MARTIN JAKOBSSON

The Long Timeline of the Ice

A Geological Perspective on the Arctic Ocean

ABSTRACT Ice ages constitute a significant part of Earth's climate history with the first signs of widespread ice sheets occurring at about 2.4 billion years ago. In 2004, a nearly 450 metres thick accumulation of seafloor sediments on the submarine Lomonosov Ridge in central Arctic Ocean was drilled by the international Arctic Coring Expedition (ACEX). This geological archive has provided insights into the long-term history of the Arctic Ocean back to 56 million years. The first signs of extensive sea ice along the Arctic coasts appear 47.5 million years ago (Ma), while evidence for the type of pack ice we have today that survives more than one season occurs first 15–13 Ma. The Earth's climate changed mode at about 2.6 Ma. Cold periods, characterized by large ice sheets covering the Northern Hemisphere, were intervened by warmer periods with climates more similar of today. These glacial-interglacial cycles were largely controlled by changes in solar insolation resulting from cyclical variations in Earth's orbit around the Sun. In this article, I tell the personal story of how we mapped the Lomonosov Ridge and found evidence supporting a controversial hypothesis of the existence of kilometre-thick floating ice shelves in the Arctic Ocean during past glaciations.

KEYWORDS Arctic Ocean, sea ice, ice sheets, geology, climate, cryosphere, glaciation, ice age, ice shelf, glacial history

Ice ages have come and gone throughout the long history of the Earth.[1] The first signs of widespread glaciation are as old as 2.4 billion years. That long ago, the continents had a completely different configuration than today. It is therefore hardly meaningful to talk about the northern polar region at this time in terms of "an Arctic." It is only when a land mass has been formed around the geographical North Pole that we can begin to recognize today's Arctic geography in geological reconstructions. The oldest part of the Arctic Ocean began to form about 130 million years ago (Ma) (Pease *et al*. 2014: 7). Our side of this sea, called the *Eurasian Basin*, north of Svalbard, is much younger, having first begun to develop about 58–56 Ma (Vogt *et al*. 1979: 1; Brozena *et al*. 2003: 826). This was during the transition between the geological epochs *Paleocene* and *Eocene*. At that time there was a sea around the North Pole, but it can hardly be called an Arctic Ocean because it had the character of an inland sea. The Eocene was characterized by a much warmer climate than today, even in comparison to the temperature increase we have experienced over the last century.

Along the bottom of the Arctic Ocean is a ridge 1,500 kilometres long called the *Lomonosov Ridge*, which divides the Arctic Ocean into the Amerasian and the Eurasian basins. During the 56 million year geological history of the Eurasian Basin, marine sediments have been deposited on this long mountain ridge. From a human perspective this is a very slow process, about 1–2 millimetres growth per century. As a result of these sediments, the Lomonosov Ridge is a natural archive preserving a record of how the environment of the Arctic Ocean has developed and how climate has interacted with the ocean. One can even view the seabed sediments as a library, where the various layers are the books and the pages in them are filled with the contents of the sea. Instead of texts and pictures there are sediment particles with different rock fragments and clay minerals, along with remains of zooplankton, phytoplankton and organisms living on the seafloor and in the uppermost sediments. Marine geologists can read the history of the oceans in these seabed sediments. They do so through a microscope, qualitatively identifying the contents of the sediment and by means of quantitative measurements of physical properties and geochemical analyses which can give information about factors such as the temperature and salinity of the oceans at the time the sediment was accumulated.

The roughly 450-metre thick accumulation of seabed sediment in the Lomonosov Ridge was the goal of the international Arctic Coring Expedition (ACEX) in 2004 (Backman & Moran 2009: 158–160). A string of cores from several boreholes that can be connected to a single long sedimentation sequence from the Lomonosov Ridge would give us an archive of how the Arctic ice caps and sea ice have evolved over several million years. But the expedition entailed—to say the least—logistical challenges.[2]

The Swedish-registered icebreaker *Vidar Viking*, equipped with a drilling rig, had to lie still for several weeks only about 250 kilometres from the North Pole, in drifting pack ice over a drilling area of just over a kilometre of water depth. Coring for samples and being able to maintain one's position over the drilling hole within a radius of 60–100 metres required support from Sweden's largest icebreaker, the O*den*, and the Russian nuclear powered icebreaker *Sovetsky Soyuz*. As a scientist on board the O*den*, I was responsible for the geophysical data that showed where we could drill.

