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The Thrill to Drill in the Chill
Julie Brigham-Grette, Martin Melles, Pavel Minyuk and Christian Koeberl
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The Thrill to Drill in the Chill

Probing one of Earth's best-preserved impact craters to learn secrets of Arctic change

The location in Chukotka, Russia, where the team drilled is marked by the yellow star. Alaska is to the east, across the Bering and Chukchi seas.

Julie Brigham-Grette, Martin Melles, Pavel Minyuk and Christian Koeberl

Nearly 3.6 million years ago, a large asteroid slammed into Earth in what is today northeastern Russia. Within minutes, the impact formed an 18-kilometer-wide hole in the ground that then filled with water. The sediments that collected in the bottom of that lake since the impact may provide one of the best stratigraphic records of high-latitude climate change over the last 3.6 million years. Last year, we traveled to this remote region to drill into these sediments to see what we could learn about Arctic change.

The crater

The impact occurred in a region of rolling, low mountains; it left behind one of the best-preserved large impact structures on the planet. But the crater has hardly been studied because of its remote location: At 100 kilometers north of the Arctic Circle in central Chukotka, on the continental divide between the Arctic Ocean and the Bering Sea, El'gygytgyn (pronounced el ghee-git-gin) Crater — now Lake El'gygytgyn — is inaccessible by road.

But because it is so remote and well-preserved, Lake El'gygytgyn offers a unique opportunity to learn more about impact processes and past climate change. Large, deep lake systems are not uncommon throughout the world, but Lake El'gygytgyn holds untapped scientific potential principally because of the crater's age and strategic geographic location.

The structure is a classic "complex" impact crater with a raised portion in the center, which is currently still buried underneath lake sediments. It is also the only impact crater known on Earth that has formed in siliceous volcanic rocks. Its study thus not only allows us to gain unique information about shocked volcanic rocks (which is useful for comparison with other planets), but also about the effects of a large impact event in a delicate environment.

The formation of an impact crater is a surprisingly rapid geological process — the main sequence of events is over in just a few minutes. In the case of El'gygytgyn, an asteroid about 1 kilometer in diameter traveling at about 15 to 30 kilometers per second hit the surface of the Cretaceous-aged volcanic rocks, almost instantaneously melting and vaporizing the top layers of rock. The energy released during this impact was orders of magnitude larger than the combined nuclear arsenal of the whole world. The melted material splashed mostly outside the crater rim. A shock wave spread out radially through the ground, compressing the volcanic rocks and

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All: El'gygytgyn International Science Crew

Above: Panorama of the drill site in February 2009. Bottom: Schematic sequence of the formation of a complex impact crater like El'gygytgyn.

