

located near Monte Verde, thought to be the oldest archaeological site in the Americas¹⁸. Remains interpreted as partially burned plant and animal artefacts in association with hearths have been cited as evidence for the presence of humans and their use of fire between ~12.5 and 12¹⁴Ckyr BP. Possibly, the high climate variability between ~11.2 and 9.9¹⁴Ckyr BP afforded the conditions that allowed humans to set small-scale fires that altered the vegetation near the Huelmo and Lago Condorito sites.

Our data suggest that climate approaching modern conditions prevailed in the Chilean Lake District between ~13 and 12.2¹⁴Ckyr BP. This was followed by a general reversal in trend with cooling events at ~12.2 and ~11.4¹⁴Ckyr BP, and then by subsequent warming at 9.8¹⁴Ckyr BP. The total temperature depression between ~11.4 and 9.8¹⁴Ckyr BP was relatively minor ($\leq 3^\circ\text{C}$), as indicated by the persistence of rainforest vegetation. The timing, direction, and relative magnitude of these events matches the late-glacial record from nearby Lago Mascardi¹⁹ (Fig. 1), which indicates retreat of the Monte Tronador ice cap between 13 and 12.4¹⁴Ckyr BP, a reversal starting at ~12.4¹⁴Ckyr BP and culminating with glacial readvance between 11.4 and 10.2¹⁴Ckyr BP. These records from the Andean region of mid-latitude South America show a notable resemblance in timing and structure to palaeoclimate fluctuations recorded in Europe and Greenland. In contrast, Bennett *et al.*⁴ found no palynological evidence for climate change during late-glacial time in the Chilean channels (45°–47°S). If this interpretation is correct, their results would imply that: (1) a major climate boundary existed between 42° and 45°S during late-glacial time; or (2) late-glacial climate changes did not reach a critical threshold to trigger discernible vegetation changes in palynological records, and thus the impoverished late-glacial flora of the Chilean channels was insensitive to the magnitude of late-glacial cooling; and/or (3) plant succession, soil development, and migration from glacial refugia were the dominant factors controlling vegetation change in this newly deglaciated region during the critical time period.

Our results suggest that mid-latitude climate in the Southern Hemisphere changed in unison with the North Atlantic region between ~13 and 10¹⁴Ckyr BP. This is in contrast with the palaeoclimate signal derived from sediment cores in the South Atlantic Ocean²⁰ and ice cores from interior Antarctica²¹, where the pattern of climate change is opposite to that found in the Chilean Lake District between ~13 and 10¹⁴Ckyr BP. Determining the representativeness of these opposing results on a hemispheric scale has important implications for understanding the climate mechanisms operative during ice ages, because one set of data supports an in-phase interhemispheric linkage in the atmosphere^{2,22,23}, whereas the other favours an out-of-phase relationship via a bipolar see-saw in deep ocean circulation²⁴. The solution could well be that synchronous climate changes, propagated in the atmosphere over much of the planet, were counteracted in Antarctica by a bipolar see-saw of thermohaline circulation, whose effects in the Southern Hemisphere were confined to the high southern latitudes. □

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Evidence of recent volcanic activity on the ultraslow-spreading Gakkel ridge

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Seafloor spreading is accommodated by volcanic and tectonic processes along the global mid-ocean ridge system. As spreading rate decreases the influence of volcanism also decreases^{1–4}, and it is unknown whether significant volcanism occurs at all at ultraslow spreading rates ($<1.5\text{ cm yr}^{-1}$). Here we present three-dimensional sonar maps of the Gakkel ridge, Earth's slowest-spreading mid-ocean ridge, located in the Arctic basin under the Arctic Ocean ice canopy. We acquired this data using hull-mounted sonars attached to a nuclear-powered submarine, the USS *Hawkbill*. Sidescan data for the ultraslow-spreading

($\sim 1.0 \text{ cm yr}^{-1}$) eastern Gakkel ridge depict two young volcanoes covering approximately 720 km^2 of an otherwise heavily sedimented axial valley. The western volcano coincides with the average location of epicentres for more than 250 teleseismic events detected^{5,26} in 1999, suggesting that an axial eruption was imaged shortly after its occurrence. These findings demonstrate that eruptions along the ultraslow-spreading Gakkel ridge are focused at discrete locations and appear to be more voluminous and occur more frequently than was previously thought.

