Seismically active subcrustal magma source of the Klyuchevskoy volcano in Kamchatka, Russia

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ABSTRACT

Klyuchevskoy volcano in Kamchatka (Russia) is unique in the island arc systems of Earth in having nearly continuous seismic activity beneath it at depths in excess of 20 km. Seismograms from these deep earthquakes carry an unmistakable signature of their tectonic nature. We use P-to-S (compressional to shear) converted teleseismic waves to constrain the depth of the crust-mantle transition beneath Klyuchevskoy at ~25 km, and to delineate a deeper seismic boundary at ~50 km. Earthquakes directly beneath Klyuchevskoy have hypocentral depths of 25–35 km. S-P delays in records of these earthquakes are always larger than delay times of P-to-S converted waves originating at the crust-mantle transition and traversing nearly identical paths. Thus, deep seismic activity under Klyuchevskoy is definitely beneath the crust-mantle transition. Compositions of the Klyuchevskoy parental melts (inferred from melt inclusions and the most primitive lava) interpreted using a barometer based on Si activity in melts saturated with orthopyroxene + olivine show that Klyuchevskoy parental melts form at pressures within the range of 13.9 (±2) kbar (at depths of 46 ± 7 km). Together, the estimates of melting depths, the locations of seismic velocity features, and the occurrence of tectonic earthquakes all point to the existence of a subcrustal volume beneath Klyuchevskoy volcano where processes of magma accumulation are vigorous enough to promote brittle failure in mantle rock.

INTRODUCTION

In a subduction zone, seismic activity typically is in the descending plate (the Wadati-Benioff zone) and in the crust of the overriding plate. Basaltic magma formed in the mantle wedge above the descending plate collects within the crustal magma chamber, undergoes additional evolution to lighter composition, and erupts (Stern, 2002). Klyuchevskoy volcano in Kamchatka (Russia) is the highest active volcano in Europe and Asia, nearly 5 km in elevation (Ozerov et al., 1997). Its shape is that of a classic stratovolcano (Khrenov et al., 1991). However, multiple lines of evidence suggest that Klyuchevskoy does not have a crustal magma chamber, and did not have one over the course of its ~6–7 k.y. existence (Braitseva et al., 1995).

Seismic activity beneath Klyuchevskoy volcano occurs at three depth regions. Shallow earthquakes occur within the cone of the volcano and the upper ~15 km of the crust (Senyukov et al., 2009). The Wadati-Benioff zone of the descending Pacific plate is located at 150–170 km depth (Avdeiko et al., 2007). A third region of seismicity occupies a depth range between 20 km and 40 km. In Kamchatka, earthquakes in this depth range occur only in the vicinity of the Klyuchevskoy Volcano Group (KVG).

No obvious mechanism links the earthquakes concentrated beneath the KVG (Fig. 1) to the process of magma accumulation and eruption. One complication is the uncertainty in the position of the earthquakes with respect to the crust-mantle boundary. In this study we use waveforms of local earthquakes recorded directly above their hypocenters to show that they are taking place in the mantle. Given the geochemical constraints on the likely depth range of magma formation, we conclude that Klyuchevskoy volcano has a seismically active subcrustal magma chamber.

MANTLE SOURCE OF KLYUCHEVSKOY LAVAS

The edifice of Klyuchevskoy (~270 km^3; Melekescev, 1980) consists entirely of mafic rocks, ranging from high-magnesia basalts (primitive) to high-alumina basalts and basaltic andesites (evolved) (Ariskin et al., 1995). The absence of more evolved andesites and dacites suggests that there is no crustal magma chamber.

Despite its typical arc volcano features, Klyuchevskoy has unusually hydrated magmas (parental melt H_2O content is at least 3.5 wt%; Mironov and Portnyagin, 2011), possibly due to the subduction of the Emperor Ridge beneath it (Dorendorf et al., 2000). The high H_2O content could be an explanation for the exceptional volcanic productivity of Klyuchevskoy (Mironov and Portnyagin, 2011). Furthermore, an influx of hot asthenosphere past the truncated edge of the Pacific slab could enhance productivity (Portnyagin et al., 2005).