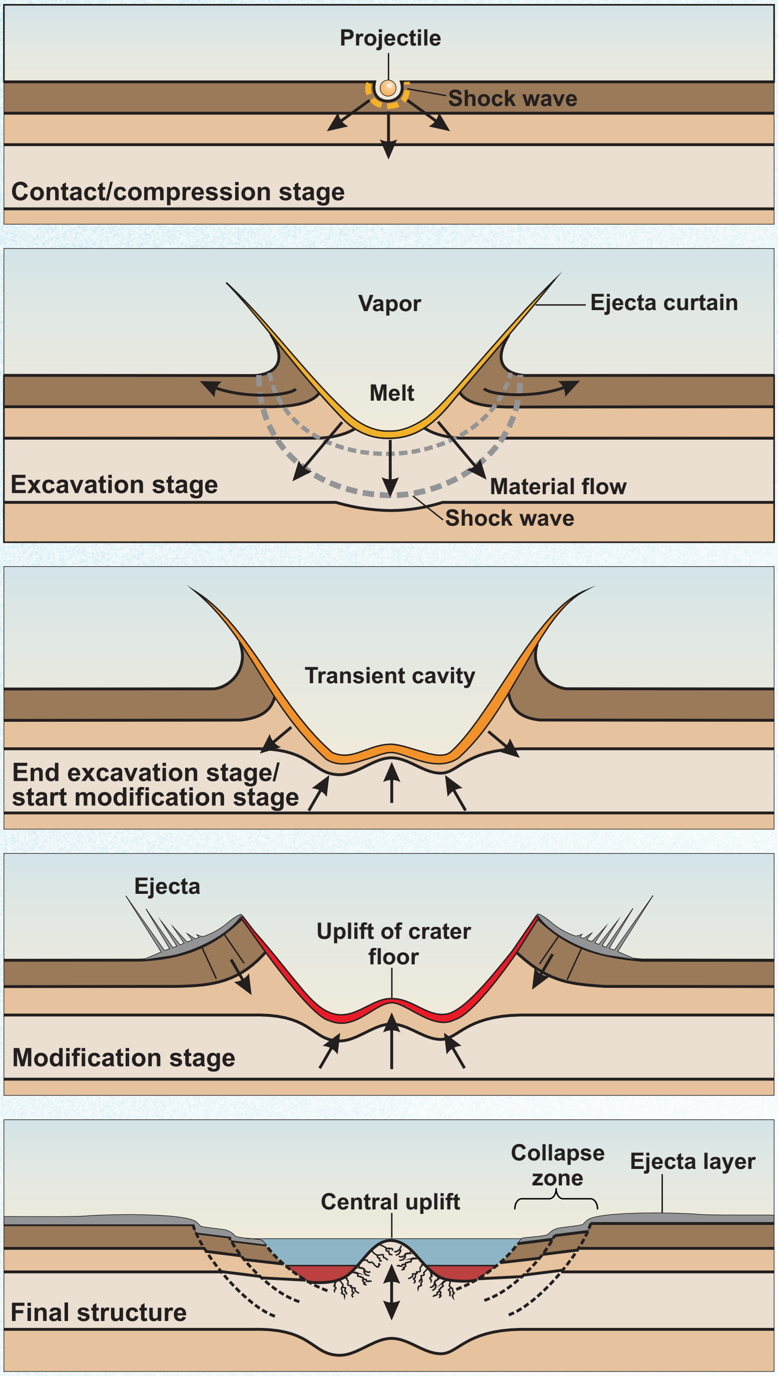
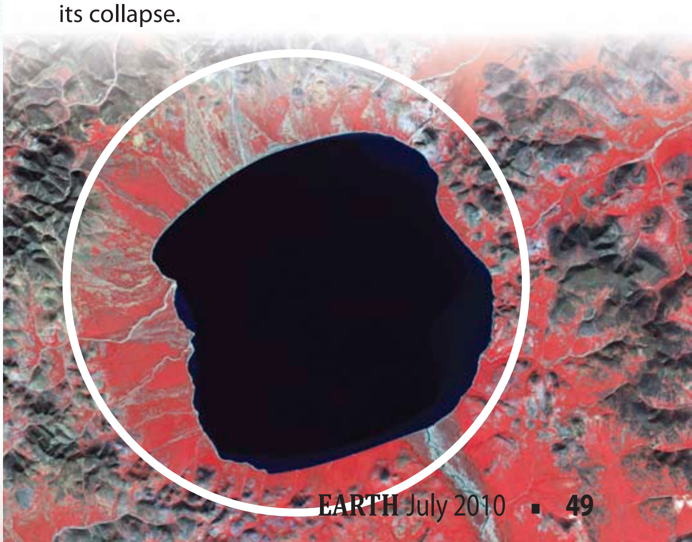


Diagram: Christian Koeberl, University of Vienna; right: NASA image created by Jesse Allen, using data from NASA/GSFC/METI/ERSDAC/JAROS, and the U.S./Japan ASTER Science Team

- Moment of impact: As the asteroid hits the ground with a velocity of several tens of kilometers per second, a shock wave is generated that penetrates radially into the ground and compresses the rocks.
- A few seconds after the impact: The shock wave proceeds into the ground and a release wave moves back toward the surface, causing material to flow downward and outward, which leads to the excavation of the crater. Early in the impact phase, both the projectile and some rocks are vaporized and melted, lining the cavity of the crater.
- A few tens of seconds after the impact: The maximum crater depth is reached. Shocked, broken (brecciated) and melted rocks are thrown into the air. Some of these ejecta are deposited outside the crater, some fall back into the crater. The crater floor starts to rebound, leading to a central uplift formation.
- A few minutes after the impact: The central uplift has formed and is being buried by the cooling melt rocks and breccias that are falling back to Earth. The steep crater rim starts to collapse and slide into the crater, leading to a wider and shallower crater. The formation of the crater structure is over after just a few minutes. Breccia and debris continue to fall back into the crater for a few hours.
- A few years after the impact: The crater floor is now covered by melt rocks and fallback breccia (dark red), and rain and groundwater have formed an early crater lake (blue), and some early lake sediment deposition has begun. The crater rim has completed its collapse.



Right: Today, El'gygytgyn Crater is filled with water and called Lake El'gygytgyn.

Top right: Truck at the drilling platform. Middle: In these remote work areas, self-reliance and a good set of tools are mandatory. All of the tools were labeled in Russian and English. Bottom: Flags lined the road from camp to the drill site.

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causing irreversible changes in the structure of the minerals in those rocks. Shocked minerals, high-pressure minerals and melted rocks from this shock wave are still preserved at the impact site today.

As a result of the shock wave, the layers of rocks in the main crater were broken, melted and thrown many tens of kilometers in the air. Some of the material fell back into the crater — even as the bottom of the crater rebounded from the impact to form what's known as a central uplift. Within tens of seconds, a mountain of rock about 1.5 kilometers in height and several kilometers in diameter was uplifted.

As the rocks that were thrown into the sky rained back down, they buried the central uplift and formed a layer of different types of rocks (called suevites), including some impact melt or glass inclusions, that is hundreds of meters thick, maybe even a kilometer or two.