Problems with the drilling equipment meant that we were very close to obtaining no sediment cores at all. After spare parts of damaged drill-rig components had been manufactured by the crew of the O*den*, the material for spare parts was exhausted. The Swedish Air Force then helped out by sending one of their transport planes to drop new parts by parachute. The operation was able to start, and one core after the other was brought up from the information-rich sediment of the Lomonosov Ridge.

Through time a large amount of new data would provide new knowledge about the geological development of the Arctic Ocean. The deeper part of the sediment package from the ACEX expedition turned out to contain, among other things, pollen from palm trees! There were also geochemical indications that the sea around the North Pole, during the warm period called PETM (Palaeocene-Eocene Thermal Maximum) about 55.5 Ma ago, may have been as warm as around 23 °C at the water surface (Backman & Moran 2009: 166). This is in stark contrast to the Arctic Sea as it is today, when the surface water is currently approaching –2 °C. How can the great depth of the geologists' lens help us to understand the consequences of today's climate change, which, even from a human perspective, seems so drastic and full of contrasts? When in the long planetary history of the Earth did the first sea ice appear in the north?

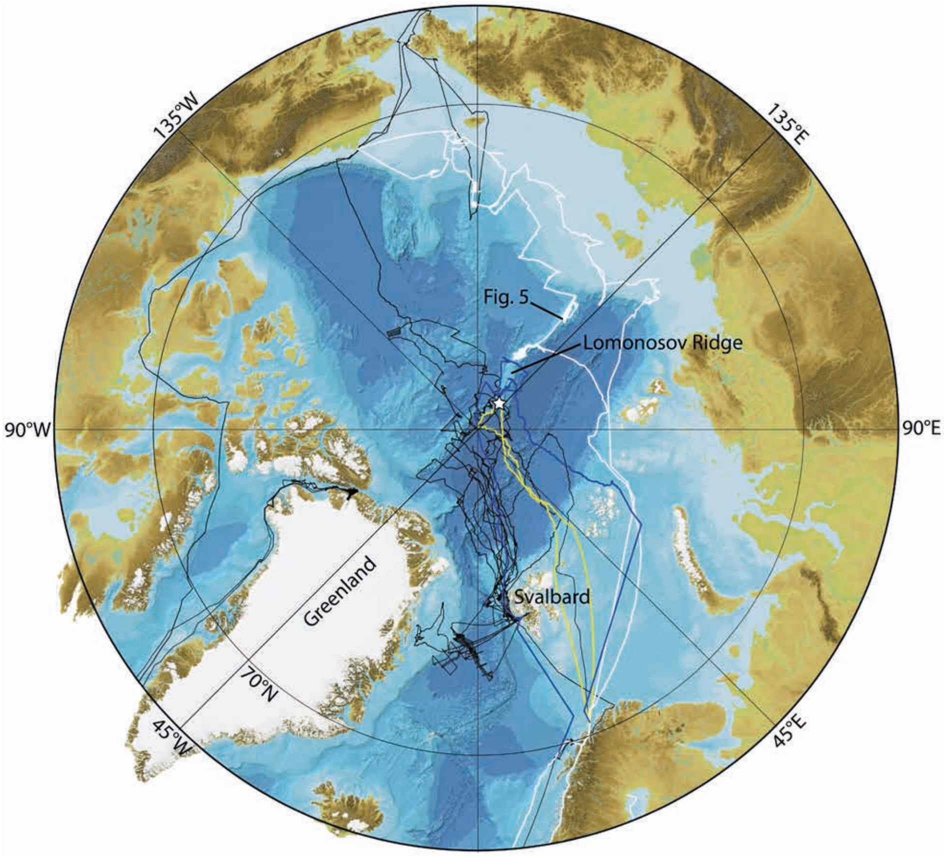

Fig. 1. Map of the Arctic Ocean from the International Bathymetric Chart (IBCAO). The black lines show the routes of expeditions with the icebreaker *Oden*, from the first in 1991 until 2017. The expeditions with the *Oden* discussed in the text are shown in different colours: The yellow line shows the Arctic Coring Expedition (ACEX), the blue line shows the route of the Arctic Ocean in 1996 and the white line is the route of the SWERUS-C3 expedition (Swedish-Russian-US Arctic Ocean Investigation of Climate-Cryosphere-Carbon Interactions). The ACEX drill site location is shown with a white star.

Fig. 2. To carry out the drilling operation during ACEX 2014, three icebreakers were required. Farthest away in the picture, the Russian nuclear powered icebreaker *Sovetsky Soyuz* is splitting the largest ice floes. The role of the Oden was to break up the medium-sized ice floes so that the icebreaker *Vidar Viking* (closest) could maintain its position with the drill string anchored in the seabed. Photo: Martin Jakobsson.

The First Sea Ice and Icebergs of the Arctic Ocean

The cores from the Lomonosov Ridge contain the algae known as diatoms, which, among other things, have formed species that specialize in living in sea ice. It was the discovery of these ice-living diatoms which, together with an admixture of coarser particles in the seabed sediment, showed that there has been sea ice in the Arctic Ocean for several tens of millions of years. Was there no alternative explanation for the presence of these traces of sea ice?