Kersting and Arculus (1994) used whole-rock chemistry and barometry based on the experimental phase relationships (Grove and

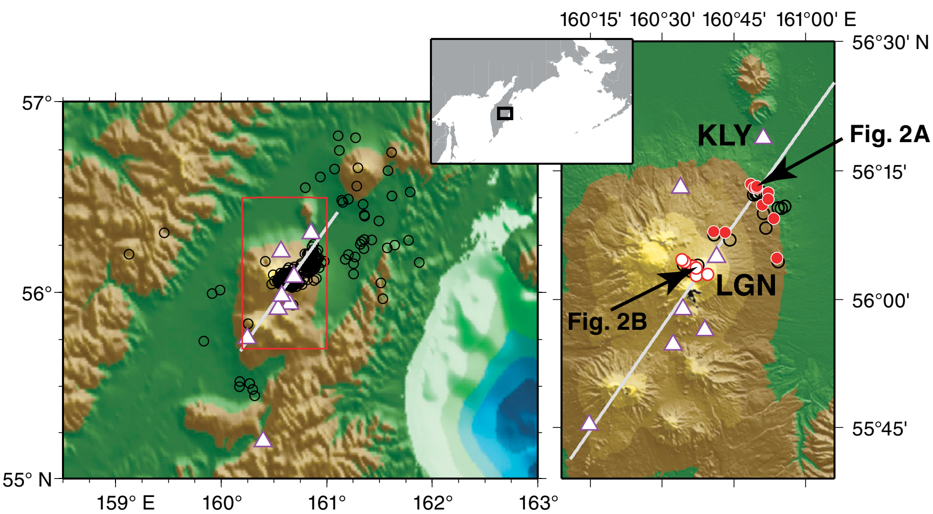

Figure 1. Maps of deep crustal seismicity beneath Klyuchevskoy volcano, Kamchatka, Russia; inset shows location of figure on left. Left: Circles—earthquakes with hypocenters below 20 km and local magnitude (M_L) > 2; triangles—seismic stations used in this study. White line marks the trace of the cross sections shown in Figure 3; red box is area of close-up map on the right. Right: 20 earthquakes selected for relocation (open circles—original locations, colored circles—relocated). LGN and KLY are seismic stations; arrows labeled a and b mark the epicenters of events shown in Figure 2.

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Baker, 1984) to infer the existence of a magma chamber near the base of the crust beneath Klyuchevskoy, where primitive high-magnesia basalts evolve to high-alumina basalts. Estimated pressures of 5–9 kbar translate into 17–30 km depth if we use a density profile from Fedotov et al. (2010). According to Ariskin et al. (1995) and Ozerov et al. (1997), Klyuchevskoy does not have a magma chamber and the varied basaltic magmas erupting from it are derived through decompression crystallization during continuous ascent in the magma conduit that extends from ~60 km depth to the surface. The absence of a garnet signature (Churikova et al., 2001; Portnyagin et al., 2005) suggests that the generation pressure of primary Klyuchevskoy magmas could not exceed ~20 kbar, or ~60 km depth. The volatile content (H_2O, CO_2) of Klyuchevskoy magma suggests a minimum depth of initial magma crystallization in the range of 30–40 km (Mironov and Portnyagin, 2011).

Our first depth estimation relies on the barometer based on Si activity in melts saturated with orthopyroxene + olivine (Lee et al., 2009). The barometer's uncertainty is ±2 kbar or ~7 km of depth. We find that Klyuchevskoy parental melts form at 13.9 ± 2 kbar, corresponding to 46 ± 7 km, assuming the crust and upper mantle densities from Fedotov et al. (2010). Our second depth estimate (after Danyushevsky et al., 1996) relies on the greater pressure sensitivity of clinopyroxene crystallization compared to olivine. The most primitive lavas contain olivine and clinopyroxene phenocrysts, which crystallize together at pressures of 12 ± 1 kbar (~40 km depth). Details on barometric estimates are in the GSA Data Repository[1].

DEEP SEISMIC ACTIVITY BENEATH KLYUCHEVSKOY VOLCANO

Deep crustal earthquakes beneath the KVG are a long-standing observation. Unlike the sparse and intermittent middle and lower crustal seismic activity found beneath other arc volcanoes (e.g., McNutt, 2005; Nichols et al., 2011), the seismic activity at depths >20 km is nearly continuous (Fedotov et al., 2010). These seismic events are unquestionably tectonic, with clear radiation of compressional and shear waves (Fig. 2).

Deep earthquakes beneath the KVG are similar to the low-frequency earthquakes (LFEs) of "volcanic earthquake" type beneath Japan reported by Aso et al., (2013). However, events beneath the KVG may exceed the M_L ~2 limit for LFEs in Japan, and their spectrum is broader.

