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RESEARCH ARTICLE

Lower-crustal earthquakes caused by magma movement beneath Askja volcano on the north Iceland rift

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Abstract The lower crust of magmatically active rifts is usually too hot and ductile to allow seismicity. The Icelandic mid-Atlantic rift is characterized by high heat flow, abundant magmatism generating up to 25–30 km thick crust, and seismicity within the upper 8 km of the crust. In a 20-seismometer survey in July-August 2006 within the northern rift zone around the Askja volcano we recorded ~1700 upper-crustal earthquakes cutting off at 7–8 km depth, marking the brittle-ductile boundary. Unexpectedly, we discovered 100 small-magnitude (M_L <1.5) earthquakes, occurring in swarms mostly at 14–26 km depth within the otherwise aseismic lower crust, and beneath the completely aseismic middle crust. A repeat survey during July-August 2007 yielded more than twice as many lower-crustal events. Geodetic and gravimetric data indicate melt drainage from crustal magma chambers beneath Askja. We interpret the microearthquakes to be caused by melt moving through the crust from the magma source feeding Askja. They represent bursts of magma motion opening dykes over distances of a few meters, facilitated by the extensional setting of the active rift zone.

Keywords Lower-crustal earthquakes · Askja volcano · Iceland · Rift · Magma transport · Dyking · Brittle failure

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Introduction

Deep earthquakes thought to be related to magmatic activity have been reported from a small number of localities around the world, mainly in intraplate hotspot and collisional tectonic contexts, including several Aleutian arc volcanoes (Power et al. 2004), Mammoth Mountain (Hill and Prejean 2005), Lake Tahoe (Smith et al. 2004), Kilauea (Koyanagi et al. 1987; Wright and Klein 2006), Iwate volcano and several others in northeast Japan (Hasegawa et al. 1991; Nakamichi et al. 2003), Las Cañadas caldera (Almendros et al. 2007) and Klyuchevskoy (Lees et al. 2007).

Here we report a discovery of persistent, small-scale, lower-crustal seismicity in the Askja region of Iceland (Fig. 1), which we interpret as due to melt movement beneath the mid-Atlantic rift in a region of newly created, thick, hot crust well beneath the normal brittle-ductile boundary. Lateral melt movement along the Icelandic rift has been documented in the upper brittle crust, such as in the case of the Krafla volcano north of Askja (Einarsson and Brandsdóttir 1980; Buck et al. 2006) and postulated on petrological grounds for the Grímsvötn volcano to the south (Sigurðsson and Sparks 1978) (Fig. 1 inset). We believe

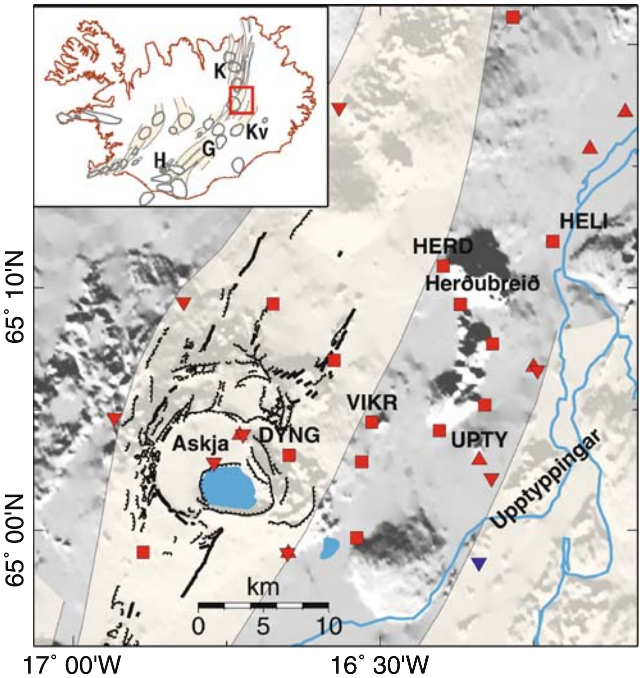

Fig. 1 Location of Askja within the neovolcanic zone of Iceland, and the seismic network. Red triangles mark seismometer sites operated during summer 2006 only and red inverted triangles those that operated during summer 2007 only. Red squares are sites occupied during both summers. The five sites occupied in the three-week pilot study in August 2005 are named. Inverted blue triangle is the only permanent station within this area. The calderas and fissures of the Askja volcanic system are shown with thick black lines. The fissure swarms of Askja and Kverkfjöll are shaded. Lakes and rivers are shown in blue. Inset shows the volcanic systems: central volcanoes are circled and their fissure swarms shaded, after Einarsson and Sæmundsson (1987). Kv marks the Kverkfjöll volcanic system, K the Krafla system, G the Grímsvötn system, and H the Hekla volcano, respectively