For a few thousand years after the violent impact, heat from the event fueled hot springs and hydrothermal waters that circulated in the fractured rocks. Only after the fractured rocks from the impact, called breccia, cooled was the impact phase over, giving way to a calmer post-impact history, when a lake formed on the crater floor and sediments were deposited over the next few million years, perfectly preserving the Arctic's climatic history.

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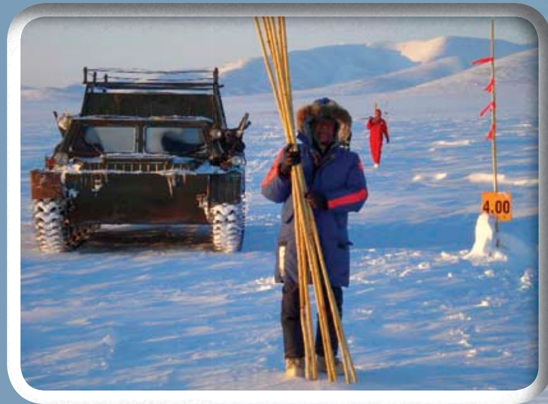
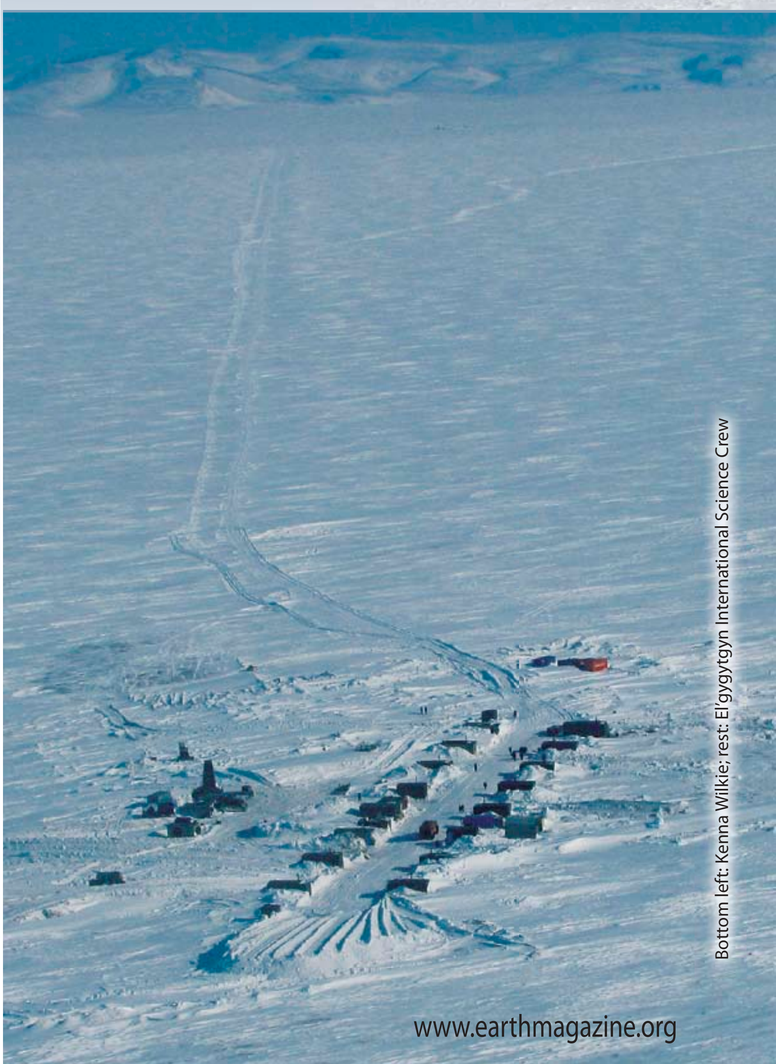
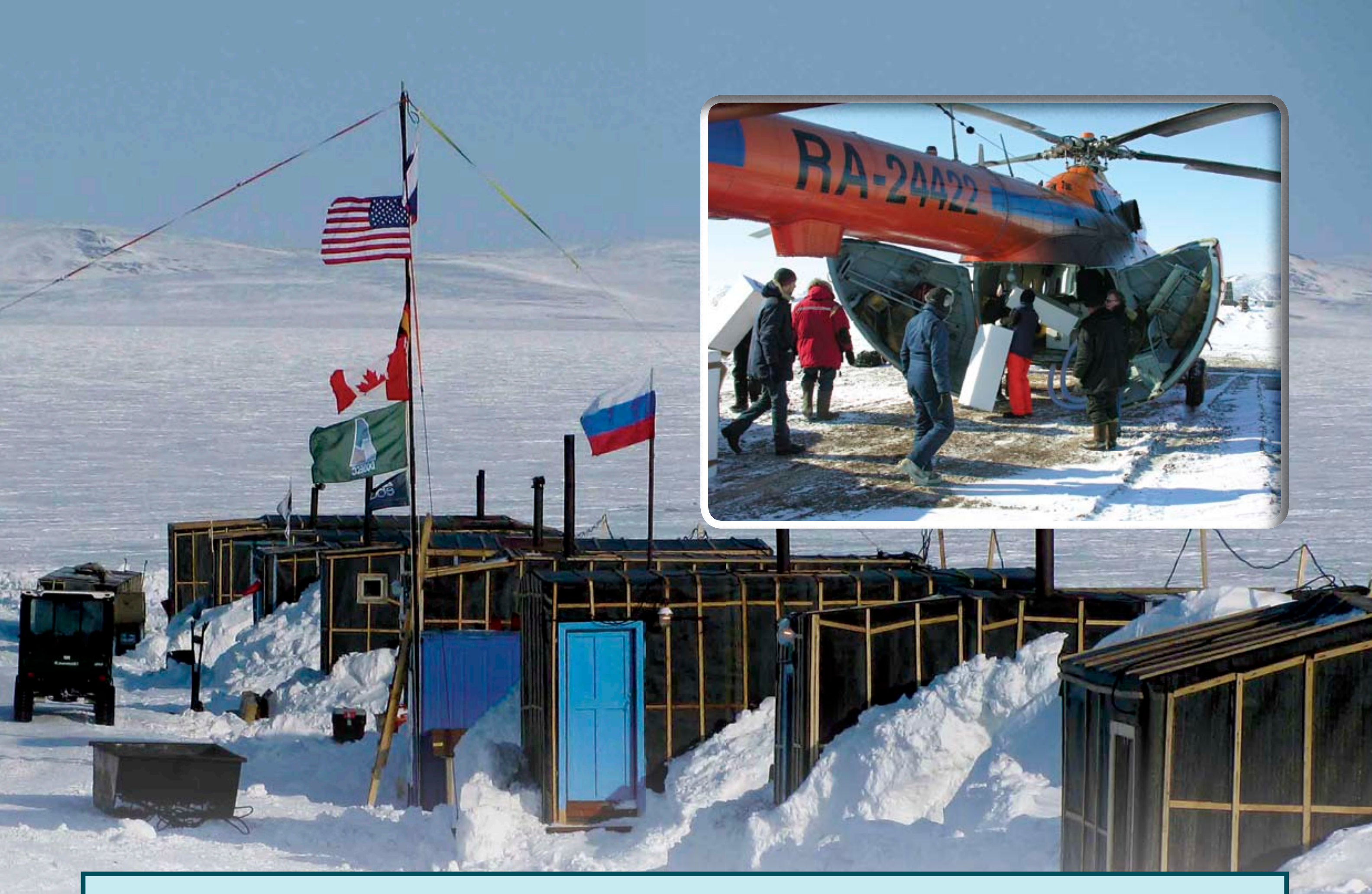
Below: Lake El'gygytgyn today. Bottom: Boya Lake in British Columbia; around the time the impact struck 3.6 million years ago, the landscape surrounding El'gygytgyn may have looked more like this.