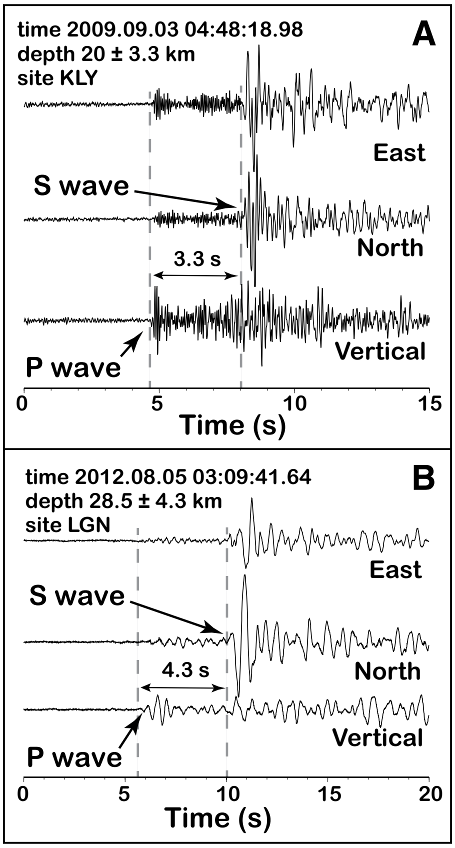

Figure 2. Examples of earthquake records from two regions of deep seismicity, from seismic stations closest to the respective epicenter. Clear records of P and S waves are present. Epicenters and site locations are shown in Figures 1 and 3.

While frequencies of ~2–5 Hz dominate, energy up to 20 Hz is present in the waveforms.

A regional network operated by the Kamchatka Branch of the Russian Geophysical Service (KBGS) monitors seismicity of the KVG region, with digital recording since late 1990s. The seismicity catalog contains events as small as energy class $K_S = 4$ ($M_L = 1.25$; see the GSA Data Repository[1] for details on the K_S-M_L relationship). For earthquakes with $K_S = 5.5$ (M_L ~ 2) and larger, there are >1700 events with hypocenters below 20 km in the period from 2000 to early 2013 (Fig. 1). Chosen hypocenters form two distinct volumes (Fig. 3). The shallower volume, between 20 and 25 km depth, is subhorizontal and planar, and occupies an area to the northeast of the Klyuchevskoy volcano. The deeper volume is directly beneath the volcano, with hypocenters at depths of 25–35 km forming a nearly vertical column.

To verify the quality of catalog locations, we selected 20 representative earthquakes with simple waveforms, clear records, and a maximum number of stations recording. We performed relocation of their hypocenters with the algorithm and the velocity model used by the KBGS to produce the catalog. Extra care in picking

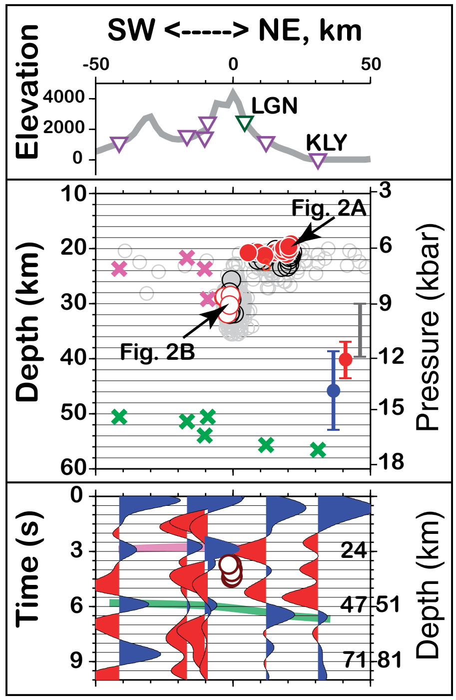

Figure 3. Topography, earthquake hypocenters, seismic boundaries, and petrological depth estimates projected onto a vertical plane through the Klyuchevskoy Volcano Group (Kamchatka, Russia), shown by white line in Figure 1. Top: Elevations and seismic station positions. Middle: All earthquakes from 2000 to 2012 (gray circles), 20 best events (solid circles), best events, relocated (colored circles). Labels mark sources of seismograms in Figure 2. Colored crosses are seismic boundary depths estimated from times of phases chosen on individual receiver function (RF) time series (purple, ~3 s; green, ~6 s). Petrologic depth estimates: gray—range from Mironov and Portnyagin (2011); blue—mean and error calculated following Lee et al. (2009); red—mean and error calculated following Danyushevsky et al. (1996). Bottom: RF time series plotted at positions of corresponding seismic stations. Depth axis on the right shows time-to-depth conversion based on two choices of average seismic velocities (see text). Red open circles show S-P times at the seismic station LGN for events in the earthquake group beneath Klyuchevskoy volcano (red circles with white centers in the middle panel). Purple and green lines mark positive P-to-S converted phases at ~3 and ~6 s delays. Times of peaks are used to estimate interface depths (crosses in middle panel).

arrivals and special attention paid to assembling all available data for each event ensured a high quality of resulting hypocenter determination. All relocated earthquakes plot within the limits of two volumes outlined by the routinely located seismicity (Figs. 1 and 3).