that we have detected melt in the act of moving in the lower crust in a plate spreading boundary tectonic setting.

The mid-Atlantic plate boundary in north Iceland comprises an *en echelon* set of volcanic systems with central volcanoes transected by faults and swarms of tensional fissures (Fig. 1). In the Askja region the spreading rate is ~20 mm/yr aligned in a direction N106°E – N74°W (DeMets et al. 1994). The Askja fissure swarm is oriented approximately perpendicular to this direction. The active rift zone is approximately 50 km wide (Fig. 1). The nested caldera of Askja was formed by a series of major eruptions, with the latest in 1875 (Sigvaldason 2002). After the most recent, minor eruption in 1961, Askja inflated until 1973 and has subsequently been deflating at an exponentially decaying rate (Sturkell et al. 2006). The subsidence and associated change in the gravity signal cannot be explained by cooling contraction alone: magma drainage from beneath the volcano is also required (Sturkell et al. 2006; de Zeeuw-van Dalfsen et al. 2005). The Askja magmatic system has been geodetically modelled with at least two magma chambers; a shallow one with a point source at ~3 km depth, and a deep one at ~16 km depth beneath the volcano (Sturkell et al. 2006; Pagli et al. 2006). Petrological evidence supports this interpretation (G.E. Sigvaldason, cited by Sturkell et al. 2006). The crustal thickness in this area is not well defined, but is estimated from regional seismic studies to be approximately 30 km (Darbyshire et al. 2000).

Data and methods

We deployed and operated a network of 20 broadband Güralp CMG-6TD seismometers in the Askja region during July-August 2006, and a network of 22 seismometers during July-August 2007 (Fig. 1), supplementing one nearby permanent Icelandic network station and a number of others several tens of kilometers away. With the 100 Hz sample rate we used for all sensors, the 6TD frequency response curve is flat between 0.03 and 50 Hz. Combining this dataset with that from the national network, in 2006 we detected over ~1800 earthquakes (local magnitudes, $M_L \leq 2$), which were located using the HYPOINVERSE-2000 program (Klein 2002). We used a one-dimensional linear velocity-gradient crustal model, modified from a model derived by B. Brandsdóttir and A.B. Lassen (unpublished manuscript 1989) from local seismic profiles within the Askja region and the RRISP experiment (Angenheister et al. 1980; Gebrande et al. 1980) (Table 1). Individual station time corrections were applied.

The Continuous Microseismic Mapping (CMM) algorithm (Drew et al. 2005; Drew 2008), which undertakes a search in time and space (Kao and Shan 2004), using an energy onset (STA/LTA — short time averaging vs. long time averaging) functional, was used for event detection and initial location. The identified events were then re-picked by hand. In 2006, ~100 of the earthquakes, of which 84 are well-located, occurred in the lower crust and in 2007 the number increased to 250, of which 235 are well-located. The criteria for well-located events are: rms time error

Table 1 The Askja crustal model

The original model by Brandsdóttir and Lassen		Our modified model	
Depth (km)	P-wave velocity (km/s)	Depth (km)	P-wave velocity (km/s)
0.0	2.5	0.0	3.5
0.5	4.0	0.5	4.0
6.5	6.2	6.5	6.2
11.0	7.0	11.0	7.0
32.0	7.4	40.0	7.6

≤0.2 s, largest azimuthal gap ≤180°, horizontal and vertical location errors (one standard error) ≤1 km for upper-crustal earthquakes (impulsive phase arrivals) and ≤1.5 km for lower-crustal events (emergent phase arrivals). The minimum number of observing stations for most events was eight or more, and the distance to the closest station from the epicenter was less than 3 km for events around Askja and less than 5 km elsewhere.