Bottom left: Kenna Wilkie; rest: El'gygytgyn International Science Crew



Above: "Main Street" at the camp. Inset: The team received helicopter support from Pevek, Russia.

Both: El'gygytgyn International Science Crew

An arduous logistical process

Drilling into a broad, deep lake in the center of Chukotka — in Beringia, north of the Arctic Circle in Russia — was a massive logistical undertaking. It took years of planning with international funding.

The first step was to set up a field camp on the western shore of the lake that could house and feed 40 people, enough to sustain both drilling operations and core inventory in two 12-hour shifts.

Importing our supplies was another challenge. Our DOSECC GLAD-800 drill rig and supplies of casing, mud and spare parts were shipped in 16 containers from Salt Lake City, Utah, and imported into Russia by way of Vladivostok. These 6-meter-long shipping containers, as well as two more containers of scientific equipment delivered by Siberian Rail, were transported by barge via the Bering Strait to Pevek, Russia, a small village located on the coast of the East Siberian Sea. In Pevek, the containers were inspected and loaded onto trucks and driven (with bulldozer assistance) more than 350 kilometers over snow-covered "roads" — over the last 90 kilometers our equipment was basically dragged over snow and frozen tundra — to the drill site in one of the most remote areas of the world.

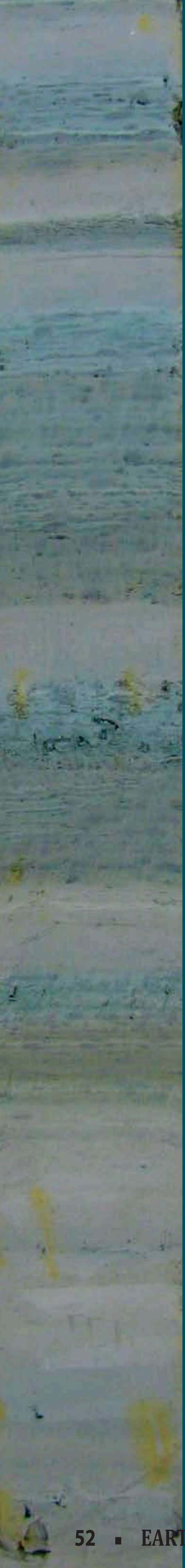
Then there was the actual drilling. Heavy drilling operations took place on a drill pad of 2.3 meters of artificially thickened lake ice that was monitored by ice engineers. The last thing anyone wanted was for a 100-metric-ton drilling system to end up on the floor of the lake! And constructing the drill rig in the dim light of February by means of three languages and one Russian crane proved to be a test of perseverance for the team.

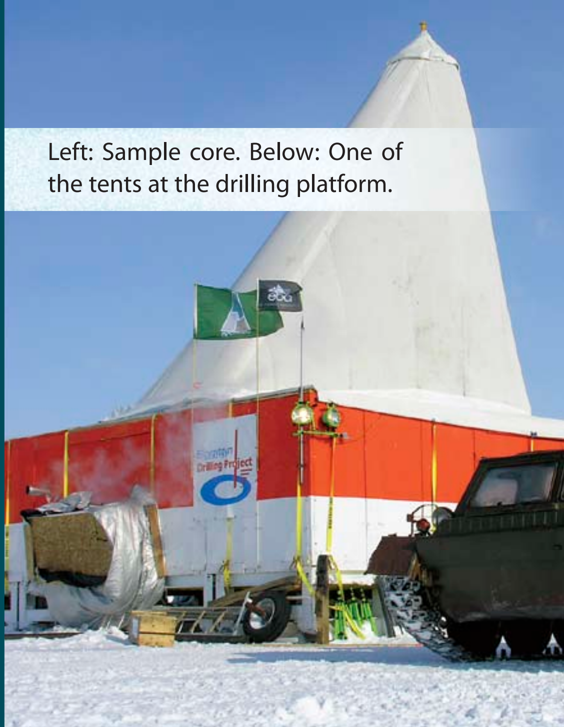
The weather at Lake El'gygytgyn during operations from November 2008 to May 2009 was what you might expect for northeastern Russia: cold and windy with air temperatures at about minus 30 degrees Celsius. Temperature extremes ranged from about minus 40 degrees Celsius in winter (without taking the wind chill factor into account) to as high as 4 degrees Celsius in early May, when the regional caribou herds gathered for seasonal calving.

But the challenges didn't end with the drilling. We weren't initially able to open the sediment cores in the field because of the remoteness of the drilling and the delicate nature of open core halves. Moreover, the rough overland transportation issues in central Chukotka would have jeopardized the quality of the sediment cores with undue shaking and possible spillage. Also, we were not allowed by Russian Customs to import a small radiation source — routine in such drilling projects — that would have allowed us to measure a number of physical properties on the full cores for immediate results.

Eventually, however, our hard work and tenacious spirits were rewarded with the successful recovery of a complete sediment record from Lake El'gygytgyn.

Pavel Minyuk





Left: Sample core. Below: One of the tents at the drilling platform.

Early results

Although our final results won't begin to be published until early next year, our team met in May to review all the data we had collected so far.

We had drilled several types of cores. Our initial pilot cores, taken in 1998 and 2003, provided proof of concept, demonstrating the importance of these cores as a climate record, as they contain climate data that extend back in time 300,000 years — roughly three times longer back in time than the oldest portions of the Greenland ice core records.

Our main cores, drilled from November 2008 to May 2009, took the concept even further, extending the record back in time more than 30 times longer than that drilled in Greenland. The temporal length and geologic significance of this climate record are therefore unprecedented in the entire Arctic region.

We recovered sediment and rock from three holes drilled in the center of the lake. While the sediment cores provide information about the climate record over the last 3.6 million years, the rocks beneath the sediment — impact formations such as breccias and suevites — tell us about the impact itself.

From these three holes, at a depth of 130 meters, we recovered sediments that cover roughly the last 2.6 million years. We also collected sediment cores from 100 to 315 meters below the lake floor to the time of impact at 3.6 million years ago, albeit with lower recovery due to surprising sequences of coarse sand and gravel interbedded with lake mud. These coarser units suggest unexpected glacial sources for these materials. Beneath the lake sediments we also collected various impact breccias and suevites (breccia with melted rock) over a depth interval of 207 meters.

Equally exciting is that we recovered roughly 40 meters of the earliest history of the lake in the warm middle Pliocene with nearly 100 percent recovery. This interval is especially fascinating as a possible analogue for future climate due to carbon dioxide forcing.

A weekly diary of all drilling operations is available online at www.icdp-online.org/front_content.php?idart=2265.

Interestingly, in the cores covering the last 2.6 million years, we see warm and cold cycles like those we saw in the much younger pilot cores. Furthermore, we confirmed the age of the impact using the initial paleomagnetic reversal stratigraphy of the Earth's magnetic field recorded in the sediments.

