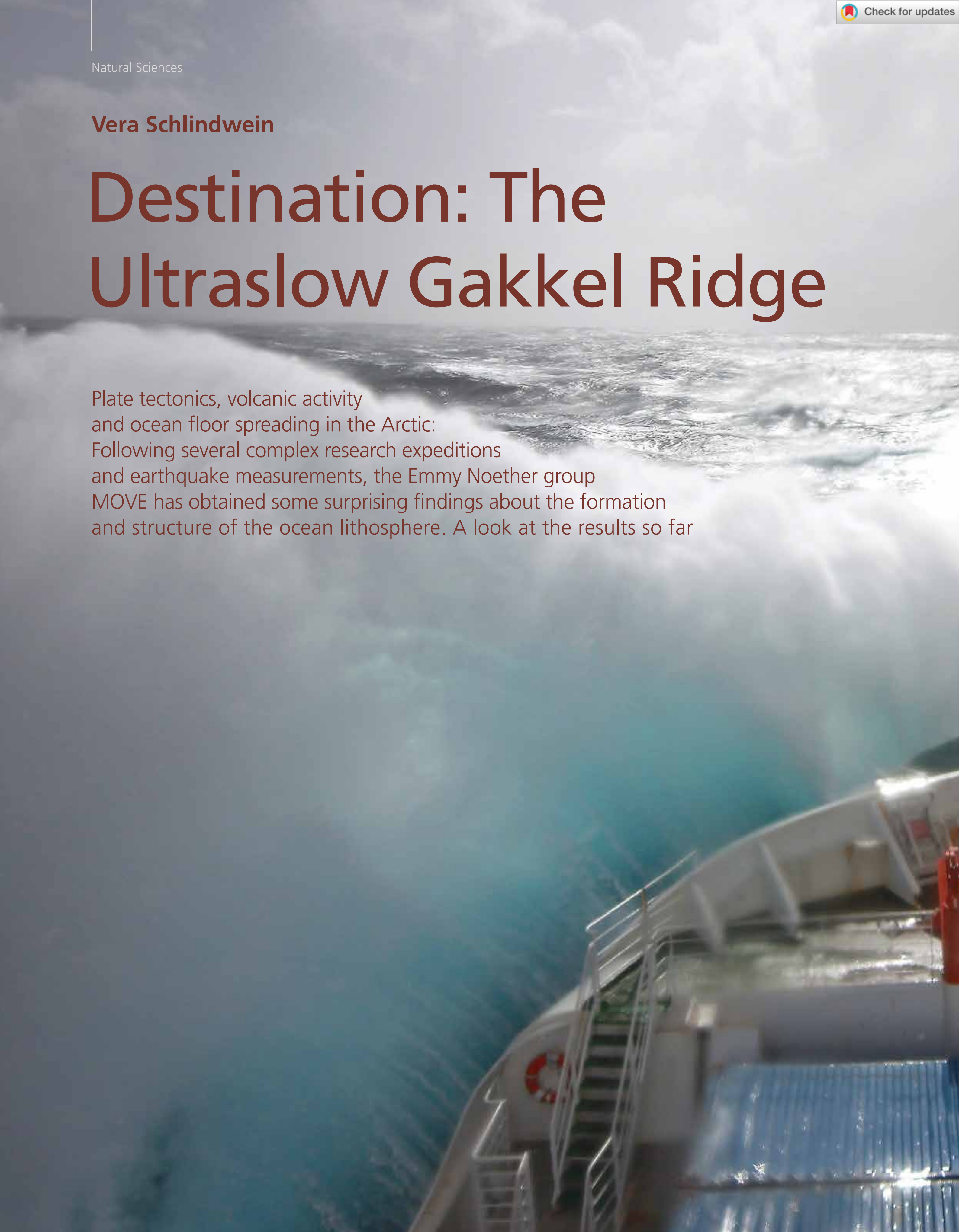
Vera Schlindwein

Destination: The Ultraslow Gakkel Ridge

Plate tectonics, volcanic activity and ocean floor spreading in the Arctic: Following several complex research expeditions and earthquake measurements, the Emmy Noether group MOVE has obtained some surprising findings about the formation and structure of the ocean lithosphere. A look at the results so far



The research vessel has to brave stormy seas, for example here in the "Furious Fifties" near the Southwest Indian Ridge.