The Arctic basin is the last of Earth's oceanic frontiers. Permanent pack ice covers the Arctic Ocean, restricting the free motion of surface ships, making it impossible to map the sea floor comprehensively. The ice canopy impedes the use of satellite altimetry data to derive the predicted bathymetry models that now exist for every other ocean^{6,7}. Nuclear submarines are ideal for Arctic research because they operate beneath the pack ice and are thus independent of surface conditions. In 1995 the US Navy and National Science Foundation cooperatively developed the Science Ice Exercises (SCICEX), a five-year programme supported by nuclear-powered Sturgeon-class submarines to study the ice canopy, oceanography, biology and geology of the Arctic basin. For SCICEX-98 and SCICEX-99 the US Navy's submarine USS *Hawkbill* was equipped with the Seafloor Characterization and Mapping Pods (SCAMP), a geophysical mapping system built to create the first three-dimensional maps of the Arctic sea floor. SCAMP instrumentation includes a 12-kHz Sidescan Swath Bathymetric Sonar (SSBS), a swept frequency (2.75 kHz to 6.75 kHz) High-Resolution Sub-bottom Profiler (HRSP), a BGM-3 gravimeter and the Data Acquisition and Quality Control System (DAQCS)⁸. We used the Submarine Inertial Navigation system to navigate under the ice, supplemented by occasional fixes from the Global Positioning

Satellite network when the USS *Hawkbill* surfaced. Our relative positional accuracy was better than 3 km.

The SCICEX-99 survey of Gakkel ridge was carried out at an operating depth of 225 m and a speed of 16 knots. The average usable swath width for bathymetry data is 10 km; the average swath width for sidescan data is 16 km. Typical sub-bottom penetration in sedimented areas is 100 m. SCICEX-98 and SCICEX-99 data provide approximately 100% bathymetric and sidescan coverage for the western Gakkel ridge rift valley and flanks out to 50 km on both sides of the ridge axis. Full spreading rates range from 1.33 cm yr^{-1} to 1.15 cm yr^{-1} (ref. 9) at the ends of this region (Fig. 1). During SCICEX-99 a reconnaissance survey of the eastern Gakkel ridge extended coverage of the axial zone out to 1.0 cm yr^{-1} full-spreading rate⁹.

One goal of the SCICEX surveys was to resolve a debate regarding the nature of volcanism at the ultraslow-spreading Gakkel ridge. The presence of lineated magnetic anomalies^{10,11} over the entire ridge suggests that seafloor volcanism occurs. Three bathymetric profiles across the axis of Gakkel ridge near 15° E depict a central high with 200 m relief¹² on the axial valley floor that may be a constructional ridge analogous to those observed on the slow-spreading Mid-Atlantic Ridge^{13,14}. However, theoretical modelling predicts that melt production should be diminished, or even inhibited, at spreading rates less than 1.5 cm yr^{-1} (refs 1–4). Analysis of SCICEX-96 gravity data suggests that the Gakkel ridge crust is anomalously thin¹⁵, supporting a hypothesis of diminished volcanism. The paucity of high-resolution bathymetry and sidescan data for Gakkel ridge has prevented unequivocal identification of any volcanic features until now.

SCICEX-99 sidescan and bathymetry data for the reconnaissance survey of the eastern Gakkel ridge show two amorphously shaped