The drilling site on the Lomonosov Ridge is too far from land for coarse sediment particles to have been transported by ocean currents along the sea bed, and the particles are too large and heavy to be carried with the wind. Thus, transport by ice remains the most likely possibility. The sedimentation sequence with the diatoms and the coarser particles has been dated to 47.5 Ma (Stickley *et al*. 2009: 376). This is the first trace of sea ice that we know of in the Arctic Ocean, although it was probably a seasonal ice and not the kind of pack ice we have around the North Pole today. There is a great deal to suggest that the Arctic Ocean at that time, 47.5 MA, was similar to today's Baltic Sea. The surface water could be warm in the summer but larger areas froze in the winter. Geological reconstructions show that the comparison is reasonable in several respects. The strait between Greenland and Svalbard had not yet opened to become the sound that it is today with a depth of thousands of metres. The Arctic Ocean therefore lacked deep water connections to other seas such as today's Baltic Sea. The diatoms also show that the upper layer of the Arctic Ocean consisted of slightly brackish to almost fresh water, just like the Baltic Sea, where the salinity is around 0.6 percent at the latitude of Stockholm. In general terms, the whole Earth 47.5 Ma was significantly warmer than today. It was not until many millions of years later that sea ice was formed of a kind that did not melt during the summer months.

Exactly when this occurred is harder to detect in the sediment core from the Lomonosov Ridge, but studies suggest that year-round ice was formed about 15–13 Ma (Darby 2008: 1; Krylov *et al*. 2008: 1). This is assumed to have happened when coarser grains of sand and some specific mineral particles, which are assumed to have come from eastern Siberia, appeared in the sedimentary sequences. The change in the composition of the sediment indicates that this was transported over many years by sea ice, taking a longer time than one seasonal winter ice is likely to manage. This is not to say that year-round ice, i.e., what we know today as the pack ice of the Arctic Ocean, has endured since then. But we can say that the Arctic Ocean has had seasonal or year-round ice for several tens of millions of years, with the exception of several short periods with a limited extent of sea ice or completely ice-free. A stone with a diameter of one centimetre was found in sediment dated to 45 Ma (Moran *et al*. 2006: 601). This stone, which consists of gneiss, was probably brought to the Lomonosov Ridge with an iceberg, thus probably indicating the start of the first land-based glaciers, somewhere around the Arctic Ocean.

