was the foreshock–aftershock process of the Tolud Earthquake rather than an earthquake swarm, which is a very common occurrence in volcanic areas;

—The Tolud Earthquake was caused by a tensional stress across the deep-seated magma-conducting fault (rift) that supplied magma to the Holocene fissure eruptions in the Tolbachik Dol;

—The focal mechanisms of the Tolud Earthquake and of its largest aftershock are oblique-normal events, in agreement with faulting on a tension fissure (fault) in the rift zone;

—The strike azimuth of one of the nodal planes in these events is consistent with the trend of the rift and this allowed us to select it as the responsible fault plane.

We showed that the Tolud Earthquake and its foreshock–aftershock sequence constitute one of the larger seismic activizations that have ever been recorded in the volcanic areas of Kamchatka.

The Tolud earthquake cloud furnished another confirmation of the fact that, similarly to the 1975–1976 Great Tolbachik Fissure Eruption, the eruption-associated processes involved considerable spatial areas rather than concentrating in the zone of eruptive centers only. Comparison with the Great Tolbachik Fissure Eruption suggests the hypothesis that there was a similar magma movement at depth in 2012 from under Ploskii Tolbachik Volcano southward, which did not however terminate in an eruption, but manifested itself as the Tolud earthquake sequence.

This study is the first example of the use of broadband seismic records to compute focal mechanisms for earthquakes in the Klyuchevskoi Volcanic Cluster. This experience has been a success and shows that the existing network of broadband stations provides good azimuthal coverage of this volcanic cluster. The technology, as developed and applied in the present study, can be used in the future to perform analogous calculations of focal mechanisms and moment magnitudes for sufficiently large ($M \sim 4$–5) earthquakes in the area that are not routinely reported by world data centers.

## ACKNOWLEDGMENTS

This study was supported in part by the Russian Foundation for Basic Research, project nos. 13-05-00117 and 17-05-00127.

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*Translated by A. Petrosyan*