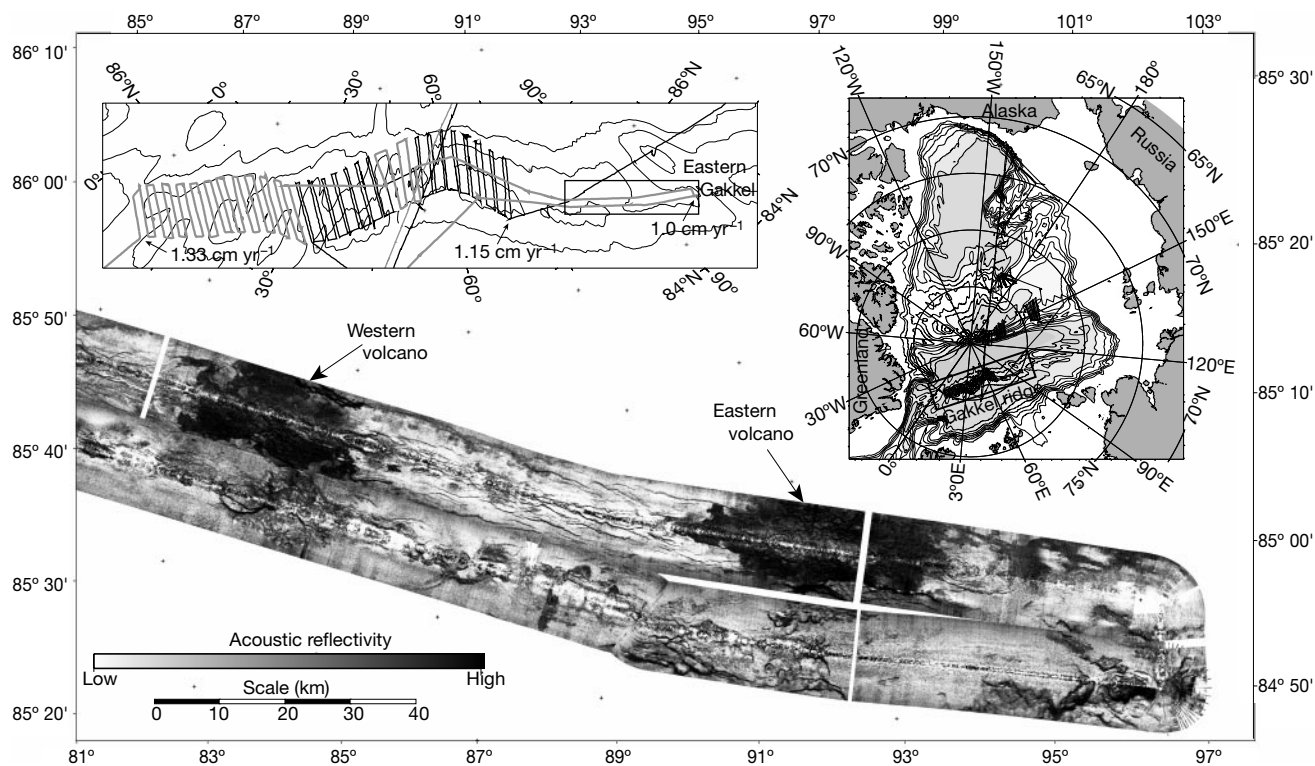


Figure 1 SCAMP sidescan data for the eastern Gakkel ridge. Two areas with high acoustic return strength, labelled the western volcano and eastern volcano, are probably younger than the weakly reflective terrain, presumably covered with thicker sediments, that surrounds them. Upper right inset, location map showing the Gakkel ridge survey within the Arctic basin. Bathymetric contour interval is 500 m; deeper regions are indicated by

darker shades of grey. SCICEX-99 tracklines are shown in black. Upper left inset, detail of the SCICEX-98 (black) and SCICEX-99 (grey) tracklines for the Gakkel ridge surveys. Full spreading rates are indicated in three locations. The rectangle on the right side of the map shows the location of the sidescan data displayed below the insets.

areas with highly reflective acoustic character (Fig. 1) that are also topographic highs with 1,000 and 500 m relief, respectively (Figs 2 and 3). The sidescan data show long, sinuous channels of very reflective (dark grey) terrain, adjacent to and occasionally surrounding less reflective (light grey) terrain. The regions with lower acoustic reflectivity are interpreted to have thick sediment cover; the attenuation of sound waves in sediments reduces the strength of acoustic echoes¹⁶. Average sedimentation rates for the eastern Arctic are estimated to be 1–3 cm kyr⁻¹ (ref. 17), increasing as Gakkel ridge approaches the Laptev shelf. Given the 12.5-cm operational wavelength of the SSBS and the estimated sedimentation rate, it would take thousands of years to create sediment cover thick enough to attenuate the strength of the acoustic return significantly. We thus interpreted regions of low acoustic return to be older than strongly reflective regions.

Portions of the strongly reflective regions in the SCICEX-99 sidescan data abut lineaments, consistent with the ponding of lava against fault scarps (Fig. 2). Terminations of acoustically reflective terrain in regions devoid of lineaments have shapes characteristic of lava flow fronts or ‘toes’ (Fig. 3). The flow toes are radially distributed around the topographic highs. The morphology of the

strongly reflective regions is consistent with submarine volcanic flows mapped at other mid-ocean ridges by acoustic and optical systems^{18–20}. The acoustic character of the highly reflective Gakkel ridge terrain is very similar to a lava field at 8° S on the East Pacific Rise that was first detected because of its strong acoustic reflectivity¹⁸ and was subsequently shown to contain fresh, glassy basalts²¹. The two acoustically reflective regions are thus probably volcanoes that are largely devoid of sediment cover, and therefore erupted recently. The presence of these two young volcanoes, covering approximately 20% of the 3,750 km² surveyed along this portion of the eastern Gakkel ridge, proves that significant volcanism occurs at ultraslow spreading rates.