Overall, the record so far suggests that the cores will produce new and exciting information on the style and onset of Northern Hemisphere glacial cycles seen for the first time with such clarity in an Arctic terrestrial setting.

Julie Brigham-Grette

Middle: Tim Martin, the National Science Foundation PolarTREC Teacher on this expedition, cutting the core. The PolarTREC program puts teachers and researchers together in field collaborations. Martin teaches 8th grade in Greensboro, N.C. Bottom: Christian Koeberl with a section of an impactite core.

All: El'gygytgyn International Science Crew

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Lake El'gygytgyn in the Pliocene

Lake El'gygytgyn is located nearly in the center of Beringia — the largest contiguous landscape in the Arctic to have escaped widespread, continental-scale glaciation throughout time. As a consequence, sediments accumulated since the time of impact should chronicle a long, unbroken terrestrial record of past climate change.

When the impact occurred in the warm middle Pliocene 3.6 million years ago, northeastern Russia was not the snow-covered wasteland it resembles today. It was free of permafrost; instead, the Arctic borderlands were forested all the way to the northernmost coasts, blanketed largely by coniferous forests, complete with alder, birch, hemlock, fir, several types of pines and larch.

Mean annual temperatures were probably 10 to 14 degrees Celsius warmer than today. Meanwhile, the Arctic Ocean was many degrees warmer, lacking summer sea ice (though the surface may have frozen over briefly in the winter), and the Greenland Ice Sheet did not exist in its present form. In fact, nearly a million years passed between the asteroid's impact and the onset of the first major glaciation of the Northern Hemisphere.

It has seen a lot of changes since then, which is precisely why we wanted to study it.