Upper-crustal earthquakes

In this study, the upper-crustal seismicity is not the main focus but is treated as a background feature. Persistent shallow small-scale seismicity, with earthquakes typically well below magnitude 3, is a long-known phenomenon in the Askja region (Einarsson 1991; Jakobsdóttir et al. 2002). The majority (~95%) of earthquakes during summer 2006 occurred within a conspicuous upper-crustal belt (mainly 1–6 km depth below sea level, (b.s.l.)) with a lower cut-off depth marking the brittle-ductile boundary (Fig. 2). This belt extends northeast from Askja to Herðubreið mountain (Fig. 1 and green diamonds on Fig. 3). Earthquakes are more common towards the base of this upper crustal seismic zone, with a tendency to deepen towards the northeast, away from Askja. This is consistent with higher thermal input and therefore raised crustal temperatures near Askja volcano, resulting in a shallower brittle-ductile transition depth. The seismogenic, brittle upper crust in the area is of a typical thickness for Iceland (Menke and Sparks 1995; Foulger et al. 2003). The temperature at the base of the seismicity is likely to be ~600°C, the highest temperature at which brittle failure occurs, based on global observations (McKenzie et al. 2005) and laboratory experiments (Boettcher et al. 2007). This temperature is higher than is usually assumed for continental crust.

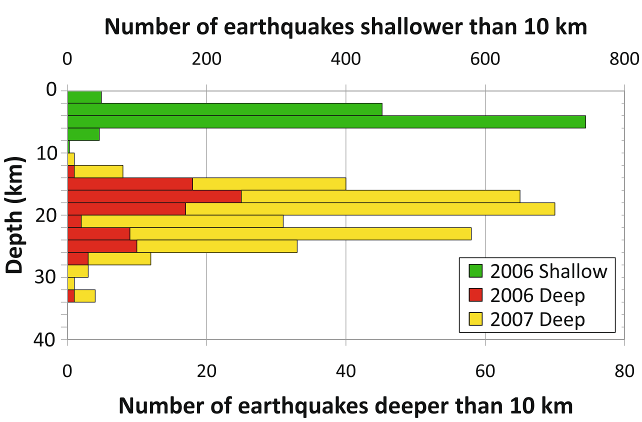

Fig. 2 Histogram showing the hypocentral depth distribution of the earthquakes. Only well-located events are plotted: horizontal and vertical location errors are ≤1 km for the upper-crustal 2006 earthquakes and ≤1.5 km for the lower-crustal 2006 and 2007 events

A cluster of shallow earthquakes occurs in the south-eastern part of the main Askja caldera at depths of 1–5 km b.s.l., consistent with the shallowing trend of the base of the upper-crustal seismicity towards Askja. Since the seismicity cluster coincides with the region of most conspicuous geothermal activity at Askja, we speculate that the earthquakes are caused by hydrothermal circulation above a shallow magma body.

We constructed fault-plane solutions for 52 shallow events with clear arrivals, the majority of which showed strike-slip movement. Based on the seismicity distribution for earlier swarms in this area, we interpret the NE-SW striking nodal plane as the fault plane since the hypocenters align in that direction, with left-lateral motion. A composite plot of all the tension (T) axes (Fig. 3) shows a close alignment with the plate spreading direction, N106°E, indicating that the plate motion dominates in generating the local stress field in the brittle upper crust.

The lower-crustal earthquakes

Our new and unexpected observations are of lower-crustal earthquakes at depths of 12–34 km, with the majority clustering at depths of 14–26 km (Figs. 2 and 3). The upper-crustal earthquakes in the same area are ordinary tectonic events with impulsive P- and S-phases and a broad spectral range, ~2–20 Hz. The lower-crustal events, however, are distinctly different in appearance. They have more emergent P- and S-phases — the S-phase being distinctly observable at stations in all azimuthal directions — and possibly a low-frequency coda. Characteristically, the main energy of the spectrum is below 5 Hz, which is observed at all stations and is lower than for typical tectonic earthquakes in the region. During the location procedure, it was immediately obvious visually whether each observed earthquake was an upper-crustal or a lower-crustal event. Figure 4 shows examples of different waveforms and spectra of two representative earthquakes: a lower-crustal (Fig. 4a and 4b) and an upper-crustal event (Fig. 4d and 4e), recorded by the same station. These earthquakes are of similar sizes and have similar station-hypocenter distances.