Illustration: AWI/Florian Schmid

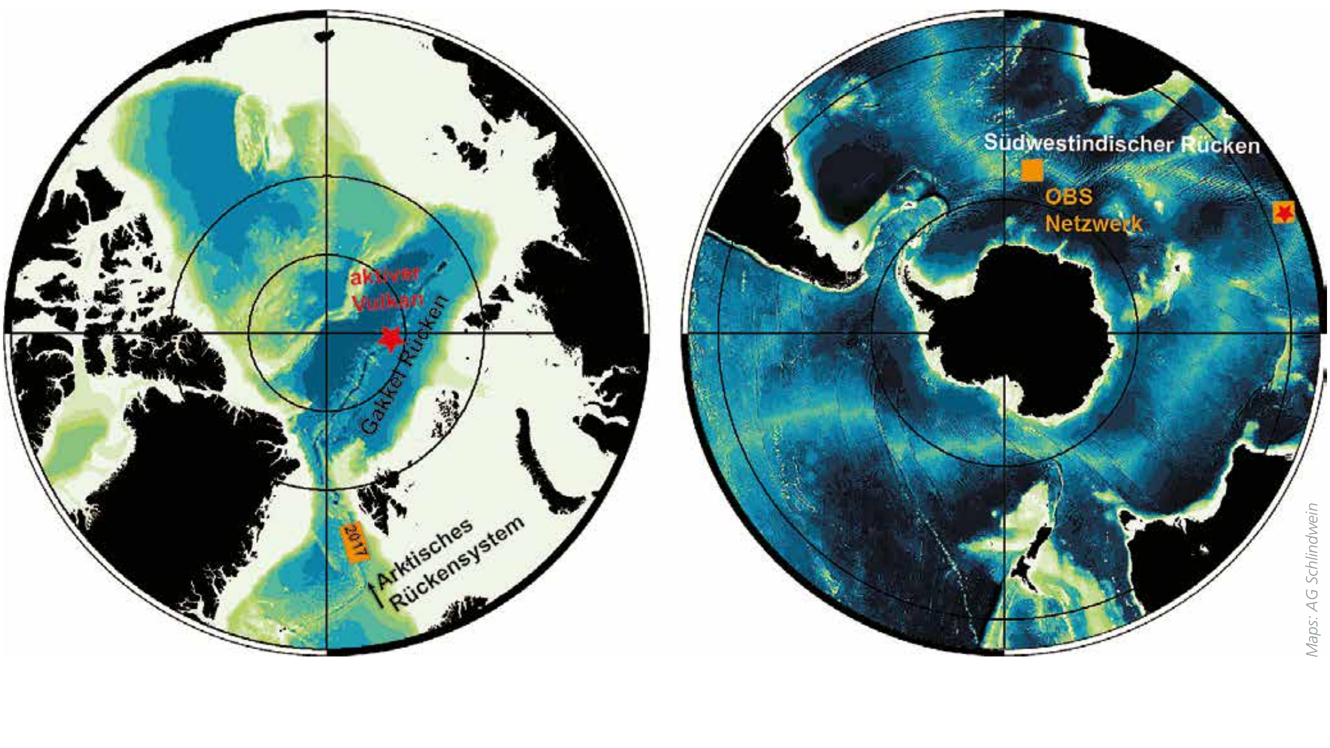
In the icy grip of the long winter, the Arctic slows everything down. Progress is difficult and inevitably slow. Like earlier generations of polar researchers, the scientists of today need patience and endurance. Even deep under the Arctic sea ice, things move slowly – in fact, they're "ultraslow". While the world's oceans grow by more than 20 millimetres a year at the seams of the mid-ocean ridges, along the Arctic ridge system and its cousin, the Southwest Indian Ridge (SWIR) midway between Africa and the Antarctic, new ocean floor forms at a rate of less than 15 millimetres a year.

For a long time, ultraslow mid-ocean ridges were largely ignored in plate tectonics research. On top of that, the Arctic ridge system is difficult to access because it is covered by sea ice, while the sea in the "Furious Fifties" around the SWIR is too rough for ambitious research projects. Scientists also believed that conclusions could be drawn about ultraslow ridges based on the much better studied processes of ocean floor formation at slow ridges. But in 1999, a powerful earthquake swarm in the Arctic Ocean forced geophysicists to sit up and take notice. The quakes continued for nine months, sometimes registering at magnitude 5, near a large volcano on the Gakkel Ridge.

