LETTERS

Explosive volcanism on the ultraslow-spreading Gakkel ridge, Arctic Ocean

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Roughly 60% of the Earth's outer surface is composed of oceanic crust formed by volcanic processes at mid-ocean ridges. Although only a small fraction of this vast volcanic terrain has been visually surveyed or sampled, the available evidence suggests that explosive eruptions are rare on mid-ocean ridges, particularly at depths below the critical point for seawater (3,000 m)[1]. A pyroclastic deposit has never been observed on the sea floor below 3,000 m, presumably because the volatile content of mid-ocean-ridge basalts is generally too low to produce the gas fractions required for fragmenting a magma at such high hydrostatic pressure. We employed new deep submergence technologies during an International Polar Year expedition to the Gakkel ridge in the Arctic Basin at 85° E, to acquire photographic and video images of 'zero-age' volcanic terrain on this remote, ice-covered ridge. Here we present images revealing that the axial valley at 4,000 m water depth is blanketed with unconsolidated pyroclastic deposits, including bubble wall fragments (limu o Pele)[2], covering a large (>10 km^2) area. At least 13.5 wt% CO_2 is necessary to fragment magma at these depths[3], which is about tenfold the highest values previously measured in a mid-ocean-ridge basalt[4]. These observations raise important questions about the accumulation and discharge of magmatic volatiles at ultraslow spreading rates on the Gakkel ridge[5] and demonstrate that large-scale pyroclastic activity is possible along even the deepest portions of the global mid-ocean ridge volcanic system.

The Gakkel ridge, stretching ~1,800 km across the eastern Arctic Basin, is the ultraslow-spreading end-member of the global mid-ocean ridge (MOR) system, and in 1999 the Global Seismic Network (GSN) detected the largest MOR earthquake swarm ever recorded[6] on the ridge at 85° E. Several lines of evidence suggest that the swarm was associated with a major volcanic event[6–10], but our ability to characterize volcanic processes in this region has been limited by its remote location and ice cover. From 15 to 31 July 2007 the Arctic Gakkel Vents (AGAVE) expedition aboard the icebreaker *Oden* surveyed the presumed eruption site with a Kongsberg EM120 1° × 1° multibeam echo sounder, a conductivity–temperature–depth rosette, two autonomous underwater vehicles and a sub-ice camera and sampling platform (CAMPER).

We produced a high-resolution bathymetric map of the axial valley floor at 85° E by operating the sonar system while drifting quiescently in the ice pack. The combination of the low-noise survey mode and the decrease in variance obtained from ping-averaging several dozen overlapping tracklines allowed us to produce a highly detailed (30-m pixel resolution) sonar image of the eruption site (Fig. 1), showing that the axial valley is filled with distinctive volcanic features. These volcanoes are up to ~2,000 m in diameter and a few hundred metres high. They are commonly flat-topped, contain a prominent central

