

# Seismic character of volcanic activity at the ultraslow-spreading Gakkel Ridge

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## ABSTRACT

Never before has a volcanic eruption on a slow- or ultraslow-spreading mid-ocean ridge been both observed seismically and confirmed on the seafloor. During the first half of 1999, a long-lived volcanic-spreading event occurred on the ultraslow-spreading Gakkel Ridge in the Arctic Ocean. The seismicity associated with this event was unprecedented in duration and magnitude for a seafloor eruption. Sonar images from the U.S.S. *Hawkbill*, which passed over the area within four months of the start of activity, are consistent with the presence of a large, recently erupted flow and a volcanic peak directly in the area of seismic activity. Seismic activity began in mid-January and continued vigorously for three months; a reduced rate of activity persisted for an additional four months or more. In total, 252 events were large enough to be recorded on global seismic networks. Although a limited number of volcanic-spreading events have been observed globally, the duration and magnitude of the Gakkel Ridge swarm, when compared with volcanic seismicity at ridges spreading at intermediate and fast spreading rates, suggest that a negative power-law relationship may exist between these parameters and spreading rate. Fault activation, in response to magmatic emplacement, appears to have occurred over a broad region, suggesting that magma may have been tapped from mantle depths. The slow migration of the largest magnitude events along the axis of the rift valley suggests multiple magmatic pulses at depth. In combination with bathymetric setting and sidescan sonar confirmation, the seismic data for this event have provided a unique look at the scale and character of eruption processes at ultraslow-spreading rates.

**Keywords:** Arctic, earthquakes, eruptions, mantle, mid-oceanic ridges.

## INTRODUCTION

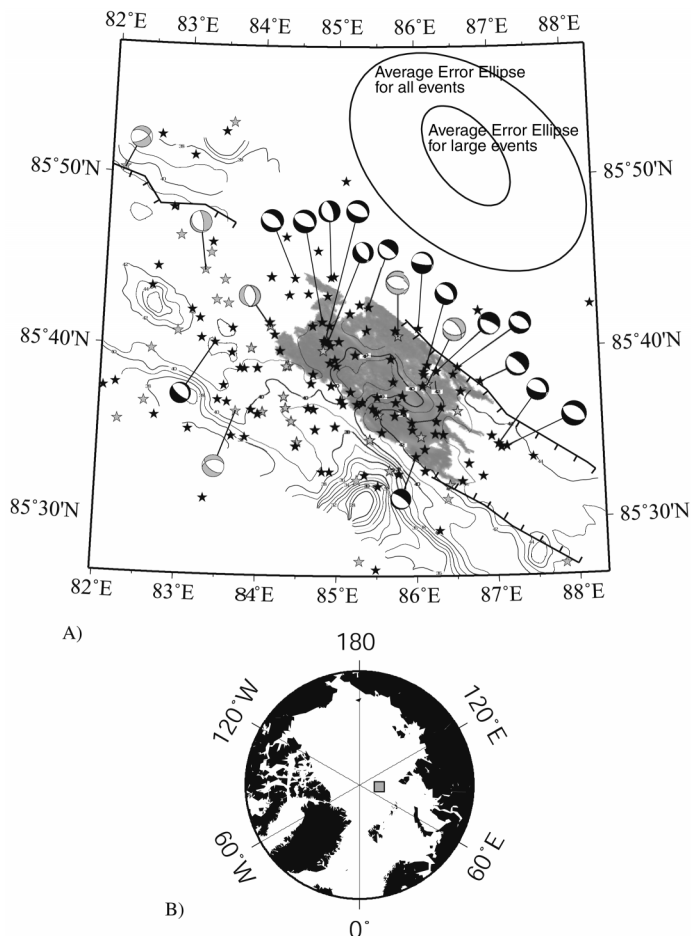
The Gakkel Ridge, located in the Arctic Basin, is the slowest-spreading ridge on the planet, with a full spreading rate of  $\sim 1.1$  cm/yr (at  $\sim 85^\circ\text{E}$ ). The ridge is unusually deep, with a broad axial valley and 1–2-km-high bounding walls, and has been inferred to have very thin crust (Coakley and Cochran, 1998), suggesting a low magma supply and cold upper mantle.