Normally, the numerous volcanic eruptions that occur at mid-ocean ridges go completely unnoticed: around volcanic ridges the young ocean lithosphere is too warm for major earthquakes, which can be registered on land over 1,000 kilometres away. Volcanic eruptions were also considered to be rare at ultraslow ridges. When the lithospheric plates move apart at mid-ocean ridges, the decrease in pressure causes the Earth's mantle to melt. Material from the mantle then wells up as magma and continuously fills the gap between the plates. This creates a crust around 6 to 8 kilometres thick across all the oceans. At ultraslow ridges this process is reduced to a sputter, and little magma is produced. But how does this eruption fit into our understanding of a region which is reckoned to have a spreading rate of just 9 to 10 millimetres per year?

In 2001, an interdisciplinary expedition set out on board the icebreakers USGC *Healy* and RV *Polarstern*, with the objective of systematically mapping the Gakkel Ridge, collecting rock samples from the seabed, measuring the thickness of the crust, searching for hot springs on the ocean floor – and measuring earthquakes in situ. The expedition was certainly groundbreaking, resulting in four articles published in *Nature*, but it also lent further support to the idea that ultraslow ridges are not simply slow versions of "slow ridges", but a category of their own. Their main characteristic seems to be that the

Maps of the ultraslow-spreading ridges in the Arctic (left) and the Southwest Indian Ocean (right).



Maps: AG Schlindwein

Hard at work in the icy cold: Setting up a seismometer on an ice floe in the Arctic sea ice.

thickness of the Earth's crust varies considerably along the length of the ridge. While some sections of the ridge have a thin crust and many volcanic structures, others have little magma and the sea floor may be up to 5,000 metres deep, with mantle rock being found on the ocean floor itself. These amagmatic areas, which are often as much as 100 kilometres long and without notable volcanism, are punctuated by gigantic volcanic centres with a thick crust. This was the kind of volcano that appeared to have erupted in 1999, causing a series of earthquakes.

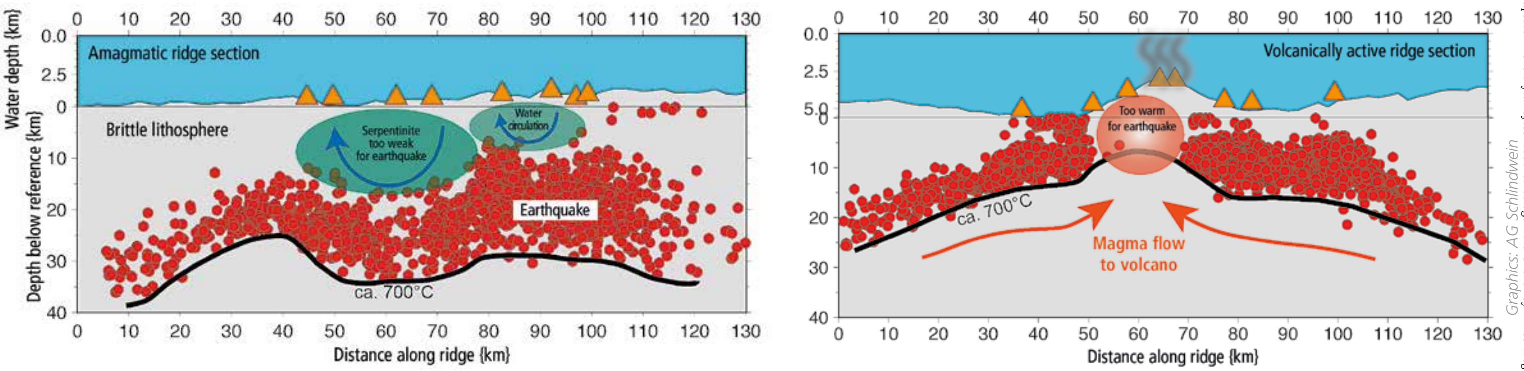
It was in early 2003 that the researcher who would later become the project leader had her first experience of ultraslow ridges. No one was quite certain what to do with the seismological data recorded during the cruise. The measuring technique used, of placing seismometers on drifting ice floes to record earthquakes, seemed too unusual. But she had previously worked with unusual seismological data and was fascinated. The technique worked, and a number of minor earthquakes were detected between the cracking of the ice floes. This indicated that small gas explosions were occurring near the volcano under the enormous pressure of the four-kilometre water column. This surprising discovery was all the motivation the researchers needed to take a closer look at the seismic activity of this ultraslow ridge.