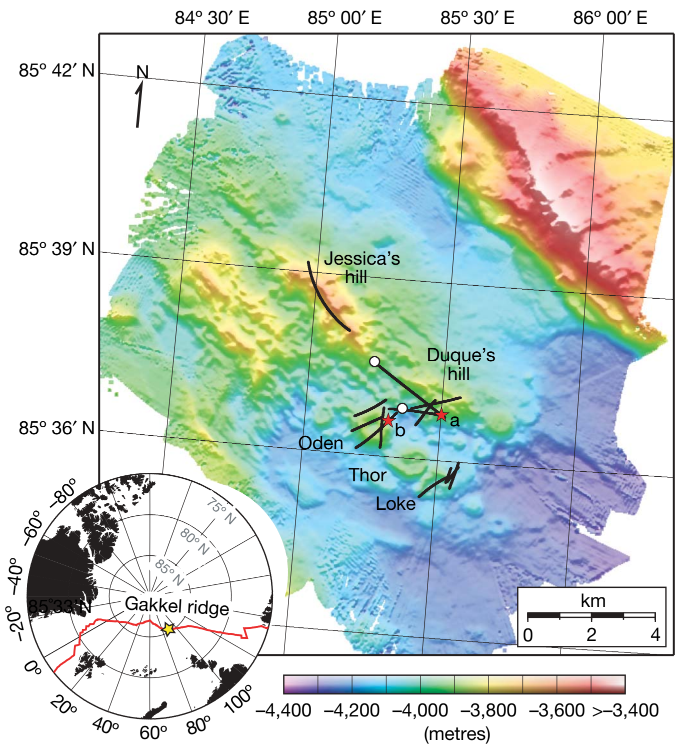

Figure 1 | Detailed bathymetry (30 m grid spacing) of the Gakkel ridge at 85° E in the Arctic Ocean. The inset map shows the location of the 85° E segment (yellow star) along the Gakkel ridge (red line) in the Arctic basin. The main panel shows illuminated, colour bathymetry of the 85° E segment acquired during the AGAVE expedition. The axial valley contains large numbers of distinctive, cratered volcanoes, including a cone on a fault terrace of the northern valley wall. Photographic bottom surveys were conducted along profiles shown as thin black lines on the map. Pyroclastic deposit samples were collected at sites shown by white circles, and the photographs shown in Fig. 2a, b were taken at the sites shown by the lettered red stars. Named features include two volcanic ridges in the centre of the axial valley (Jessica's hill and Duque's hill), and three cratered volcanoes along a ridge-parallel fissure to the south (Oden, Thor and Loke). The bathymetry data were plotted with Generic Mapping Tools[22].

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crater and cluster on ridge-parallel faults or fissures. The type example is perhaps Oden volcano, which is ~300 m tall and ~1.5 km in diameter, and contains an ~50-m deep central crater ~500 m in diameter (Fig. 1).

A real-time fibre-optic connection allowed scientists aboard the icebreaker to 'fly' the CAMPER vehicle 2–5 m above the sea floor within the region of the suspected eruption and acquire photographic still imagery and high-definition video imagery of the volcanic terrain. The images reveal that the axial valley topography is blanketed with unconsolidated pyroclastic deposits up to 10 cm thick. The thickest deposits overlie the weathered and broken lava flows (Fig. 2a) on Jessica's hill and Duque's hill in the centre of the axial valley (Fig. 1), whereas the fresh (that is, unweathered, glassy surfaces with delicate ornamentations) lava flows on the Oden and Loke volcanoes are covered with a light dusting of material. Pyroclasts are piled atop pillows and other high-standing features, indicating deposition by fall rather than flow. Multiple falls are implied by spatial variations in the apparent age (colour) and thickness of the deposits. The maximum extent of the pyroclastic material is not known, because the deposits were observed to cover every portion of the sea floor that we surveyed (~20 linear kilometres within an ~5 × 10 km region).