The lower-crustal seismicity has an episodic character. Earthquakes typically occur in swarms of short duration, lasting up to a few minutes, with several consecutive events which sometimes merge into bursts of tremor typical of magmatic events. They appear to be persistent: in the short measuring period of 2 months in 2006 we located ~100 such events, occurring almost on a daily basis and 1 year later during 2 months in 2007 this activity, observed by an almost identical local network, had increased over two-fold

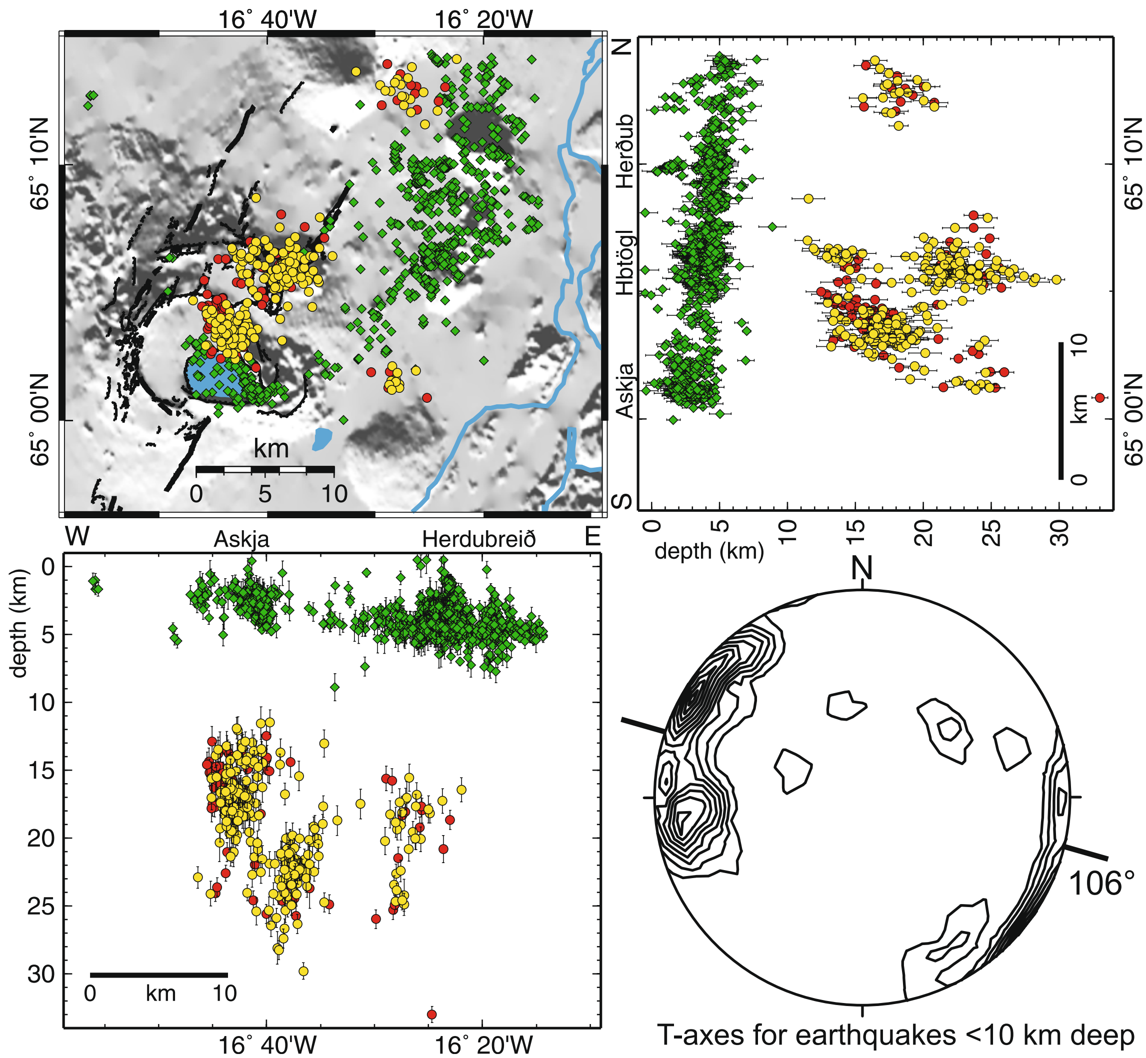

Fig. 3 Epicentral and hypocentral distribution of seismicity, relative to sea level, in the Askja area. Coloring of the different event populations is the same as in Figure 2. Green diamonds mark ~1300 well-located upper-crustal earthquakes (horizontal and vertical location errors ≤1 km) from July-August 2006. Red dots are 84 well-located lower-crustal earthquakes from July-August 2006 and yellow dots are 235 well-located earthquakes from July-August 2007 (horizontal and vertical errors ≤1.5 km). Vertical error bars are shown. The stereographic plot shows the distribution of the tension axes of 52 fault plane solutions of upper-crustal earthquakes near Herðubreið mountain

to ~250 events. Since they are small in magnitude, the more distant, permanent network detected only five of them (M_L 0.3–1.5) in 2006 and eight (M_L 0.8–1.8) in 2007. It is not possible to construct reliable fault plane solutions for these small-amplitude, emergent and intermingling events.

During both summers the lower-crustal seismicity occurred in three distinct clusters, with the epicentral locations of the clusters not overlapping with those for upper-crustal seismicity (Fig. 3). The largest cluster, containing the majority of the lower-crustal events, is located at the northeastern edge of the main Askja caldera, in a NE-SW trending belt ~10 km long. This large cluster appears to be split into two sub-clusters, with the majority of events inside the caldera having depths of 13–21 km and those to the northeast and outside the caldera having depths of 20–27 km. The shallower of these two sub-clusters is immediately north of the deeper magma chamber proposed from geodetic measurements and lies beneath the area of the latest eruptive activity in 1961 (Sigvaldason et al. 1992).

Still within the Askja volcanic system, but 20 km to the northwest of Herðubreið mountain, a second cluster of deep earthquakes occurs at 15–21 km depth. It is located on the same northeasterly trend as the main cluster (Fig. 3). Deep seismicity in this region is not restricted only to the Askja system. The third cluster of deep earthquakes is located to the east of Askja, halfway between Askja and Kverkfjöll volcanic systems (see Figs 1 and 3). The seismicity clusters at approximately 24 km, with one, well-located event at a