The sidescan data reveal that both volcanoes are cut by lineations interpreted to be faults formed by tectonic processes that occurred subsequent to volcanic emplacement. The western volcano (Fig. 2) is significantly less faulted than the eastern volcano (Fig. 3), suggesting that lava on the western volcano experienced less post-emplacement tectonism and is therefore younger. The few faults evident on the western volcano are located near the southern flank of the topographic high. Two of these faults traverse abrupt changes in acoustic reflectivity; these light/dark contacts indicate significant

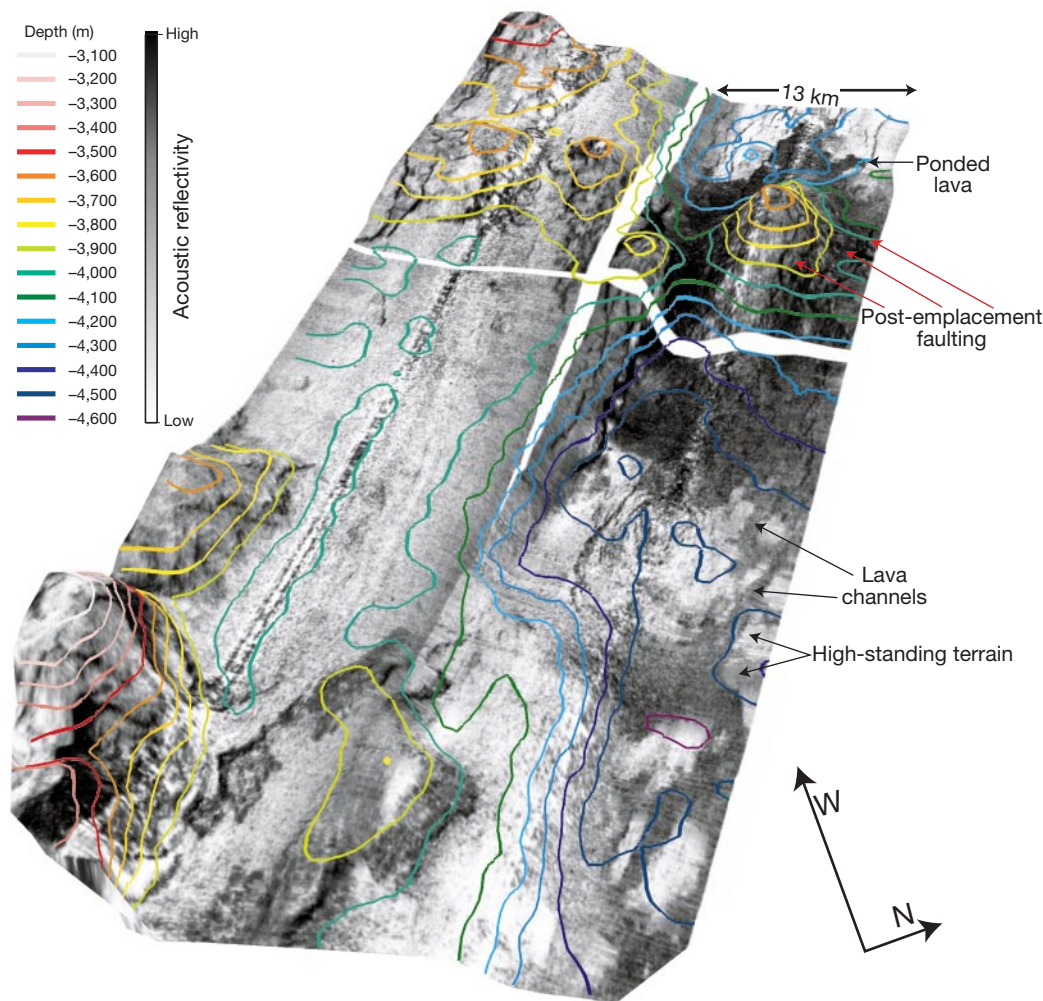


Figure 2 Three-dimensional view of the eastern volcano looking from east to west. In this image sidescan data are overlaid on a digital terrain model derived from SCAMP bathymetry. Colour-coded contours indicate depth. The region of highly reflective terrain located near the upper right corner of the data is approximately centred about a 1,000-m topographic high. To the west and east of the topographic high, sinuous channels of reflective terrain spill downslope. Where these channels adjoin lineations or higher-

elevation terrain they abruptly terminate or flow around features. This morphology is consistent with submarine lava flows observed on other mid-ocean ridges. The reflective terrain on the eastern volcano is laced with WNW–ESE trending lineations. These lineations are interpreted to be faults caused by tectonism that occurred after the emplacement of the reflective volcanic terrain. See Fig. 1 for the location of the eastern volcano.