CRUSTAL STRUCTURE BENEATH KLYUCHEVSKOY VOLCANO

Seismological studies of the crust in Kamchatka show it to be 30–40 km thick (cf. review

[1]GSA Data Repository item 2014347, constraints on the crustal structure from receiver function analysis, and constraints on the depth of melting beneath Klyuchevskoy, including Figures DR1–DR3 and Table DR1, is available online at www.geosociety.org/pubs/ft2014.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

by Iwasaki et al., 2013). Most studies note the complexity of crustal structure beneath the KVG. Early work using regional earthquakes identified an unusually slow upper mantle beneath the KVG (7.7 km/s; Fedotov and Slavina, 1968), a finding generally supported by the most recent tomography of Koulakov et al. (2013). Studies using surface explosions detected multiple reflecting boundaries in the 25–45 km depth range (Utnasin et al., 1975).

We develop new estimates of crustal thickness beneath the KVG using seismic waves from distant earthquakes that convert from compressional (P) to shear (S) wave type at abrupt impedance contrasts, providing a means to probe the crustal structure beneath the observing station (Phinney, 1964). Receiver function (RF) analysis (Ammon, 1991) isolates such waves within the coda of first-arriving P waves and removes earthquake source signatures from resulting time series. Figure 3 (and Figs DR1 and DR2 in the Data Repository) shows the results of applying RF analysis to data from portable and permanent seismic stations within the KVG (see the Data Repository for data and instrument descriptions). In Figure 3, all available data for each site are combined into a single RF time series characterizing average isotropic velocity structure beneath it. Figures DR1 and DR2 show details of RF wave fields that guide our interpretation of individual phases in time series in Figure 3.

The crust-mantle boundary is the most significant impedance contrast within the upper 100 km of Earth's interior, and thus it is natural to associate a pulse reflecting a downward increase in impedance with this boundary. Beneath the KVG, we see two candidate pulses that reflect an increase in impedance. A pulse at ~3 s is seen at sites beneath and southwest of Klyuchevskoy, while a pulse at ~6 s appears throughout the region.

A delay time of the RF time series pulse provides a measure of depth to the converting boundary if velocities of P and S wave are known. For a single homogeneous layer, the depth to its lower boundary *h* may be estimated as

$$h = \frac{t}{\left(\sqrt{\frac{1}{V_S^2} - p^2} - \sqrt{\frac{1}{V_P^2} - p^2}\right)}, \qquad (1)$$

where t is the delay time, V_P and V_S are mean P and S wave velocities in the layer, and p is the ray parameter for the incoming P wave (Gurrola and Minster, 1998). Average crustal values in the standard velocity model used to locate earthquakes beneath the KVG are V_P = 6.1 km/s and V_S = 3.5 km/s (Fig. DR3). For a P wave from a source at a distance of 60°, the ray parameter is ~0.06 s/km. Figure 3 shows depth estimates based on specific delay times of target pulses for all sites. For the later pulse, average velocities above the interface (V_P = 6.6 km/s; V_S = 3.8 km/s) take into account a fraction of the path in the mantle with V_P = 8.1 km/s and V_S = 4.7 km/s.

The depth of a single converting boundary may also be estimated from a set of RF time series by stacking data at times predicted for direct (P_S) and reverberating (P_PP_S, P_SP_S + P_PS_S) converted waves above it (Zhu and Kanamori, 2000). Results of such stacking performed on our data (Figs. DR1 and DR2) show evidence for two or more candidate features at each site. Beneath Bezymiany volcano a converter ~25 km deep is most prominent, while both south and north of it (sites KMN and KRS) a converter ~50 km deep yields a more energetic stack.

LOCATING DEEP EARTHQUAKES RELATIVE TO SEISMIC BOUNDARIES

In light of existing and new constraints on the crustal thickness beneath the KVG, we can be confident that earthquakes between 20 km and 25 km depth are within the crust. The horizontal aspect of this seismicity cluster suggests a stress regime consistent with ponding of magma beneath a density contrast in the crust, and development of sills. However, the provenance of seismicity between 25 and 35 km is unclear. To resolve it we rely on the similarity of physical observables used to determine earthquake focal depths, and the depths of converting boundaries from RF pulse timing. In both cases the differential time between P and S waves traversing the same path is evaluated. For an earthquake both wave types radiate from the source toward the receiver, while a mode-converted "daughter" P_S wave forms from the "parent" P wave at a boundary. In the crust ray paths of P and P_S converted waves from distant earthquakes are close to vertical. Seismic station LGN is virtually above the deep earthquakes (Fig. 3), thus waves from them follow nearly vertical paths to it. This allows direct comparison of RF pulse delays and S-P delays in earthquake records. For an event illustrated in Figure 2 the horizontal distance to the epicenter is 4.8 km.