Since the Earth's climate, in this million-year perspective, has varied so much, the sea ice has likewise undoubtedly undergone major changes during warmer and colder periods. About 2.6 Ma, during the geological *Quaternary* period, the Earth entered a longer ice age. Gigantic ice sheets spread at regularly recurring intervals, known as glaciations (also called *glacials*). During the longest glacials, ice sheets are known to have covered the whole of Scandinavia, parts of northern Europe, Asia and North America. In the northern hemisphere, the glacials alternated with interglacials, when the ice sheets al-

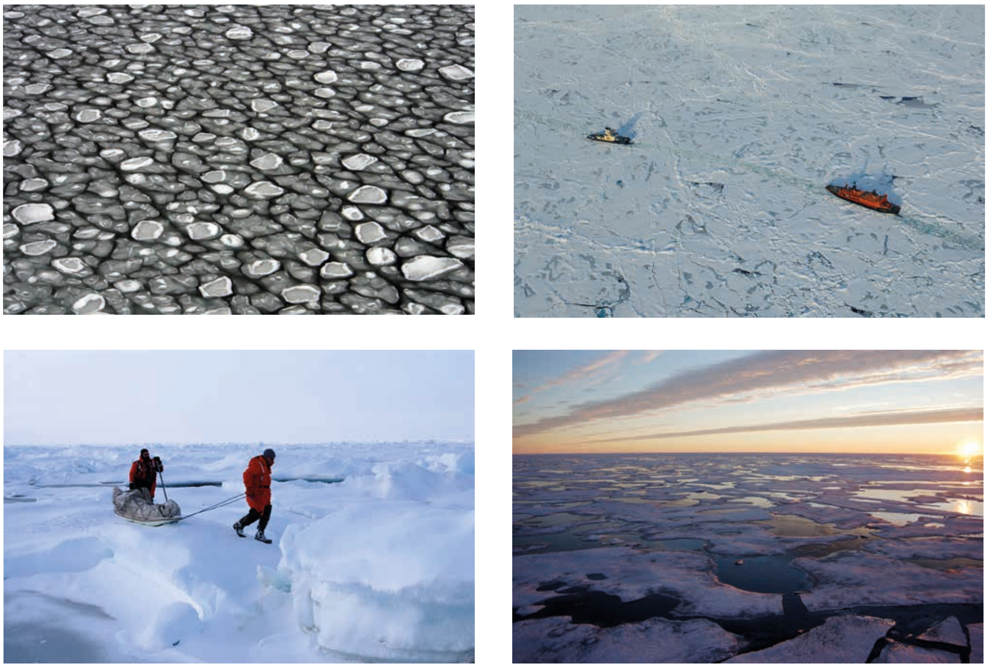

Fig. 3. The sea ice of the Arctic Ocean in various appearances. Top left, so-called ***pancake ice***. Top right, the icebreaker *Oden* and the biggest Russian atomic icebreaker *50 Let Pobedy* ['50 Years of Victory'] are seen during the Lomonosov Ridge off Greenland (Lomrog) 2007 expedition. They are north of Greenland, where the dense and multiannual pack ice can be more than five metres thick. Bottom left, the central part of the Arctic Ocean, where the drifting of the ice over the sea often makes the ice floes overlap each other in what are called ***pressure ridges***. Bottom right, the edge of the pack ice with large open areas of water between the ice floes. Photo: Martin Jakobsson.

most completely disappeared. The Greenland ice is an exception, as it is unlikely to have disappeared completely during any interglacial. However, it may have been much smaller during the warmest interglacials. How small they became is a highly relevant question today, given that we are at a stage where the Greenland ice has decreased in mass through melting and calving of icebergs at an increasing rate.