A sequence of earthquakes began on the Gakkel Ridge during January 1999 in the area of  $86^\circ\text{N}$ ,  $85^\circ\text{E}$  (U.S. Geological Survey, 1999; Muller and Jokat, 2000) (Fig. 1). Vigorous seismic activity was sustained for about three months and persisted at a lower level for an additional four months or more; occasional events continued into September 1999 (Fig. 2A). The characteristics of this sequence were suggestive of volcanic activity (Sykes, 1970); i.e., no large mainshock, no decrease in magnitude with time, and a consistent event rate during an extended period of time. The  $b$  value of the swarm is  $\sim 1.5$  (estimated by using both least-squares and maximum-likelihood methods, with a magnitude of completeness  $m_b$  of 4.5), which can be interpreted as consistent with volcanic activity. Fortunately, the SCICEX (Science Ice Exercises) expedition, aboard the U.S.S. *Hawkbill*, mapped this

area on May 6, 1999, directly following the period of intense activity and still within the period of continued lesser activity. Sidescan sonar images and bathymetric data show a large area ( $\sim 40$  km<sup>2</sup>) of unfaulted flows, centered in the area of intense seismic activity (Edwards et al., 2001). Thus, we are presented with our first opportunity to characterize the seismicity associated with an eruption on an ultraslow-spreading ridge and consider the implications.

## ERUPTION SCALE

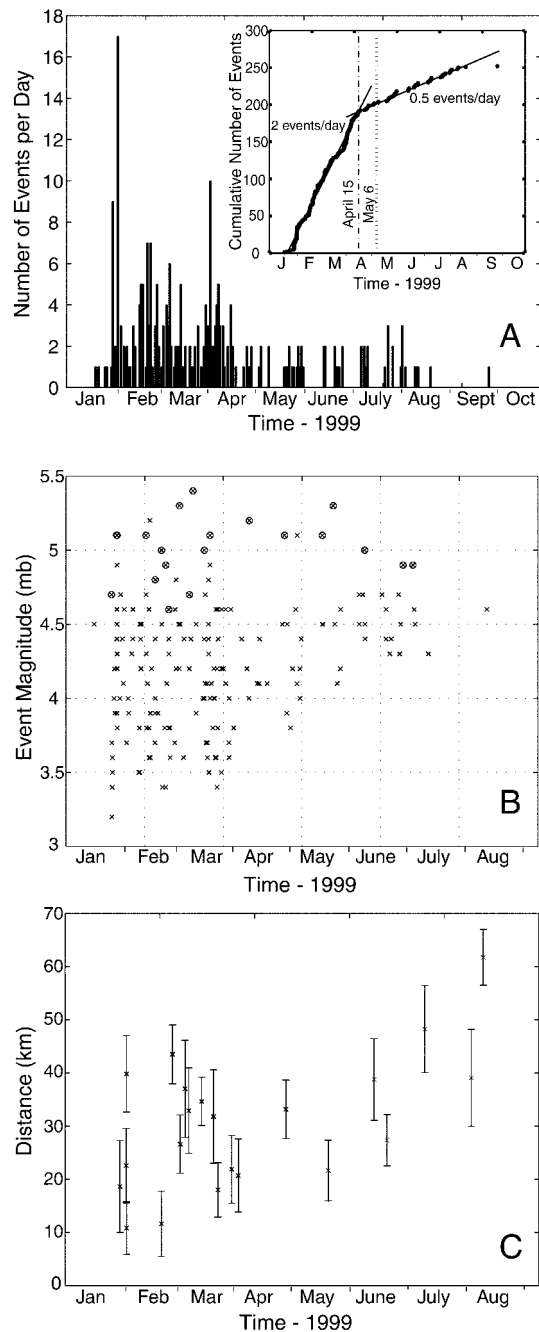
The most immediately notable and surprising aspect of this eruption is the duration and magnitude of the seismicity, which can be used to define the duration of volcanic activity and mechanics of emplacement. The consistent event rate and volcanic character of the earliest activity suggest that volcanism began immediately and continued at least until April 15, when there was a distinct decrease in the rate of activity (Fig. 2A). Because this later activity still lacks tectonic characteristics, it is possible that volcanism continued beyond April 15 at a lower rate. Unlike a previous analysis of these data (Muller and Jokat, 2000), when accounting for the completeness level of the data set and the variable scales used in reporting event magnitude, we find no evidence for a statistically robust (Utsu, 1992) increase in  $b$  value, which might indicate a transition from tectonic to volcanic events over time. Rather, the entire swarm exhibits a magnitude-frequency distribution ( $b$  value =  $\sim 1.5$ ) consistent with a volcanic-spreading event. The non-double-couple nature of some later earthquakes could be interpreted as representing a transition toward caldera collapse, with slip occurring on nonplanar, cone-shaped faults (Muller and Jokat, 2000); however, sidescan data (Edwards et al., 2001) show no indication of a circular collapse feature. Furthermore, these largest earthquakes were located primarily on the valley walls; none occurred near the volcanic edifice in the axial valley. In light of these observations, it seems possible that the apparent non-double-couple nature of these events reflects the distortion of the focal mechanism due to spatial variability of the elastic moduli within the source volume (Julian et al., 1998), as might be expected if shear faulting occurs adjacent to a large magma body. In addition, we note that the epsilon values (a measure of the non-double-couple component of each event) for this swarm increase with decreasing magnitude, suggesting that higher epsilon values may simply reflect higher signal-to-noise ratios. The immediate initiation of volcanic activity, in association with large-magnitude normal-faulting events, is consistent with observations in the Afar region during a documented volcanic-spreading event in 1978 (Abdallah et al., 1979). In that event, volcanism and large-magnitude earthquake activity lasted for only one week and produced  $\sim 2$  km<sup>2</sup> of observable lava (some of the activity was under water). Perhaps the closest analogue to the Gakkel event would be the 1783 Laki fissure eruption in Iceland, which produced  $\sim 14$  km<sup>3</sup> of lava over about 8 months of seismic activity covering a section  $\sim 27$  km long with 10 en echelon fissures (Thordarson and Self, 1993).