For all deep earthquakes recorded at site LGN, the S-P times are between 3.5 s and 5 s (Fig. 3). Consequently, earthquakes in the deep volume of hypocenters beneath Kyuchevskoy are definitely below the feature giving rise to the RF pulse at ~3 s, while they are above the feature related to the pulse at ~6 s.

DISCUSSION

Deep seismic sounding studies of the KVG (Utnasin et al., 1975; Iwasaki et al., 2013) found numerous sharp seismic boundaries in the 25–45 km depth range. Interval velocities >7.6 km/s associated with deepest reflectors were taken to indicate upper mantle rocks, and thus the crustal thickness was estimated at 30–35 km. From the same data, Balesta et al. (1977) reported likely crustal thinning to ~20 km along the coast. The dispersion of surface waves traversing eastern Kamchatka (Shapiro et al., 2000) is also consistent with the ~30 km crustal thickness. A larger thickness of crust with low shear wave speed will trade off with significantly higher shear wave speed values in the upper mantle directly beneath the volcanoes, which would be in contrast to both expectations (mantle is melting there) and observations (e.g., low P wave speed of Fedotov and Slavina, 1968). Finally, the area around the KVG is close to sea level and the gravity values are modest (Avdeiko et al., 2007), making an excessively thick crust unlikely.

Thus we believe that RF time series pulse at ~3 s corresponding to ~25 km depth (Fig. 3) marks the lower limit of crustal material beneath Klyuchevskoy, while the pulse at ~6 s (corresponding to ~50 km depth) separates two strata of upper mantle material. Consequently, our overall conclusion is that persistent deep earthquakes under the Klyuchevskoy volcano occur beneath the crust. They populate a depth region with multiple sharp boundaries in seismic wave speed (Utnasin et al., 1975; Iwasaki et al., 2013). The ~6 s delay pulse in RF time series (Fig. 3), and the ~50 km deep converter inferred from stacked RF wave fields (Fig. DR2) likely denote the lower bound of this depth region.

To explain low P wave speed in the upper mantle down to 40 km beneath the Izu arc, and the presence of reflectors within it (i.e., conditions similar to those beneath the KVG), Tatsumi et al. (2008) proposed a scenario where the lower arc crust transforms into a material seismologically similar to the arc upper mantle. This scenario, built for a mature intra-oceanic arc, yields about half of the vertical extent of the material with properties we find beneath the KVG. The tectonic history of eastern Kamchatka involves multiple terrane accretion episodes (e.g., Park et al., 2002), and the KVG is a relatively young feature (Braitseva et al., 1995). Thus we do not think that Tatsumi et al. (2008) scenario can explain the presence of the low-velocity upper mantle beneath the KVG.

The combination of geochemical and petrological constraints puts the locus of Klyuchevskoy magma origin below the crust-mantle boundary, and above ~60 km. We interpret the match between the estimates of melting depth and the location of seismic velocity boundaries as evidence for a magma accumulation region extending from the bottom of the crust at ~25 km to the depth of 50–60 km. Since melt dramatically reduces the shear wave speed of the upper mantle rock, the lower bound of this region may give rise to positive P-to-S conversions seen in RF time series. Melt concentrations between 25 km and 60 km depth may be the cause of laterally discontinuous seismic reflections of Utnasin et al. (1975). The presence of tectonic earthquakes reflects brittle deformation caused by magma accumulation within these features. Movements of magma within the 25–60 km depth region are a likely source of subsidence noted around the KVG by Grapenthin et al. (2013).

The process of magma formation and eruption at the KVG follows a standard island arc template, with fluid flux off the slab promoting melt formation in the supraslab wedge. However, the process acts much more vigorously than anywhere else on Earth, yielding an exceptional rate of volcanism. This vigor likely reflects a confluence of two stimulating factors: the elevated temperature of the supraslab wedge (Portnyagin et al., 2005) and the presence of unusually high quantities of water in the melt-forming regions (Dorendorf et al., 2000). Together these processes lead to melt generation at a rate sufficient to promote nearly constant seismic activity.

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