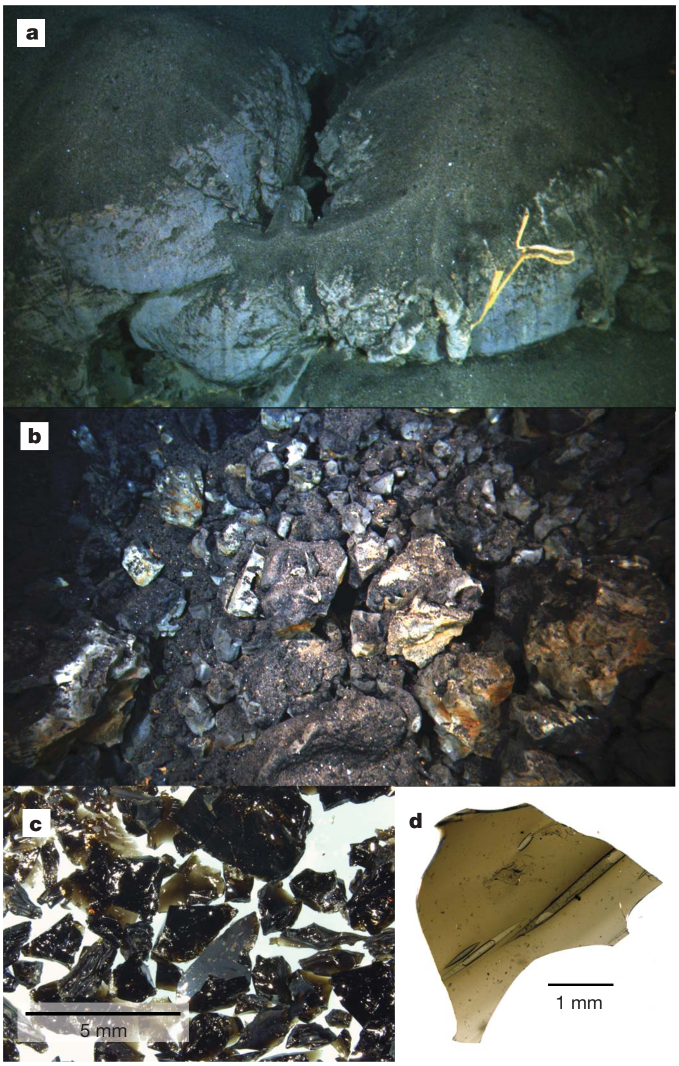

Figure 2 | Photographs of pyroclastic deposits. a, Frame grab from a high-definition video camera taken on the south side of Duque's hill (see Fig. 1 for location). About 10 cm (visually estimated and confirmed during sampling) of pyroclastic material is piled atop a high-standing, weathered, pillow feature. The exoskeleton of an as yet unidentified species of hexactinellid sponge[23] is visible in the foreground. **b**, High-definition video frame grab of talus blocks possibly representing ejecta from a vulcanian explosion on Oden volcano (see Fig. 1 for location). **c**, Glassy, granular, pyroclastic material. **d**, Bubble wall fragment from pyroclastic deposit.

A series of eight dives across the Oden and Loke volcanoes suggests that the ubiquitous cratered volcanoes may be source vents for pyroclastic eruptions, possibly including vulcanian explosions. These volcanoes contain most of the fresh lava flows observed in our survey, which consist primarily of pillows but also include ropey sheet flows, covering small areas (~100–200 m^2) on the top and around the outer edges of the constructional features. The mixture of young and old lava flows that we observed demonstrates that the high-acoustic-backscatter region imaged in 1999 does not represent a single, fresh lava flow[8]. The crater of Oden volcano is filled with weathered, basaltic talus but contains no visible fault scarps. The talus is covered by small amounts of pyroclasts, and the block sizes generally decrease on moving away from the crater centre, extending onto the outer slopes of the volcano (Fig. 2b). These observations are consistent with an interpretation of the talus blocks as country rock ejecta from a vulcanian explosion, which may also participate in crater formation, but at this point we cannot unequivocally exclude the possibility that the talus was formed by mass wasting.

About 0.8 kg of clasts was collected from two sites along our tracklines with a retractable slurp (suction) device mounted on the CAMPER vehicle. The samples consisted nearly entirely of juvenile clasts of glassy basalt (Fig. 2c) with a small (≪5%) component of crystalline and altered crystalline rock. The clasts are primarily angular fragments, many with cuspate surfaces, that range in size from 1 to 20 mm (the suction sampler does not preserve *in situ* sorting). The clasts contain minor olivine and plagioclase microphenocrysts, and have low (<5%) vesicularity. In addition, the deposits contain small amounts of limu o Pele[2,11], which are thin, glassy, bubble wall fragments, 3–20 mm across, with fluidal folded morphologies (Fig. 2d).

Large-volume pyroclastic deposits have been found in shallow water (500–1,750 m water depth) on the Azores Plateau[12–14], but the only previous evidence of pyroclastic material at water depths greater than 3,000 m (the critical depth for steam) is limited to small fragments recovered in sediment cores[15,16]. Hydrostatic pressure inhibits volume expansion, and below the steam threshold any explosive activity must result from magmatic volatiles rather than secondary surface effects. CO_2 is the most plausible exsolved volatile component for MOR basalts[15], and at 4,000 m water depth a CO_2 weight fraction of ~14% (ref. 3) is necessary to achieve the volume fraction of ~75% needed to fragment an erupting magma[17]. This value exceeds the maximum dissolved CO_2 concentrations measured in a MOR basalt (~1.4 wt% in a 'popping rock')[4] by an order of magnitude.