**Figure 1. A:** Event locations for 1999 Gakkel Ridge swarm. Black stars indicate epicenters for earthquakes prior to May 6, when U.S.S. *Hawkbill* passed over area. Gray stars indicate epicenters after that time. Focal mechanisms are shown for 21 largest events (those with Harvard centroid moment tensor solutions). Flow-covered area (shaded gray) and 100 m contours indicate local bathymetry (Edwards et al., 2001). Depth within valley floor is ~3.9–4.4 km; contours are marked in hundreds of meters. Flow appears to cover most of width of valley floor; valley-wall bounding faults (thick black lines with ticks on downthrown block) are apparent in some places in bathymetry and sidescan sonar data. Focal mechanisms for events located on, or just south of, northern valley wall are consistent with slip at depth on this southwest-dipping structure that projects beneath valley floor at angle of ~45°. U.S. Geological Survey (USGS) listed total of 207 events associated with this swarm. Accuracy of event locations varies from event to event and is particularly dependent on magnitude. Median error ellipses are shown for entire swarm: 14.7 km (semimajor axis) and 9.55 km (semiminor axis); and for 21 largest events: 6.38 km (semimajor axis) and 3.49 km (semiminor axis). Reviewed Event Bulletin (REB) listed 252 events, but includes more small-magnitude events, which tend to be poorly located (Prototype International Data Center, 1999). Here we use USGS event locations, because that catalogue consistently uses larger number of stations to locate events (Wuster et al., 2000). However, we include additional REB events in Figure 2A. B: Global location of swarm site (gray box).

#### RELATIONSHIP TO SPREADING RATE

Although typical eruption characteristics at ridges spreading at intermediate and fast rates have been determined with hydroacoustic monitoring followed by on-site confirmation, an eruption never has been observed seismically and then confirmed on a slow- or ultraslow-spreading ridge. It has been suggested that eruptions on slow-spreading ridges are associated with small discrete magma pockets beneath the axis (Macdonald, 1986; Kong et al., 1992); however, it also has been



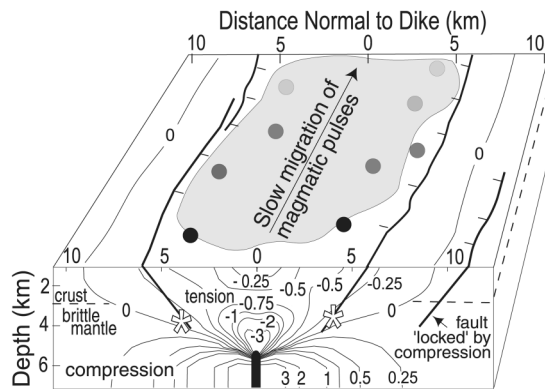
**Figure 2. A:** Histogram showing progression of swarm through time; each bar represents number of events per day. Inset figure shows cumulative number of events through time. Rate of activity clearly decreases on April 15 (dot-dash line). Dashed line shows May 6, when U.S.S. *Hawkbill* mapped flows. B: Event magnitudes over time. Events with Harvard centroid moment tensor (CMT) solutions are circled. Earthquake catalogue is complete for events of >4.5  $m_b$ . C: Migration trend of 21 events large enough to have Harvard CMT solutions. Distance is plotted relative to reference point on axis, at southeastern end of swarm (85.5°N, 88°E). Errors shown are maximum value in error ellipse, because ellipse's semimajor axes are oriented approximately along axis. Note that after April 15 there is slight southward shift of events toward valley floor. Because most of these later events occurred after U.S.S. *Hawkbill* had left area, we do not know whether they were associated with additional lava flows.