This brings us to human impact on the climate and what we can learn from a longer geological time perspective. The basic causes of the overall variations in the Earth's climate must be sought beyond the emergence of the human species and of vertebrates, in the planetary and cyclic changes of Earth's orbit around the sun. The theory describing the effects on climate from Earth's orbital variations through time was put together by the Serbian scientist Milutin Milanković and is well described in the now classical article by Imbrie and Imbrie (1980). Periods when ice sheets spread, alternating with periods when the inland ice melts and recedes, follow these cycles when both solar irradiance and seasonal variations are affected. Some interglacials are characterized by high solar irradiance and large seasonal variations; there are indications that, in some warm periods, the sea ice in the Arctic Ocean may have melted completely during the summer months. For example, the solar irradiance was much higher than it was today in the period between 11,000 and 5,000 years before the present. Some 11,000 years ago we had roughly 50 W/m^2 higher solar irradiance at latitude 80°N in June than we have today at the same latitude, a difference of about 10 per cent. This is often brought up as the main reason why today's ongoing and dramatic warming of the Arctic cannot be blamed on natural climate changes caused by solar irradiance; it is judged to be mostly due to human emissions of greenhouse gases. The sea ice has been continuously studied using satellites since 1979 and has shown a clearly decreasing trend during the summer months, in terms of both distribution and thickness (Peng & Meyer 2017: 191). This reduction thus cannot be explained in the same way as when the sea ice decreased during earlier warm periods with higher solar irradiance.

A Gigantic Ice Shelf

During the Quaternary, glacials became increasingly extensive. Their geological footprint is also clearly visible in the landscape, as the naturalist Louis Agassiz discovered in the Alps and in Scandinavia in the nineteenth century. The landscape in the Nordic region is still full of visible traces of the movements of ice sheets. You just have to go to any area of flat rock and you will often see parallel grooves in the surface. These are striations, formed when stones that were frozen into the bottom of a moving ice sheet scraped against the rock.

We therefore know quite well how the ice sheets moved over large areas. But what about the conditions in the Arctic Ocean during the glacials? That knowledge came much later because for a long time the sea ice in the Arctic Ocean today made it almost impossible to examine the seabed. To be able even to get to the areas where traces of ice that extended into the sea should theoretically exist, would not have been possible without modern icebreakers and research programs using submarines of Arctic class.

When there are no data, there is plenty of scope for creative hypotheses. In the 1950s Maurice Ewing and William L. Donn presented a theory of how cold periods with large-scale glaciation and intermediate periods without ice have come and gone through the Earth's history (Ewing & Donn 1956; Ewing & Donn 1958). Their hypothesis was that the Arctic Ocean must initially have been ice-free so that large ice sheets could have spread on land. The argument was that it must have required moisture from the sea to create precipitation which then, during a glaciation of the Arctic, could freeze to ice. When it is cold enough for sea ice to form on the Arctic Ocean, the moisture source disappears, which means that the large inland ice sheets shrink and recede. A cycle is completed. The British glaciologist John Hainsworth Mercer arrived at a diametrically opposite conclusion. He conceived of a sea where a floating *ice shelf* a kilometre thick spread out around the North Pole while there were large ice sheets here and there on land (Mercer 1970: 19). (An ice shelf is a floating extension of one or more glaciers that can be on land but flow into the sea. Today there are large ice shelves around the South Pole in the Antarctic. The biggest is the Ross Ice Shelf, with an area of about 470,000 square kilometres, slightly larger than the whole of Sweden. There are also ice shelves in the Arctic, although much smaller than those at the opposite pole. Some fiords around Greenland, where the Greenland ice sheet flows into the sea, also have ice shelves. They can also be found along the northern part of Ellesmere Island, in the north-easternmost part of Arctic Canada. When the inland ice flows into a fiord, we usually call it an *ice tongue* instead of an *ice shelf*.)

Mercer's hypothesis of a giant ice shelf in the Arctic Ocean was based, among other things, on comparisons with the western Antarctic—where the floating Ross Ice Shelf is fed by ice floating from the West Antarctic ice cap. That both areas are located at the geographical Poles he felt was important because this gives long, cold winters with no sunlight. He also cited the Swedish glaciologist Valter Schytt and the physical geographer Gunnar Hoppe, who suggested that the Barents Sea was covered by ice during the last glaciation, which culminated about 20,000 years ago, which meant that ice must have floated north towards the Arctic Ocean north of Svalbard (Schytt *et al*. 1968: 207). The hypothesis of a huge floating ice shelf in the Arctic Ocean provoked extensive debate among scientists. Most were very dubious, but there were some who embraced the idea. These included the Russian geographer Mikhail G. Grosswald and the American glaciologist Terence J. Hughes, who developed the concept in several articles (e.g. Hughes *et al*. 1977). Until the 1990s there were no observations from the seabed in the central parts of the Arctic Ocean which could either confirm or refute the hypothesis, and so the debate continued.