The idea for the Emmy Noether project was born. The aim was to systematically investigate the seismicity of ultraslow ridges, comparing magmatic and amagmatic ridge sections. The team would also look at different scales, from the smallest earthquakes that give clues about local spreading processes, to major earthquakes that supply large-scale information about ocean floor formation along an entire ridge. The independent junior research group "Mid-Ocean Volcanoes and Earthquakes (MOVE)" started work in September 2006. For family reasons, the project was designed from the outset to take eight years on a part-time basis. This also had the advantage that the necessary amount of patience and persistence could be applied to the laborious process of acquiring the seismological data; in hindsight, this would not have been possible on a time scale of just five years.

Because the data for major earthquakes is publicly available in catalogues, the team was able to start analysing it. To use seismometers in situ to record microearthquakes, which provide information about active spreading processes and the structure and temperature of the lithosphere, the researchers needed ship time on board RV *Polarstern*. Starting with "piggyback" experiments on RV *Polarstern* and IB *Oden*, seismological data was gathered from instruments set up on drifting ice floes. It was essential to take traditional measurements using ocean bottom seismometers (OBS), but it was impossible to do this in the ice-covered Arctic Ocean since the OBS resurface with their precious data somewhere in a radius of one kilometre around the deployment position – often beneath an ice floe. So to use this technique, the team had to travel to geologically similar areas of the SWIR. Since a research vessel, which is expensive to operate, cannot wait around idly for fair weather to recover an OBS, in 2013 an interdisciplinary team of 35 researchers set off on board RV *Polarstern* to spend a month working together in these stormy seas. At the same time, scientists on two other cruises were able to gather data on volcanic activity at more temperate latitudes of the SWIR.

Left: Gulls are always curious about ocean bottom seismometers, which makes it easier to locate them. Right: Scientists perform a test run with a sea ice seismometer.

Illustrations: AWI/Vera Schlindwein



Pictures that tell a story: Painstakingly acquired earthquake data from the Southwest Indian Ridge provides information about spreading processes.

Seven years after MOVE got underway, the result was a comprehensive set of seismic data collected with enormous effort (no less than seven cruises). The data confirmed the conjecture that seismic activity at ultraslow ridges provides surprising insights into the formation and structure of the young ocean lithosphere.

After locating more than 5,000 earthquakes, the team discovered the deepest earthquakes of all at mid-ocean ridges, at a depth of 35 kilometres. This demonstrated that in amagmatic regions, the young ocean lithosphere is much colder than previously thought. Beneath the volcanoes the lithosphere thins considerably, allowing magma to flow along its base from cold amagmatic areas to the volcanoes. Petrologists (scientists who study rocks) had proposed such a topography to explain the uneven distribution of magma along ultraslow ridges. These results provided the first geophysical evidence for this hypothesis.

Especially exciting was another realisation: that in areas where mantle rock can be found on the sea floor, no earthquakes were detected up to a depth of 15 kilometres. When rock from the Earth's mantle comes into contact with water, it forms a very soft rock known as serpentinite which does not fracture during an earthquake but behaves more like soft soap. This means that water can penetrate to previously unsuspected depths of 15 kilometres and that an exchange of material may be taking place between the lithosphere and the ocean in much larger dimensions than previously thought. The researchers were also able to study a volcano on the SWIR which had repeatedly triggered major earthquakes over a period of ten years. Sure enough, beneath it they found a magma chamber. The OBS provided live coverage of a "magma intrusion" and its seismic tremor – a rare instance of an in-situ measurement of subsea volcanism.

Although the independent junior research group MOVE made slow progress, it produced an enormous amount of knowledge and generated a host of new questions. Because polar research proceeds at a slow pace, a follow-up project is already underway. Since 2017, the team has had access to seismological recordings from 27 OBS spread over 160 kilometres of ridge south of Spitzbergen. This is the most comprehensive set of micro-earthquake data yet obtained for mid-ocean ridges.

The prototype of an OBS suitable for deployment on sea ice is also due to start trials, to help a major interdisciplinary expedition investigate the exchange of material between lithosphere and ocean at the hydrothermal source AURORA on the ice-covered Gakkel Ridge – but for that, we'll have to wait until 2022.

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