proposed that larger volume eruptions may occur at slow-spreading ridges (Smith and Cann, 1999). It has long been postulated that certain types of swarm activity on slow-spreading ridges relate to volcanism (Sykes, 1970; Blackman et al., 2000), the time scales of activity being tens to hundreds of days. However, without field confirmation, the cause of these swarms is open to debate, because tectonic swarms on land have exhibited similar characteristics. The Gakkel eruption provides information on the ultraslow end of the spreading spectrum, and the eruption there occurred over hundreds of days. This time scale is an order of magnitude greater than eruptive events at ridges spreading at intermediate rates (tens of days) and two orders of magnitude greater than eruptive events at ridges spreading at fast rates (days) (Dziak et al., 1995; Fox and Dziak, 1998; Dziak and Fox, 1999; Tolstoy et al., 1999; Fox et al., 2001). This result indicates that a negative power-law relationship may exist between the average size and duration of an eruption and the spreading rate of the ridge at which it occurs, although continued monitoring will be needed to confirm this relationship.

Similarly, the number of teleseismic events associated with the swarm is one to two orders of magnitude greater than that reported for eruptions on ridges having intermediate or fast spreading rates (Dziak and Fox, 1999; Tolstoy et al., 1999). According to U.S. Geological Survey (USGS) estimates, there were 16 events with a body-wave magnitude of 5.0 or greater. For the 21 large events with Harvard centroid moment tensor (CMT) solutions, the focal mechanisms are consistent with those observed for valley-wall earthquakes on the Mid-Atlantic Ridge (Kong et al., 1992) and indicate normal faulting on ridge-parallel planes with a mean dip of 45° (Fig. 1). If a scaling relationship that sets seismic moment ( $M_0$ )  $\propto$  rupture length cubed ( $L^3$ ) is assumed (Scholz, 1990), rupture lengths on the order of 3–5 km, and therefore faults of equal or greater size, are required to generate these largest events. This constraint, as well as the location of large-magnitude event epicenters within or near the base of the valley walls, suggests that a series of ruptures has occurred along the large faults that bound the rift valley (Fig. 1).

#### EARTHQUAKE TRIGGERING AND MAGMA TRANSPORT FROM THE MANTLE

In other volcanic rift zones, the tensile stress field that forms above a propagating dike has been suggested as a mechanism by which to induce slip on nearby faults (Rubin, 1992) (Fig. 3). A significant reduction in the normal stress acting on a dike-parallel fault, however, only occurs out to a distance roughly equivalent to the depth of the dike. Hence, the shallow subsurface (0–2 km) propagation of a dike, as described at some faster spreading ridges (Dziak et al., 1995; Dziak and Fox, 1999; Tolstoy et al., 1999), is unlikely to trigger large-magnitude events on the bounding walls 5–10 km from the center of the flow area. It is possible that magma may have intruded along the edge of the valley, perhaps using the bounding-wall faults as conduits. However, this seems unlikely given the volcanic construct in the center of the valley floor, and young flows observed to emanate from this feature in the sidescan data (Edwards et al., 2001). If magma were emplaced near the valley center, it must have initially propagated from a much greater depth than observed along faster spreading ridges. To trigger the observed bounding-wall events, a first-order estimate suggests that a dike-like body emplaced near the center of the flow must have an initial depth greater than ~5 km. For lateral dike-propagation events that occur at shallower depths (e.g., Dziak et al., 1995), slip on the bounding-wall faults will be inhibited by dike-normal compressive stresses acting upon some, or all, of the fault plane (Fig. 3). The triggering of bounding-wall seismicity may therefore imply initial propagation directly from the mantle, because crustal thickness estimates in the area suggest that the crust is <3 km thick (and probably thinner than 1 km) (Coakley and Cochran, 1998). Delivery of magma directly