The Search for the Lomonosov Ridge

My first icebreaker expedition in the Arctic Ocean was with the *Oden* in 1996. I was a Ph.D. student and my project was to carry out geophysical mapping and sediment sampling on the Lomonosov Ridge. This was then unexplored, apart from some samples and depth measurements that could be obtained by occasional drifting ice-drift stations. Given that the area of the ridge is almost 70 per cent of the area of Sweden, available data were scarce. It would be like mapping the whole of Sweden's topography by measuring the altitude along one or two motorways! After fighting our way through the pack ice, we finally reached an area where the Lomonosov Ridge, according to the then existing maps, appeared to be suitable for sampling the bottom sediment. We carried on searching for the shallowest parts of the ridge and at places where no mass wasted sediment from the flanks could have been mixed in the layers on the seabed. To our surprise, the ridge was not located where the latest American map from 1985 showed it. It was even further from what was marked on a map from 1979 in the International Series *General Bathymetric Chart of the Oceans* (GEBCO) (Johnson *et al*. 1979). Where there was supposed to be a summit at a depth of 1,000 metres, the depth was instead almost 3,000 metres and the seabed was almost entirely flat.

With the help of echo sounding we found that the Lomonosov Ridge was actually 200 kilometres further away! There, on the other hand it was "only" 607 metres deep, suggesting that we had found the peak of the underwater ridge that rises highest from the deep basins surrounding it. We were forced to accept the fact that we had relocated an entire submarine mountain ridge on the map of the Arctic Ocean. This led me into the work of mapping the bottom of the Arctic Ocean.

It later turned out that the reason why the entire Lomonosov Ridge was displaced on the GEBCO map was that the depth contours had been determined by sonar measurements from one of the first US nuclear submarines that crossed the Arctic Ocean. Navigation in a submarine is based on dead reckoning between different fixed points at the surface, where the submarine surfaces through the pack ice and calculates its position. The location of the American submarine was simply not known properly and thus the depths obtained by echo sounding were wrongly placed.[3]

Once we had managed to locate and reach the crest of the Lomonosov Ridge, it was time to use our *chirp sonar*. In the 1990s this type of penetrating echo sounder was still the very latest in geophysical mapping, a new way to obtain more detailed information about the upper layers of sediment than before. At best you can penetrate about 200 metres of the sediment layer and see whether this uppermost area is undisturbed or has been subjected to erosion. In practice it was not an easy task. The chirp consisted of a towed device with an echo sounder that was mounted in a part that we called "the fish." This was made of fibreglass and painted in the typical yellow colour that marine instruments often have, and it weighed over 200 kilos. It was to be towed by the *Oden* in the wake that forms behind the ship when the ice has been broken. This wake could look rather like Stockholms Ström on a day when the water from Lake Mälaren is flowing at its maximum and the thaw is in full swing. We took it in turns to stand on the aft deck, holding the radio, to make sure that pieces of broken ice floes did not get caught in the towing wire. This happened anyway on a number of occasions, and every time we thought that this had put an end to the data collection. We sounded the alarm and managed to get the person who was steering the icebreaker to slow down. With a lot of effort, a few sonar profiles were collected from the crest of the Lomonosov Ridge. However, it turned out that this was not the undisturbed seabed we had hoped for and which would have been required to take sediment cores. Instead we could see on all the profiles from depths less than 1,000 metres a very noticeable erosion surface. It looked as if a huge bulldozer had scraped every part of the Lomonosov Ridge that we had measured, shaving the crest. What could have caused this enormous trail? Could it be erosion by currents, internal waves, deep icebergs or perhaps even the widely debated kilometre-thick ice shelf?