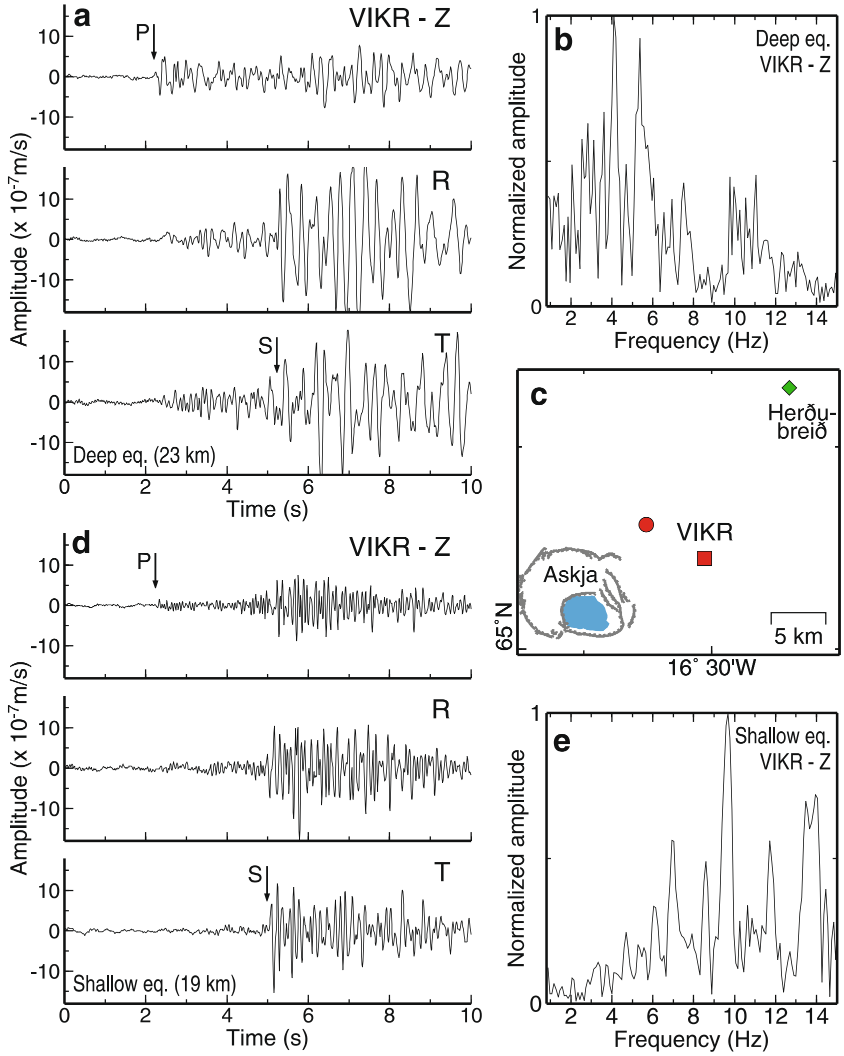

Fig. 4 Waveforms and spectra of two magnitude-1 earthquakes, illustrating similarities and differences between lower-crustal and upper-crustal earthquakes. Events with similar source-receiver distances are shown, to eliminate path length effects of the spectra. a, b: 22-km deep lower-crustal earthquake (red dot in c) northeast of Askja. d, e: 7-km deep upper-crustal event (green diamond in c) beneath Herðubreið, both recorded by the station VIKR (red square in c, also in Fig. 1). Direct hypocentral distances between the station and the earthquakes are 23 km and 19 km, respectively. The seismograms are band-pass filtered 0.8–15 Hz, to reduce background microseismic and wind noise. Vertical (Z), radial (R) and transverse (T) components are shown and picked P- and S-wave arrivals marked by arrows. The spectra are taken over the first 6 s, prior to filtering, but clipped and normalized at 0.8–15 Hz

depth of over 30 km. This locality is somewhat enigmatic, as it does not lie within any current volcanic system.

Retrospective examination of the catalogue of events recorded at the more distant stations of the national network points to the possible existence of lower-crustal earthquakes for at least 1 year prior to our 2006 survey. However, this information remains qualitative. We ran a pilot network of five stations (DYNG, HERD, HELI, UPTY and VIKR in Fig. 1) for 3 weeks in August 2005 and did not detect any events with waveforms or depths typical of the lower-crustal earthquakes, although those same five stations recorded 47 deep events over the same three-week period in 2006 and 18 events in the same period in 2007 (UPTY was replaced in 2007 by a site slightly to the southeast, see Fig. 1).

Vigorous seismicity, consisting of intermittent clusters of lower-crustal earthquakes, started in February 2007 in the vicinity of the Upptyppingar mountain within the Kverkfjöll volcanic system some 20 km to the east of Askja (Fig. 1). The Upptyppingar activity is beyond the scope of this paper, but these events are well documented with observations from the permanent Icelandic seismic network, and were also recorded on our network. This intense seismic activity in the Upptyppingar area, accompanied by crustal movements detected by GPS, has been interpreted as indicative of a magma intrusion (Jakobsdóttir et al. 2008).

Over 5000 earthquakes in the Upptyppingar region had been detected by end-December 2007, with local magnitudes (M_L) up to 2.2 and a depth range mainly within 14–21 km. However, these earthquakes have clearly different waveforms than the lower-crustal Askja events, with sharper onsets and broader spectra. They occur at the margin of the active rift zone and at the extreme northern end of that particular volcanic system, whereas Askja is located at the rift zone axis and in the center of the volcanic system.

Discussion and conclusions

Magmatic movements can be responsible for earthquakes with a variety of different frequency contents as a result of different source processes. Low-frequency or long-period events, observed at various active volcanoes in the world (e.g. Chouet 1996; McNutt 2000) are thought to be caused by fluid processes which are still not well understood, whereas high-frequency earthquakes are caused by shear failures that can be produced when magma intrusions increase stresses sufficiently for brittle failure to take place.

