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Progressive reactivation of the volcanic plumbing system beneath Tolbachik volcano (Kamchatka, Russia) revealed by long-period seismicity

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ABSTRACT

After lying dormant for 36 yr, the Tolbachik volcano of the Klyuchevskoy group started to erupt on 27 November 2012. We investigate the preparatory phase of this eruption via a statistical analysis of the temporal behavior of long-period (LP) earthquakes that occurred beneath this volcanic system. The LP seismicity occurs close to the surface beneath the main volcanic edifices and at 30 km depth in the vicinity of a deep magmatic reservoir. The deep LP earthquakes and those beneath the Klyuchevskoy volcano occur quasi-periodically, while the LP earthquakes beneath Tolbachik are clustered in time. As the seismicity rate increased beneath Tolbachik days before the eruption, the level of the time clustering decreased. We interpret this as a manifestation of the evolution of the volcano plumbing system. We suggest that when a plumbing system awakes after quiescence, multiple cracks and channels are reactivated simultaneously and their interaction results in the strong time clustering of LP earthquakes. With time, this network of channels and cracks evolves into a more stable state with an overall increased permeability, where fluids flow uninhibited throughout the plumbing system except for a few remaining impediments that continue to generate seismic radiation. The inter-seismic source interaction and the level of earthquake time clustering in this latter state is weak. This scenario suggests that the observed evolution of the statistical behavior of the shallow LP seismicity beneath Tolbachik is an indicator of the reactivation and consolidation of the near-surface plumbing system prior to the Tolbachik eruption. The parts of the plumbing system above the deep magmatic reservoir and beneath the Klyuchevskoy volcano remain in nearly permanent activity, as demonstrated by the continuous occurrence of the deep LP earthquakes and very frequent Klyuchevskoy eruptions. This implies that these parts of the plumbing system remain in a stable permeable state and contain a few weakly interacting seismogenic sources. Our results provide new constraints on future mechanical models of the magmatic plumbing systems and demonstrate that the level of time clustering of LP earthquakes can be a useful parameter to infer information about the state of the plumbing system.

1. Introduction

Seismicity is one of the main observable manifestations of volcanic unrest (e.g. Chouet, 2003; McNutt, 2005; Sparks et al., 2012; Chouet and Matoza, 2013). Most pre- and co-eruptive processes within volcanic systems are accompanied by seismic radiation that can be used to detect and identify different phases of the eruptive cycle. Seismic signals associated with volcanic unrest take many forms. Stresses induced by the ascending magma are released in the form of volcano-tectonic earthquakes (e.g. Roman and Cashman, 2006). Magmatic and hydrothermal volcanic systems also generate earthquakes and tremors with periods that are longer than those for typical tectonic earthquakes of similar sizes (e.g. Fehler, 1983; Chouet, 1988, 1996; Iverson et al., 2006). The mechanisms involved in the generation of this long-period (LP) seismicity are often believed to be different from those of tectonic earthquakes (Chouet, 1996). LP earthquakes are commonly inter-

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preted as reflecting pressure fluctuations within magmatic and hydrothermal fluids, and are considered a reliable precursor of volcanic eruptions (e.g. Chouet, 1988, 1996; Chouet and Matoza, 2013; Power et al., 2013). Possible triggering mechanisms include magma-hydrothermal interactions (Waite et al., 2008) and magmatic degassing (Ripepe et al., 1996; Lees et al., 2004; Jolly et al., 2017). Other studies have proposed mechanisms such as brittle fractures of melt and near-vent plug stick-slip (e.g Iverson et al., 2006; Neuberg et al., 2006; Kendrick et al., 2014) and crack opening during deformation of the volcanic edifice (Bean et al., 2014). Most of reported volcanic LP seismicity reflects the activity within shallow magmatic reservoirs and hydrothermal systems. In this context, volcanic deep LP earthquakes (e.g. White, 1996; Nakamichi et al., 2003; Power et al., 2004; Nichols et al., 2011; Shapiro et al., 2017a; Han et al., 2018) that occur in the lower crust and the uppermost mantle are particularly interesting, because they reflect the pressurization of deep-seated parts of the magmatic systems and the transfer of magma and pressure toward the surface.

Volcanic LP earthquakes are known to occur in bursts and are often associated with volcanic tremors (Fehler, 1983; Chouet, 1996). Shaw and Chouet (1991) used a statistical analysis of tremor to characterize the magma transport system beneath Hawaii. In our study, we use a statistical analysis of the LP earthquake catalogs to extract information about the complexity of the different parts of the plumbing system through which fluids are transported. We use the approach of Frank et al. (2016) to infer the level of time clustering of LP earthquakes. We argue that this clustering depends on the level of interaction between different seismic sources and reflects the level of connectivity of the underlying fluid transport system.

2. Klyuchevskoy volcanic group

We analyze here catalogs of deep and shallow LP earthquakes that occurred within the Klyuchevskoy volcano group (KVG) in Kamchatka, Russia (Fig. 1a) during 2011 and 2012 (Shapiro et al., 2017a). The KVG is one of the largest and most active clusters of subduction zone volcanoes in the world (e.g. Fedotov et al., 1987, 2010; Koulakov et al., 2011, 2017; Churikova et al., 2013; Ozerov et al., 2013; Bergal-Kuvikas, 2015; Shapiro et al., 2017b). The KVG is located above the edge of the Pacific plate at the Kamchatka–Aleutian junction where the Hawaii-Emperor Seamount chain is subducted. Possible explanations of the exceptionally active KVG include fluid being released from the thick, highly hydrated Hawaii-Emperor Seamount crust (Dorendorf et al., 2000), mantle flow around the corner of the Pacific plate (Yogodzinski et al., 2001), and a recent detachment of a portion of the subducting slab (Levin et al., 2002). The KVG contains 13 large stratovolcanoes, three of which (Klyuchevskoy, Bezymianny, and Tolbachik) have erupted during recent decades.

