Multiple melt injection along a spreading segment at Askja, Iceland

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[1] Lower crustal earthquakes (12–25 km depth) have been detected since August 2005 in the Askja volcanic system along the northern Iceland rift, in the normally ductile part of the crust. The earthquakes occur in three clusters, which have stable dimensions and locations through time and are interpreted as positions of repeated melt supply from the mantle to the lower crust. Seismic velocity $V_p/V_s$ ratios are consistent with the presence of partial melt in the lower crust at Askja. The spatial separation of the clusters shows that there are multiple positions of melt injection within this one magmatic segment and all three positions are currently active. This pattern of melt supply is more like that observed on fast spreading ridges than slow spreading ridges and is probably a consequence of the increased melt production beneath Iceland compared to the rest of the Mid-Atlantic Ridge. However, the relative number of earthquakes in each cluster shows that there are multiple positions of melt injection within this one magmatic segment and all three positions are currently active. This pattern of melt supply is more like that observed on fast spreading ridges than slow spreading ridges and is probably a consequence of the increased melt production beneath Iceland compared to the rest of the Mid-Atlantic Ridge.

[2] Mantle flow models suggest that beneath slow-spreading ridges, melt is focused below the Moho and preferentially injected at spreading segment centers, from where it migrates to shallow levels towards the segment ends [Whitehead et al., 1984; Schouten et al., 1985; magne and Sparks, 1997]. This is supported by crustal thickness variations [e.g., Lin and Phipps Morgan, 1992]. Seismic tomography has been used to infer positions of melt supply [Toomey et al., 1990; Magne and Sparks, 2000; Dunn et al., 2000], but this method is sensitive to long-term average rather than instantaneous melt supply locations. The petrology of the lower crust and mantle exposed at oceanic core complexes has also been used to infer melt supply [Dick et al., 2008] but since the crust records all successive processes to which it has been subjected, it is difficult to determine timings for the injection positions observed. We report earthquakes recorded in the lower crust at the Askja volcanic rift system, interpreted as caused by melt movement, delineating patterns of ongoing melt supply from the mantle along a segment of the Mid-Atlantic Ridge.

[3] The mantle plume beneath Iceland causes increased melt production and consequently over-thickened crust, raising the Mid-Atlantic Ridge above sea level. As it crosses Iceland the rift splits into several en-echelon volcanic systems (inset Figure 1a), comprising central volcanoes intersected by fissure swarms [Semundsson, 1979]. These volcanic systems are analogous to the spreading segments of normal mid-ocean ridges. The last major rifting phase at Askja was in 1874–1875 with volcanic and tectonic activity at the central volcano and along the fissure swarm, creating the youngest of the nested calderas [Sigurdsson and Sparks, 1978]. The crust beneath Askja is ~30 km thick, thinning away from the plume [Darbyshire et al., 2000]. Persistent upper-crustal (<10 km) seismicity in the Askja region has been observed for more than 30 years and is attributed to tectonic faulting caused by plate spreading at 20 mm/a full rate [Einarsson, 1991; Soosalu et al., 2010].

[4] Data for this study come from successive local seismic networks deployed in the Askja area using Guralp 6TD broadband seismometers: a week, 5 station network in August 2005; 2 month long summer campaigns of over 20 stations in 2006 and 2007 [Soosalu et al., 2010]; a 5 station trial network over winter 2007/08 and at least 15 stations deployed all year since summer 2008 (Figure 1a). Data from seven nearby national seismic network (SIL) stations run by the Icelandic Meteorological Office have also been used.

[5] The existence and characteristics of the lower crustal earthquakes at Askja were first reported by Soosalu et al. [2010]. Given that these earthquakes occur in a part of the crust that is normally aseismic and behaves in a ductile manner, we believe that they are caused by rapid melt movement generating sufficiently high strain rates to produce brittle failure. In this paper we present additional earthquakes and $V_p/V_s$ ratios and focus on the larger scale interpretations that can be made about melt supply at spreading segments as a consequence of this discovery.

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Over 1000 lower crustal earthquakes have been located using HYPOINVERSE-2000 [Klein, 2002], of which 796 are well constrained (horizontal and vertical errors < 1.0 km, azimuthal gap between stations < 180°, RMS time misfits < 0.2 s). They occur in three clusters in space (Animation S1 of the auxiliary material). The largest cluster, containing 65% of the earthquakes is beneath the northeast of the main Askja caldera, with its long axis extending along the fissure swarm (Figure 1a). This cluster looks like a continuous pipe when viewed in the across-rift profile (Figure 1d), but the along-rift profile (Figure 1c) and Animation S1 show that it is split into several smaller sub-clusters. The two remaining clusters are separated from the first by up to 10 km, one northeast and the other east of Askja. All three clusters of earthquakes can be active on the same day.

Time Distribution

The lower crustal seismicity mostly occurs in swarms of fewer than 10 events lasting a few minutes, usually lacking a clear ‘mainshock’. Earthquakes within each swarm are located closely in space. They often follow in such quick succession that their codas interfere with other events in the swarm. On a day to week scale, the activity is episodic, some weeks having more than 100 events and others only a few. On longer time scales (weeks to months) the activity is continuous, with some lower crustal seismicity every week during the entire period we have been recording with a dense network.