When we were busy with measurements and sampling, the announcement came that the Russian atomic icebreaker *Yamal* was heading towards the North Pole with tourists. The first non-nuclear-powered surface vessels that reached the North Pole were the *Oden* and the German *Polarstern*, which came there together in 1991. Four Soviet nuclear powered icebreakers had been there before, the first in 1977. In other words, active research icebreakers were few and far between in the pack ice in the 1990s. The captain of the *Yamal* therefore wanted to come aboard to see how research was conducted in the midst of the ice. It was a spectacle in its own right when tourists from the *Yamal* were flown over to the *Oden*. In view of what it cost to travel on the *Yamal* to the North Pole, most of the tourists were multimillionaires and from every imaginable nation, perhaps with more from the United States than anywhere else. Their research guide was none other than the previously mentioned geographer Mikhail Grosswald, one of the few scientists who had advocated for the theory of the huge floating ice shelf. He was of course curious about whether we had obtained any data from the seabed. I showed our sonar profiles and said that we had taken a sediment core from the mapped erosion surface that was so hard that the big sampler bent through almost 90 degrees. Grosswald threw out his arms and exclaimed: "You have found proof for the existence of our great ice shelf."

In retrospect, it seems almost uncanny that I happened to meet Mikhail Grosswald in the middle of the Arctic Ocean just after we had discovered that the Lomonosov Ridge had been eroded by a kilometre-thick ice shelf. However, with the small amount of data that we had obtained from the 1996 expedition, we did not yet dare to draw the conclusion that Mercer was the first to suggest: that a kilometre-thick ice shelf once covered the entire Arctic Ocean. After all, we had only investigated an area shallower than 1,000 metres. In any case, I published an article where the new profiles were shown in 1999 and presented the ice-shelf theory as the most plausible explanation for the erosion on the Lomonosov Ridge crest (Jakobsson 1999: 111). The dating of the sediment cores from the eroded areas showed that the traces were not from the last glaciation but much older. The erosion could be linked to the glaciation that ended approximately 125,000 years ago.

In the Right Place

There have since been more expeditions with the *Oden* and other icebreakers, which have mapped further traces of deep-moving ice that once scraped the seabed. It was not until 2014, when we performed a more systematic mapping of the Lomonosov Ridge with the *Oden* on the expedition SWERUS-C3, i.e., the "Swedish-Russian-US Arctic Ocean Investigation of Climate-Cryosphere-Carbon Interactions," that I felt confident that there had been a kilometre-thick ice shelf at these latitudes during a previous glaciation.

With the help of the multibeam echosounder that the *Oden* installed in 2007, we were able to get a detailed three-dimensional image of the seabed. This is completely different from the profile with depth values that an ordinary single-beam echosounder provides. Now it would be possible to see how land formations were created by ice shelves and icebergs on the seabed, just as clearly as when we see the traces of the Quaternary inland ice on land and from the air. I had often dreamed of returning to the Lomonosov Ridge with modern multibeam echo sounder to measure the crest of the ridge. It ended up happening eighteen years after the discovery of the erosion, on the 2014 expedition.

Towards the end of SWERUS-C3 we were working north of the New Siberian Islands, where the Lomonosov Ridge meets the Siberian continental shelf. The mapping was facilitated by the creation of an opening in the sea ice, with open water that extended far up towards the North Pole. When thick sea ice is broken during measurements with the multibeam echo sounder, there are serious disturbances in the data. Measurement results from situations where there is little or no ice are infinitely better. We therefore took advantage of this opportunity, and started systematic mapping of the shallow areas of the Lomonosov Ridge to the north. Amazing data poured in, showing clear traces of an ice shelf passing over the ridge, "planing and raking" its crest. Where the depth was less than 1,000 metres we systematically encountered these traces of the ice.

I do not know how many times a scientist can be as lucky as this—being in the right place in the right conditions and with the right measuring equipment. I was now firmly convinced that the hypothesis of a kilometre-thick ice shelf in the Arctic Ocean was correct. Already during the expedition we started writing an article that was published shortly afterwards (Jakobsson *et al.* 2016: 1).