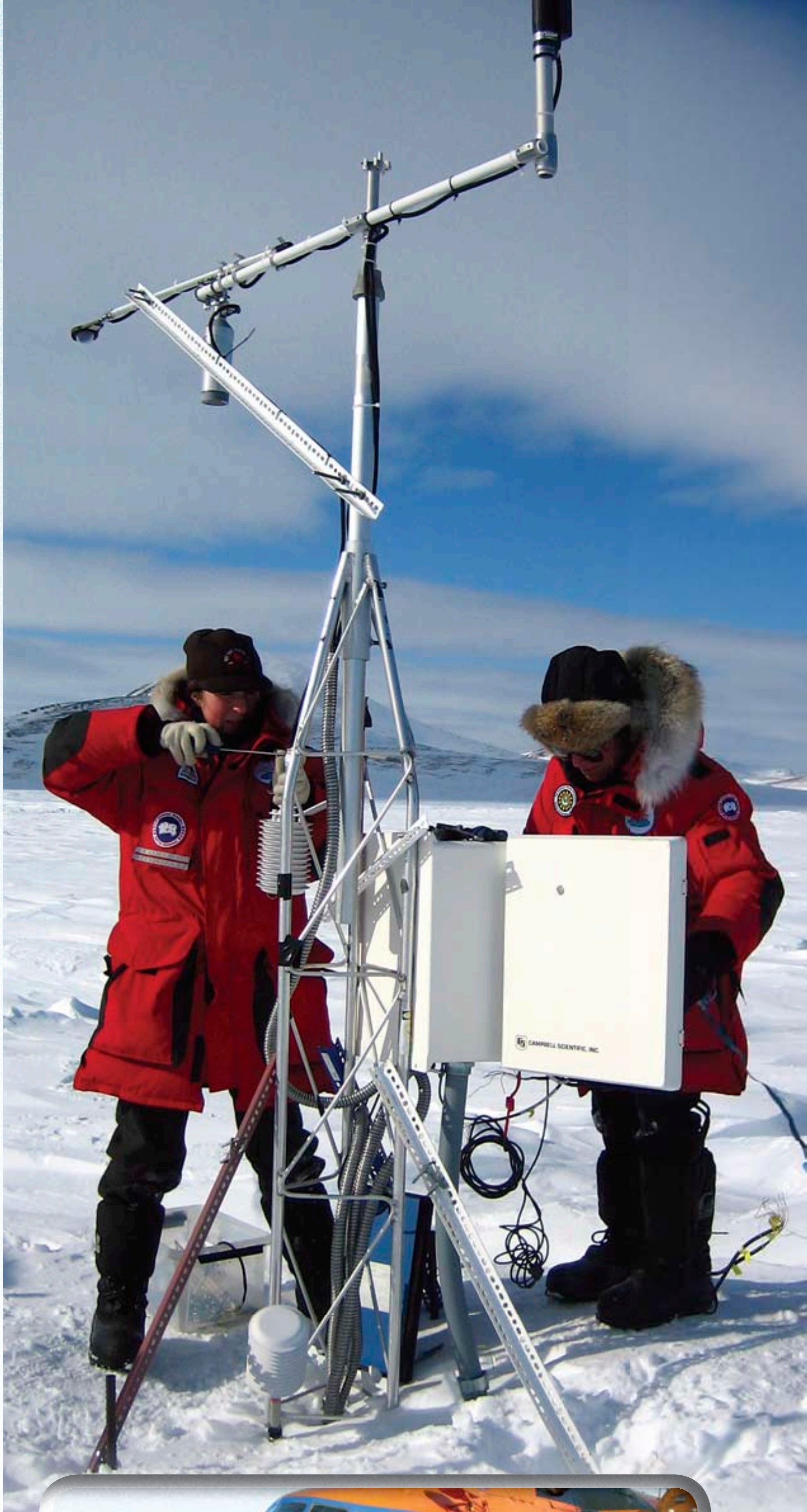
What we hope to learn

The fact that this sediment record is so continuous provided major impetus for our project. After years of challenging logistical planning and the development of international partnerships, an international team of scientists from the United States, Germany, Russia and Austria, staged scientific drilling operations at Lake El'gygytgyn to recover hundreds of meters of cores containing lake sediments and impact breccias. We hope these cores will provide new insights into the climate evolution of the Arctic and the formation of craters of this kind.

We began drilling in November 2008 and ended in early May 2009. After an arduous process getting the cores out of Russia and into our shared labs, we are just beginning to examine the cores (see sidebar).

One aspect of the project focuses on our understanding of El'gygytgyn, the impact crater. El'gygytgyn is the only crater on Earth that formed in silica-rich volcanic rocks, so the cores give us a unique opportunity to study how such rocks behave when they are shocked by an impact.

This has implications for planetary geology. For example, it will allow scientists to compare impact craters on Earth with similar targets on Mars. Studying the crater will also help us refine our understanding of impact crater formation. Recent studies at the Bosumtwi impact crater



Top right: This meteorological station in Chukotka records temperature and precipitation data. Bottom right: Martin Melles, Julie Brigham-Grette and Pavel Minyuk at the drill site.

Both: El'gygytgyn International Science Crew