The lower crustal seismicity at Askja was first identified and thought to have started during 2006 [Soosalu et al., 2010] but re-examination of the data has found over 20 events during three weeks in August 2005. It is not possible to determine how long these events were occurring prior to 2005 because of a lack of seismometers close to Askja.

Vp/Vs Ratio

The ratio of compressional to shear wave velocity, \(V_p/V_s\), is sensitive to both temperature and the presence of partial melt. Wadati plots [Wadati, 1933] were used to determine \(V_p/V_s\) ratios, averaged over the area containing...
of magma that re-open cracks used by previous intrusions could generate each earthquake swarm.

[12] Earthquakes only occur when magma is moving, causing high strain rates. The sharp gaps in seismicity at the tops and bottoms of the clusters and sub-clusters are therefore locations where magma is stalling and are interpreted as sills. Our data provide support for a model of the lower and mid-crust built by in situ crystallization of multiple stacked sills [Kelemen et al., 1997]. This is not surprising given that two thirds of the melt supplied to mid-ocean ridges solidifies within the crust [White et al., 2008]. Lower crustal sills have been identified in the Oman ophiolite [e.g., Boudier and Nicolas, 1995]; imaged seismically at the Juan de Fuca Ridge [Canales et al., 2009] and the North Atlantic rifted margin [White et al., 2008]; and proposed on geochemical grounds for other volcanic systems of the north Iceland rift [Maclean et al., 2001]. The bottom of the clusters below Askja and Vaðalda extend almost to the base of the crust calculated by Darbyshire et al. [2000] (Figure 1d), but the bottom of the Kollótta-dyngja cluster is much shallower (Figure 1c). It is possible that this difference in maximum depth could be explained by topography on the Moho, although it is more likely that the mantle melt supply recently ceased at Kollótta-dyngja and that magma temporarily trapped in a 20 km deep sill is now moving to a shallower level.

[13] Lower crustal seismicity has only rarely been recorded in Iceland [Jakobsdóttir et al., 2008; Hjaltadóttir et al., 2009; Soosalu et al., 2010] and in all other cases is associated with discrete intrusion episodes lasting only days to months. In contrast, the Askja earthquakes are persistent and ongoing, representing a long-term feature. Although this is the first observation of such activity, it is possible that similar earthquakes are occurring elsewhere in Iceland, but are undetected thus far.

[14] Typical $V_p/V_s$ ratios elsewhere in the Icelandic crust measured on seismic refraction profiles are mostly in the range 1.75–1.79 [Brandsdóttir and Menke, 2008, and references therein]. Due to the high geothermal gradient in Icelandic crust, the $V_p/V_s$ ratio should increase slowly with depth. Using the best-fit gradient determined by Allen et al. [2002] from broadband waveform inversions of local earthquakes in Iceland, $V_p/V_s$ ratios should be in the range 1.83–1.89 at the depths of the Askja lower crustal earthquakes. Laboratory values of $V_p/V_s$ for gabbros at suitable pressures for the lower crust are similar, at 1.85 [Christensen, 1996]. The high modal $V_p/V_s$ ratio of 2.26 determined here therefore far exceeds that expected for normal Icelandic lower crust (Figure 2b). Since a significant proportion of the earthquakes have $V_p/V_s$ ratios close to expected values in the lower crust, it is likely that the abnormally high values are caused by localized volumes with high $V_p/V_s$ ratios, which are not sampled by all averaged source-receiver paths. Possible causes of increased $V_p/V_s$ ratio at these depths are partial melt and/or high temperatures, but in order to create >20% increase in $V_p/V_s$ ratio in the lower crust at least some melt must be present [Hammond and Humphreys, 2000]. Only a few percent of distributed melt is required to explain the high $V_p/V_s$ values.

[15] The melt supply zones delineated by the Askja lower crustal earthquakes are ~10 km wide, a similar size to velocity anomalies imaged with tomography by Magde et al.
could be a result of the relatively high quantities of melt produced beneath Iceland by the mantle plume.

6. Summary

[18] Figure 3 shows a cartoon summary for melt supply from the mantle to the crust of the Askja rift segment. Melt is focused in the mantle into 10 km wide regions and is injected into the lower crust in small pulses. It repeatedly follows previously used pathways and re-opens small cracks, generating the earthquakes we observe. This process is simultaneously occurring at multiple locations within the magmatic segment, not just at the segment center. The melt works its way shallower, stalling in a series of sills and crystallizing some material, the last remnants freezing in the mid-crust. Through time, magma supply positions may change, leaving behind a series of frozen stacked sills that build the lower crust. Despite multiple locations of melt supply, the majority of melt enters the lower crust at the center of the magmatic segment and time-averaged supply may be greater here than elsewhere along the rift. Although not currently occurring, sometimes melt injected at the Askja cluster makes it all the way to the upper crustal magma chamber, from which surface eruptions and long distance lateral dike injection may occur, building the shallow crust.

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Figure 3. Cartoon model for melt injection on the Askja magmatic segment, shown on profile along the rift axis. K is Kollóttadyngja marked on Figure 1. Purple region is mantle with red zones showing focused melt supply. Orange lines represent networks of cracks through which melt flows before stalling in existing sills (orange ellipses). Dark gray ellipses are now frozen sills formed by previous melt pathways. Large orange ellipse at 3 km is shallow magma chamber based on geodetic models by Pagli et al. [2006]. Dark gray zones are previous paths of magma during eruptions either in the caldera or in dikes along the fissure swarm.


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