**Figure 3.** Schematic diagram showing influence of dike emplacement on axial-valley stress field. Dike-like magma body is modeled with internal magma pressure of 5 MPa above lithostatic pressure and extends from depth of 5–8 km within brittle mantle. Changes in dike-normal stress (thin solid lines) are labeled in MPa; negative values indicate tension and positive values indicate compression. Emplacement of dike near center of flow at depth of ~5 km or greater is predicted to reduce normal stress acting on bounding-wall faults of ~10-km-wide rift valley, potentially triggering large-magnitude earthquakes observed teleseismically. Dike that initiates and propagates laterally at shallower depth—as observed on some faster spreading ridges—would tend to inhibit slip within valley walls by increasing normal stress on bounding-wall faults. Hypocenters (stars) are assumed to be at depths <3 km, within frictionally unstable parts of fault where earthquakes are likely to nucleate (Scholz, 1990). Epicenters (circles) show along-axis migration of large-magnitude events during period of several months (from dark to light). Rate of this migration (~8 m/h) is consistent with emplacement of several vertical pulses of magma that are intruded progressively along axis of valley.

from the mantle might explain why both the major and trace element chemical compositions of Gakkel Ridge lavas represent end members in terms of global mid-ocean ridge basalt composition (e.g., Muhe et al., 1991; Langmuir et al., 1992).

Direct transport of magma from the mantle could explain also the observed thinning of layer 3 toward segment ends on the Mid-Atlantic Ridge (Tolstoy et al., 1993), where, similar to the Gakkel, lithospheric thickness exceeds crustal thickness (Toomey et al., 1985) and gabbroic plutons are observed in peridotite (Cannat, 1996). There is seismic (e.g., Garmany, 1990) and compliance (Crawford et al., 1999) evidence for magma at the base of the crust at the East Pacific Rise, but its role relative to the mid-crustal axial magma chamber is unknown.

#### MIGRATION

The larger valley-wall events show a migration trend over time toward the northwest along the valley (Fig. 2C). The events migrated ~40 km over 200 days, an hourly migration rate of ~8 m/h, which is significantly less than dike-migration rates observed at other seafloor eruptions, on the order of thousands of meters per hour (Dziak et al., 1995; Dziak and Fox, 1999; Tolstoy et al., 1999). The full cluster of USGS epicenters for this swarm does not exhibit any definitive long-term migration trend. This at least partially reflects the larger along-axis errors associated with the smaller events' locations.

The western extent of the flow area ends at the approximate position that the migration of large bounding-wall events had reached when mapped on May 6, hinting that the extent of the flow area may be linked to the migration. The largest daily cluster of seismicity occurred at the southeastern limit of seismic activity on February 1 and



included three magnitude 5.1 events, consistent with the rising of a major dike. However, the along-axis rate of migration (~8 m/h) of the larger events is so slow that the continued lateral propagation of a dike at depth seems unlikely. The coseismic stress changes associated with the initial large-magnitude events potentially could trigger subsequent large-magnitude events (e.g., King et al., 1994), such that the northern wall of the valley would tectonically unzip over time. Alternatively, the slow northwest migration of large-magnitude events, as well as the along-axis extent of the flow area, might indicate that subsequent events were triggered by a succession of vertical magmatic pulses that migrated slowly along the axis from a deep source. The initial pulse opening a conduit might make it easier for further pulses along the magma body to break open the lithosphere and move toward the surface in much the same way that the lateral tapping of a crustal axial magma chamber might occur. Because the largest magnitude events occur within the middle of the swarm (Fig. 2B), the latter scenario seems more likely than tectonic unzipping.

## SUMMARY

The scale of this seafloor eruption, unprecedented both in seismic event magnitude and duration of activity, provides a new picture of mid-ocean ridge processes at the slowest end of the spreading-rate spectrum. It appears that massive eruptions on a scale of some of the largest terrestrial activity can occur on the seafloor. Although it does not preclude smaller scale activity at this spreading rate, it does imply that, on the basis of events we have seen to date, eruptions appear to be longer lasting and associated with larger magnitude seismic activity as spreading rate decreases. This finding is consistent with the larger stresses required to break through the colder, thicker brittle layer found in the slower spreading environment.

The scale and longevity of activity may have significant impacts on the type of biology that might be found in the ultraslow-spreading environment. The longevity results in an unusually extended period during which a large nutrient flux is provided to the seafloor biological system.

The data presented here also provide the first seismic evidence that magma might be transported directly from the mantle during a mid-ocean ridge eruption. There have been indications from ophiolite studies, submersible mapping, compliance work, seismic reflection, and seismic tomography that melt bodies exist beneath the crust, but the Gakkel data provide the first evidence for dynamic propagation. Until now, the time scale of this deep melt transport was unknown. These data suggest that this feeding of magma from deep sources can take place over a very short time scale, clearly affecting the structure and chemistry of the crust.

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