Top inset: Lake El'gygytgyn as it might have looked during the last peak glaciation 21,000 years ago. Bottom inset: Lake El'gygytgyn as it looks today in summer, during the present interglacial.

in Ghana in West Africa indicate that the presence of water in the target rocks has played a much more important role in shaping impact craters than previously thought. By investigating El'gygytgyn's impact melt (if present), we can determine the influence of the water saturation in the target rocks, the possible presence of a meteoritic component, the maximum temperature of the melt and many other parameters. And, of course, we are interested in how such a huge impact affected the delicate Arctic ecosystem.

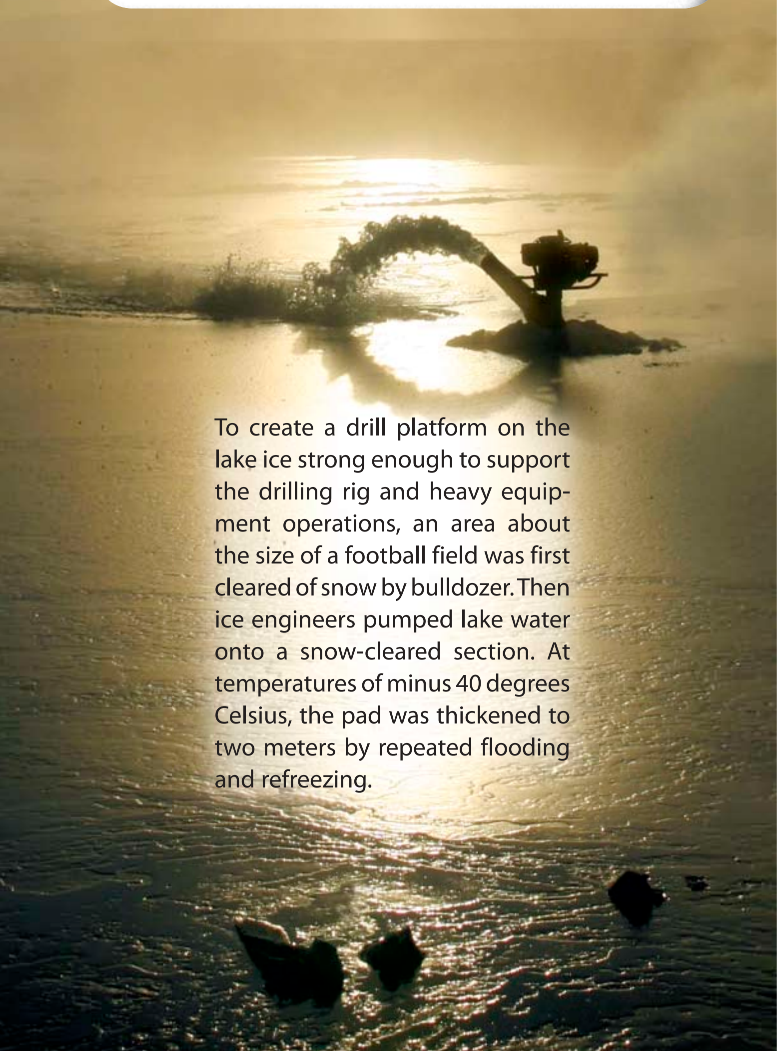
But more than anything, the El'gygytgyn cores will help us explore the evolution of Arctic climate change, allowing us to discern the rates and timing of changes to the Arctic's land and seas. Today the Arctic is undergoing remarkable rates of change. The observational instrumentation available across the high latitudes — including land-based meteorological stations, satellite measurements, ocean buoy networks and subsurface ocean moorings — provides scientists with unprecedented datasets for evaluating the complex forces and feedbacks that modulate Earth as a system. Across much of the Arctic in recent decades, winters have been warming dramatically, with only moderate warming in summer. These changes are causing remarkable alterations in snow cover, glacial retreat rates, summer sea-ice extent and the migration of both marine and terrestrial ecosystems.