differences in the amount of sediment cover. We interpret them to represent a boundary between lava flows of different ages. The presence of faults having sufficient vertical offset to be imaged by SCAMP indicates that the southern flank of the western volcano did not erupt recently. Assuming reasonable geological slip rates of a few mm yr^{-1} (refs 22, 23), faults of sufficient size to be imaged by SCAMP in $\sim 4,000$ m of water depth would require hundreds to several thousands of years to develop, although collapse events can form large scarps over short time periods²⁴. In contrast, the northern flank of the western volcano is remarkably devoid of lineations. In addition, all of the faults on the western volcano terminate abruptly to both the northwest and southeast. The abrupt truncation of faults on the western volcano and the absence of lineations in sidescan data for the northern flank support our hypothesis of a recent eruption that volcanically overprinted pre-existing faults. The volcanic overprinting and the presence of faults that cross-cut regions with different amounts of sediment cover lead us to conclude that the western volcano was formed by more than one eruption.

Teleseismic data for the Arctic basin corroborates the hypothesis

of a recent Gakkel ridge eruption. In January 1999 global seismic networks detected the beginning of an earthquake swarm on Gakkel ridge centred near 86°N , 85°E (refs 5, 26). Seismic activity continued through September 1999 although 75% of the events took place before the end of May. On 6 May 1999, the USS *Hawkbill* passed directly over the average location of the earthquake epicentres. The average location of the epicentres corresponds to the location of the western volcano (Fig. 3). The remarkable correlation between the locations of the earthquake epicentres and the location of the strongly reflective, un-tectonized western volcano together with the volcanic character of the seismic record^{5,26} provide evidence that lava erupted on the eastern Gakkel ridge days to months before SCAMP mapped the area. Because 12-kHz sonars can penetrate through thin sediments covering acoustically reflective lavas²⁵, it is possible that no eruption occurred on Gakkel ridge in 1999; however, historical global seismic records indicate that this is the only earthquake swarm detected on Gakkel ridge in about 100 years (ref. 5). SCAMP HRSP data show no evidence of sediment layering on either volcano although there is evidence of layering adjacent to both (Fig. 4). Taken together, the SCICEX and teleseismic data