Fig. 4. Traces on the crest of the Lomonosov Ridge show that this type of floating glacier ice in previous glacial periods covered the entire Arctic Ocean. The picture shows the front of the Antarctic's largest ice shelf, the Ross Ice Shelf, which has an area of about 470,000 square kilometres. Only about 11 per cent of its total thickness is above water. Several Antarctic ice shelves have fronts that are more than 50 metres tall, which means that they reach deeper than 405 metres. Where the ice shelf transitions to stand on the bottom, i.e., where it becomes inland ice, it often reaches a depth of more than a kilometre. Photo: Martin Jakobsson.

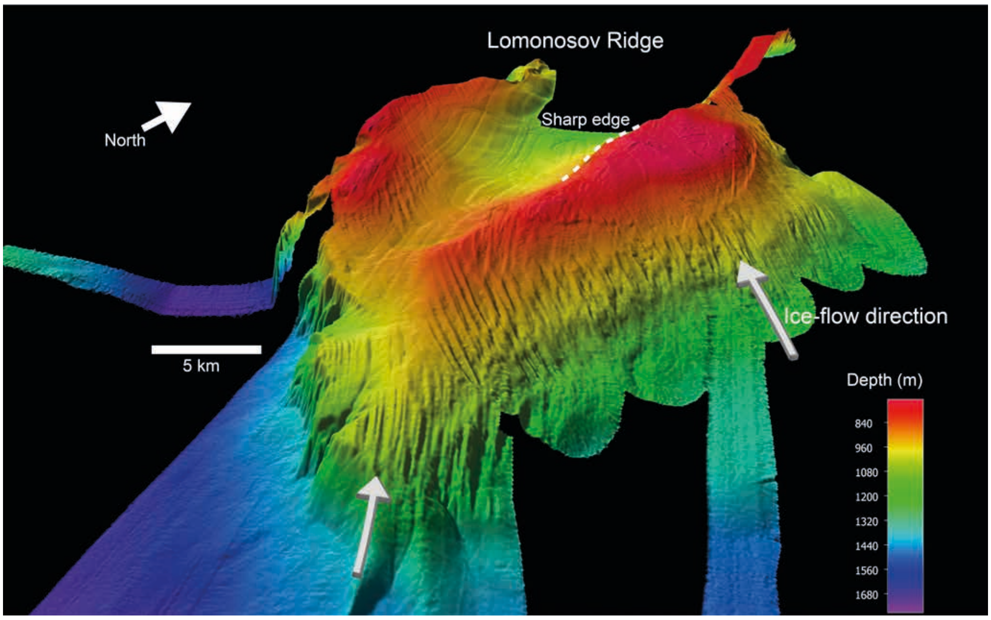

Fig. 5. Three-dimensional visualization of the crest of the Lomonosov Ridge showing where it was abraded by a kilometre-thick ice shelf. The image was created from measurements by multibeam echo sounder from the expedition on the *Oden*. The dotted line marks a sharp edge. The arrow to the right shows the direction in which the ice moved. See Fig. 1 for location on the Lomonosov Ridge.

NOTES

[1] This article is a revised and translated version of the chapter "Isens långa liv. Ett geologiskt perspektiv på Norra ishavet," in Gustafsson Reinius (ed.) (2020), pp. 50–71.

[2] It was conducted by the international drilling programme IODP (Integrated Ocean Drilling Programme) and the Swedish Polar Research Secretariat. Jan Backman, professor at Stockholm University, was the scientific leader of the expedition together with Kate Moran, then professor at the University of Rhode Island in the United States.

[2] Today, the work on the Arctic depth map is directed by researchers at Stockholm University. It is part of a project called "International Bathymetric Chart of the Oceans" (IBCAO), which was started in Saint Petersburg in 1997, one year after the expedition with the Oden.

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AUTHOR

Martin Jakobsson is Professor of Marine Geology and Geophysics at Stockholm University. His research focuses on oceanographic and geological history of the Arctic and the Antarctic. He is member of the Royal Swedish Academy of Sciences, the Swedish Royal Society of Naval Sciences and the Norwegian Scientific Academy for Polar Research.

martin.jakobsson@geo.su.se