These short-term changes are important to grasp, especially in the context of polar amplification and albedo feedbacks. For example, when Earth warms, the Arctic gets three to four times warmer than the rest of the planet due to effects like changing reflectivity: As areas of land and sea that are no longer covered with snow and ice reflect less of the sun's radiation, the region warms faster in a feedback loop. Teasing out how much of today's changes are the result of natural variability versus the climate system's response to increased greenhouse gases can only come from paleoclimate studies like this one: The El'gygytgyn cores offer a point of comparison for the climate's reaction to past instances of natural warming.

Such studies are especially important, given that it seems likely that modern change is being driven by atmospheric carbon dioxide in the face of a natural long-term decline in solar insolation due to changes in Earth's orbit, which should be cooling the planet. Lake El'gygytgyn is thus important in this context because nowhere in the entire Arctic do we have paleoclimate records of this length and fidelity.

Among the many challenges facing the scientific community is determining why and how the Arctic climate system evolved from a warm forested ecosystem into a cold permafrost ecosystem sometime between 2 million and 3 million years ago during the mid- to late Pliocene. The continuous depositional record we are now studying from Lake El'gygytgyn will provide, for the first time, an Arctic terrestrial perspective, reflecting new information of the mechanisms and dynamics of glacial-interglacial and millennial-scale change in this high-latitude region.

The cores will also clarify how systematic changes in Earth's orbit around the sun caused the ice ages of the last few



To create a drill platform on the lake ice strong enough to support the drilling rig and heavy equipment operations, an area about the size of a football field was first cleared of snow by bulldozer. Then ice engineers pumped lake water onto a snow-cleared section. At temperatures of minus 40 degrees Celsius, the pad was thickened to two meters by repeated flooding and refreezing.

All: El'gygytgyn International Science Crew

million years. In particular, many fundamental questions remain about how Earth transitioned roughly a million years ago from a world dominated by the 41,000-year-long cycle of Earth's tilt to one dominated by the 100,000-year-long cycle of eccentricity (the shape of Earth's orbit around the sun) or some combination of precession (the orientation of Earth's axis of rotation) and tilt. We hope that these cores will help us learn more about the role of the Arctic in this transition, and how it may be a responder or driver of interrelated feedbacks.

Finally, it's important to note that these sediment cores should not be studied in isolation. Comparing these cores to cores from other scientific drill sites, such as the Lomonosov Ridge in the Arctic Ocean, which was drilled in 2004, and the ongoing drilling in the Antarctic will help us create a spatially merged record that together could help us solve the ultimate puzzle of the poles: Why were the polar regions so warm in the past? How and why did they start to freeze over? What will happen there in the future?

Stay tuned. Results will be coming soon.

Brigham-Grette is a geologist at the University of Massachusetts in Amherst. Melles is a geologist at the University of Cologne in Germany. Minyuk is the paleomagnetics director at the Northeastern Interdisciplinary Scientific Research Institute in Magadan, Russia. Koeberl is a geochemist at the University of Vienna in Austria and director of the Vienna Natural History Museum.

Funding and support

The Lake El'gygytgyn Drilling Project is an international effort funded by the International Continental Drilling Program, the U.S. National Science Foundation Earth Sciences Division and Office of Polar Programs, the German Federal Ministry for Education and Research, Alfred Wegener Institute, GeoForschungsZentrum-Potsdam, the Russian Academy of Sciences Far East Branch, Russian Foundation for Basic Research, and the Austrian Ministry for Science and Research. The leading Russian institutions include the Northeastern Interdisciplinary Scientific Research Institute, the Far East Geological Institute, and Roshydromet's Arctic and Antarctic Research Institute. The deep drilling system for Arctic operations was developed by DOSECC Inc., and LacCore-University of Minnesota handled core curation.

The drilling team. Above: Drilling platform.

Both: El'gygytgyn International Science Crew