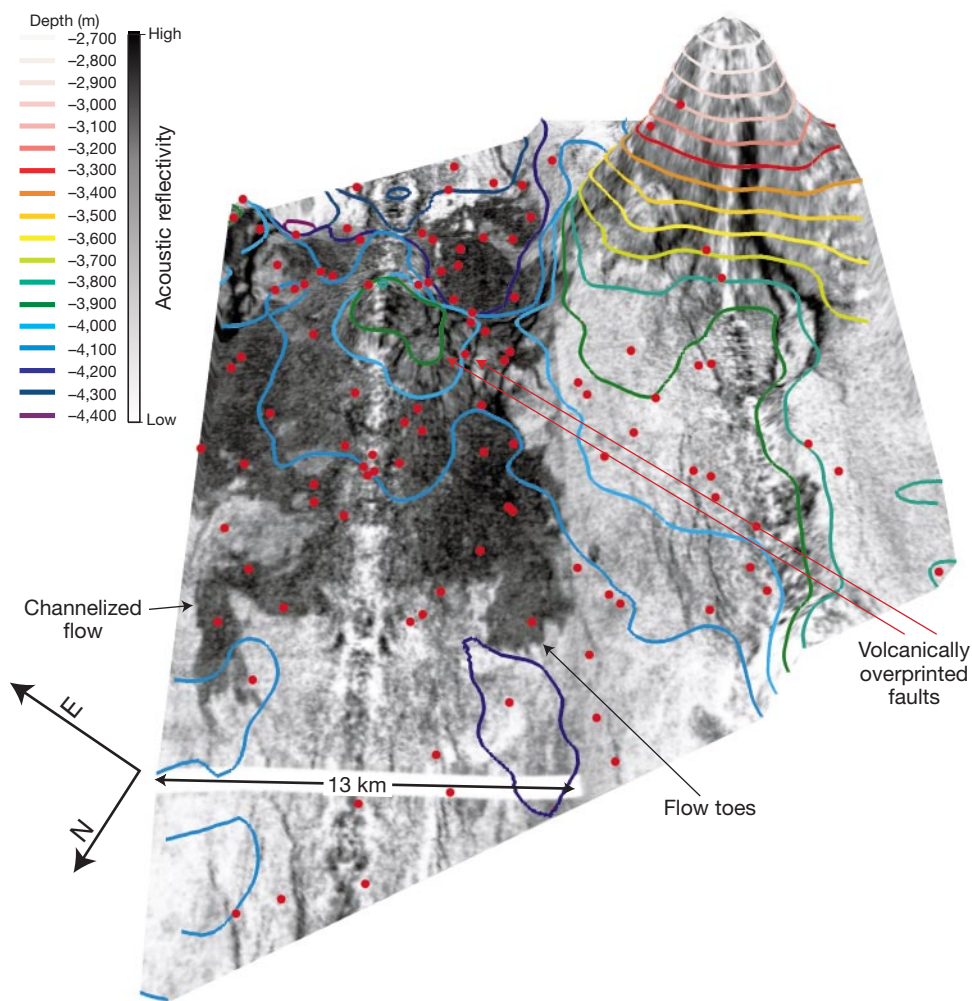


Figure 3 Three-dimensional view of the western volcano looking from west to east. Data presentation is analogous to that described for Fig. 2. The dark, reflective terrain is centred about a close-contoured high having a maximum vertical relief of 500 m. As in Fig. 2, lava channels spill downslope from the volcano, ponding against fault scarps or terminating in flow toes that are characteristic of eruptive processes. Lava on the western volcano is significantly less faulted than lava on the eastern volcano (Fig. 2). The few faults evident on the southern flank of the western volcano are located on a small saddle

between the western volcano and the prominent volcano to its south (right). On the saddle, these faults cut through both strongly and poorly reflective terrain indicating that at least some of the highly reflective terrain has undergone substantial tectonic modification. However, the faults abruptly terminate to west and east of the saddle, suggesting that they have been volcanically overprinted. Red circles show the locations of epicentres for the Gakkel ridge earthquake swarm that ran from January until September in 1999. See Fig. 1 for the location of the western volcano.

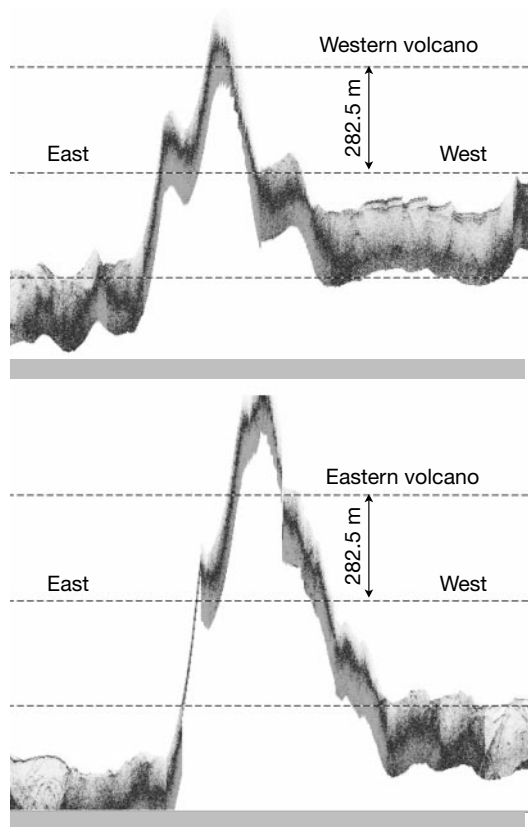


Figure 4 SCAMP sub-bottom data for the western and eastern volcanoes show no evidence of sediment layering on top of the constructs, although layers are apparent adjacent to the flanks of both highs. In these plots the *x*-axis represents time; the USS *Hawkbill* was heading from east to west when the data were collected. Vertical relief is indicated.

provide a revised model for volcanism at the ultraslow-spreading Gakkel ridge, in which voluminous, sustained eruptions focused at discrete sites may have occurred more frequently than previously thought. □

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