Despite their relative low-frequency character, we postulate that the lower-crustal Askja earthquakes are caused by brittle failure. They produce prominent shear waves (Fig. 4), which are observed in all azimuthal directions, and although the frequencies are lower than the shallow events, they are not as low as typical volcanic long-period events. We suggest that the absence of high frequency energy in the seismic arrivals may be due to high absorption caused by high temperature rock in the lower crust. Similar observations, of events containing frequencies predominantly below 5 Hz, have been made on the sporadic inter-eruption earthquakes at 8–27 km depths beneath the active volcano Hekla (Fig. 1 inset) located at a transform-rift junction in south Iceland (for waveforms and spectra, see Fig. 14 in Soosalu et al. 2005).

In the Hekla region, transform tectonics dominate the stress field between eruptions, producing brittle-failure earthquakes along two elongate north-south lineaments crossing the Hekla volcano (Soosalu and Einarsson 2005; Soosalu et al. 2005). Earthquakes occurring elsewhere along these lineaments have the broad spectrum of an ordinary tectonic earthquake. Frequencies above ~5 Hz are absent only from events occurring beneath Hekla, an effect observed in all azimuthal directions. S-waves from these events are recorded distinctly by seismic stations in all directions around Hekla. Soosalu and Einarsson (1997) infer that although the inter-eruption events beneath Hekla are tectonic, because of a low stress drop in bedrock that is hotter and weaker than the surroundings after a Hekla eruption, they contain only low frequencies. In every other respect they resemble earthquakes occurring elsewhere along the two north-south lineaments (Soosalu and Einarsson 1997).

The transition from brittle to ductile behaviour in crustal rock at 5–7 km depth depends on the temperature and confining pressure (depth), but the strain rate is also an important factor (see *e.g.,* Van der Pluijm and Marshak 2004). The most likely explanation for earthquakes occurring deeper in the normally ductile region is an abnormally high strain rate (Tuffen and Dingwell 2005), possibly combined with high fluid pressure.

A possible mechanism for generating the lower-crustal Askja earthquakes is high strain rates caused by intrusive igneous activity, facilitated by the extensional setting of the rift zone. Close to, or at the tip, of a propagating dyke the strain rates locally can grow sufficiently large to cause brittle failure (Needleman and Tvergaard 2000). This results in a short-lasting swarm of small earthquakes. Seismic energy released by the brittle failure may also cause resonance at the boundary of a fluid filled container in solid rock (either in the intrusion itself or in the magma chamber), generating a prolonged coda that is sometimes observed for the deep events (*e.g.*, Neuberg et al. 2000).

There is a possibility that the lower-crustal earthquakes have a tectonic, not magmatic origin. However, the striking mid-crustal gap in seismicity from 8–12 km depth (Fig. 2), and non-overlapping epicentral distribution between the upper-crustal (tectonic) seismicity and the lower-crustal events (Fig. 3) is evidence against this explanation. With a tectonic origin a continuum of seismicity with depth in the most active areas would be more likely. Furthermore, we locate the most intense earthquake cluster beneath the northern part of Askja, close to the northern edge of the suggested deeper magma chamber centered at 16 km depth, and the cluster deepens as it extends to the northeast along the Askja fissure swarm. As geodetic and gravimetric observations indicate that magma drainage is occurring from the plumbing system of the Askja caldera, this is a likely direction for melt movement to occur.

The small magnitudes of the lower-crustal earthquakes are consistent with faults of the order of a few meters long with motions of a millimeter or less. Thus individual swarms of a handful of events could represent melt moving sporadically over distances of a few tens of meters. Although geodetic measurements show overall deflation of the Askja system, small intrusions causing minor volume increases at a minimum depth of 15 km may not be detected by the GPS network, or by InSAR (Pagli et al. 2006). The last two magmatic eruptions at Askja were quite recent, in the 1920s and 1961. The deep earthquakes we have recorded could be the earliest indicator that recharging of the Askja magmatic system is beginning, in preparation for another eruption.

It is a matter of speculation whether the intense lower-crustal seismicity in the Askja area started some time in 2006, or whether it remained undetected at earlier times because the seismic network was too sparse. In any case, the increase in the number of detected events between summer 2006 and summer 2007 is an observed fact. It is also possible that deep seismicity at Askja is somehow linked to deep activity that started at Upptyppingar in February 2007. Interplay between neighbouring volcanic systems has been observed before in Iceland (*e.g.,* Einarsson 1991).

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