Volatiles that exsolve during magma ascent or decompression may coalesce to produce finite volumes of magma with gas volume fractions sufficient to trigger pyroclastic activity, even in magmas with primary volatile levels well below the fragmentation threshold. The nature of pyroclastic activity triggered by this process depends on the amount of volatiles and the depth at which fragmentation occurs. For example, if gas exsolution and expansion occur during the slow rise of an erupting dyke, and the rising bubbles coalesce in the upper few hundred metres of the crust (that is, slug flow), then Strombolian (bubble burst) activity may occur at the sea floor. The observation of bubble wall fragments in our pyroclastic samples is consistent with some level of Strombolian activity, but bubble coalescence and fragmentation in the shallow crust can only distribute clasts to maximum distances of ~20–40 m from the source vent[3], which is inconsistent with the widespread distribution of material over the >10-km^2 region observed in our survey.

A more energetic mechanism is required for depositing clasts more than a few tens of metres from the source vent, which is possible if fragmentation occurs deeper within the crust. The accumulation of a large volume of volatiles in the upper layer of a crustal magma chamber[18] provides the most plausible mechanism for deep fragmentation. Exsolved volatiles may accumulate in a chamber over long periods, and then discharge explosively when the roof is fractured during an eruption, spreading pyroclastic material over large

Table 1 | Variation in pyroclastic jet characteristics with magma chamber depth

Magma chamber roof depth (m)	Minimum CO_2 volume fraction in volatile-rich layer	Pyroclastic jet mixture density at vent ($kg\,m^{-3}$)	Average jet exit velocity at vent ($m\,s^{-1}$)	Plume rise height in water column (m)
1,000	0.6443	568	236	544
2,000	0.5647	462	343	956
3,000	0.5026	398	424	1,276
4,000	0.4528	355	490	1,532
5,000	0.4120	324	544	1,741
6,000	0.3779	302	591	1,916

Following the analysis presented in sections 2.4 and 2.5 of ref. 3, we calculate the minimum CO_2 volume fraction in a volatile-rich layer accumulating under the roof of a crustal magma chamber required for producing pyroclastic activity on the sea floor at a depth of 4,000 m. Magmas with the gas volume fractions shown in column 2 will fragment just before reaching the sea floor, producing very small deposits. However, if the CO_2 volume fraction in a volatile-rich layer is ~0.75, fragmentation occurs at the magma chamber depth, and a much more energetic eruption occurs as the gas accelerates during ascent to the sea floor, producing the approximate conditions shown in columns 3–5.

areas proportional to the chamber depth. For the range of parameters appropriate for our study area, we find that pyroclastic fountains may rise as high as 1–2 km in the water column if fragmentation occurs within a crustal chamber (Table 1).

These results provide a new perspective for interpreting the 1999 seismic swarm and volcanic event at the 85° E site. The seismic swarm began with extensional events, but after three months the earthquakes changed to sources with large volume changes (implosions)[6]. Large-volume-change events are rare at MORs, but they are consistent with the rapid evacuation of explosive material from a deep-lying magma chamber. The sequence of extensional earthquakes leading up to the implosions may have perturbed the stress field enough to fracture the chamber roof, thereby releasing pressurized magmatic volatiles. Rapid acceleration of decompressing volatiles may have triggered vulcanian explosions during the eruption[3], consistent with the talus distribution observed on Oden volcano. Multiple episodes of explosive volatile discharge over a prolonged period are required for producing the variations in apparent age and thickness of the deposits we observed, and we note that small-magnitude explosive acoustic signals were detected by local (ice-mounted) seismic networks at the eruption site more than two years after the 1999 seismic swarm[19]. Explosive volatile discharge has clearly been a widespread, and ongoing, process at the 85° E segment.

Our results raise new questions about volatile processes in ultraslow-spreading magmatic systems. More observations will be necessary to determine the ubiquity of pyroclastic activity at ultraslow spreading rates ($<$15–20 mm yr^{-1}, full rate), but from first principles there is reason to believe that ultraslow-spreading ridges may be especially conducive to the build-up and explosive discharge of volatile-rich magmatic foams. Long time intervals between eruptions should increase the quantity of volatiles that can be accumulated in a magma chamber, and if the global correlation between spreading rate and magma chamber depth extends to ultraslow rates, then volatile build-up will occur deep within the crust at high storage pressures. Our results add to the growing body of evidence that ultraslow-spreading ridges host unique modes of crustal accretion and tectonic extension[20,21], and motivate continuing efforts to solve the technical and logistical issues that have impeded scientific access to these unique geological environments.

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