The abundant seismic activity of the KVG volcanoes includes extended periods of tremor and numerous volcano-tectonic and LP earthquakes. The most prominent source of LP seismicity is located at approximately 30 km depth just below the Moho beneath Klyuchevskoy and is associated with the deep-seated magmatic reservoir (Levin et al., 2014). These deep LP earthquakes have occurred nearly continuously since seismological observations begun at the KVG (Gorelchik et al., 2004; Senyukov et al., 2009; Senyukov, 2013; Shapiro et al., 2017a). Shallow bursts of LP earthquakes and tremor episodes are associated with the unrest of the three active volcanoes (e.g. Gordeev et al., 1986; Senyukov et al., 2009; Thelen et al., 2010; Senyukov, 2013; Droznin et al., 2015; Soubestre et al., 2018), with the most frequent seismic and volcanic activity beneath Klyuchevskoy.

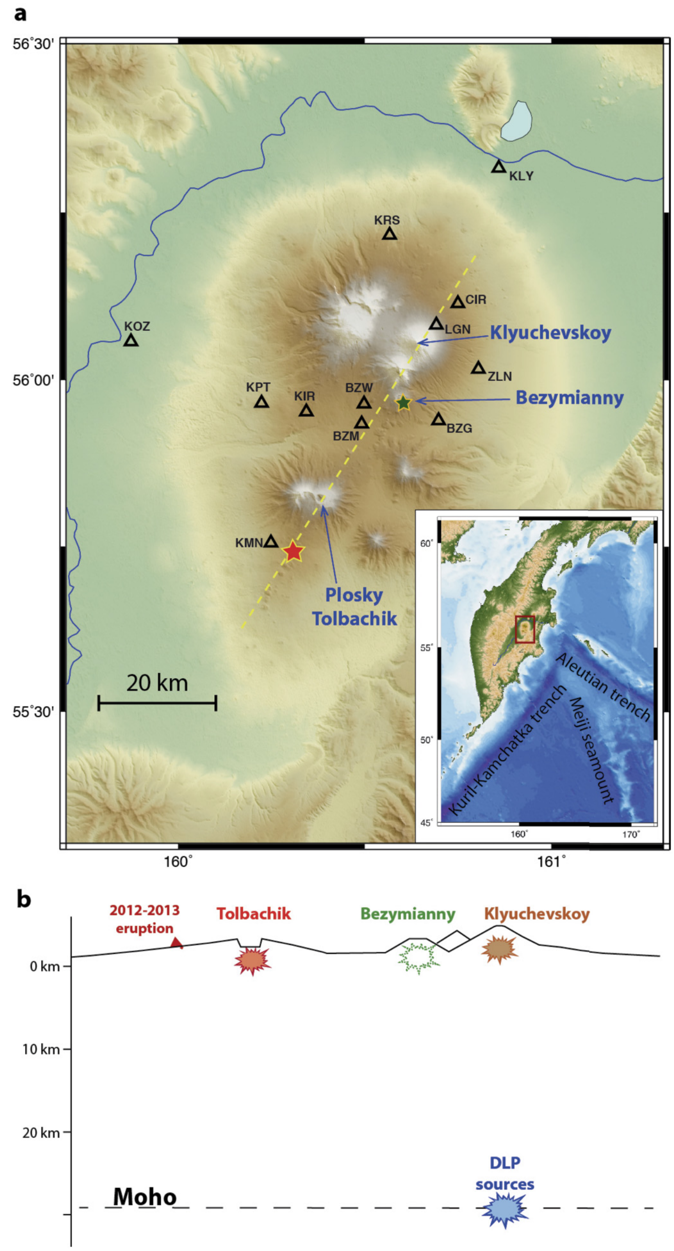

Fig. 1. (a) Map of the Klyuchevskoy volcano group. The inset shows the general geographical and tectonic settings. Triangles show the positions of the seismic stations. The recently active volcanoes are indicated with blue arrows. The red star shows the eruptive center of the 2012–2013 Tolbachik eruption. (b) Cross-section along the profile indicated in (a) by the yellow dashed line, showing a schematic representation of the KVG plumbing system and the locations of the four groups of LP sources. We do not analyze the shallow seismicity beneath Bezymianny in this study. (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

In this study we focus on the KVG LP seismic activity preceding the most recent eruption of Tolbachick, which started on 27 November 2012 and continued until September 2013 (e.g. Gordeev et al., 2013; Belousov et al., 2015; Kugaenko et al., 2015; Senyukov et al., 2015). Previous reported eruptions of this volcano have occurred in 1740, 1941, and 1975–1976 (Gordeev et al., 2013). The 2012–2013 eruption occurred after 36 yr of quiescence at Tolbachik and constitutes a major unrest event of the past 20 yr at the KVG. The analysis of seismicity during the pre-eruptive period provides an opportunity to investigate the processes that were involved in the re-activation of the Tolbachik plumbing system.