Special Report Earth

Hidden Antarctica: Terra incognita

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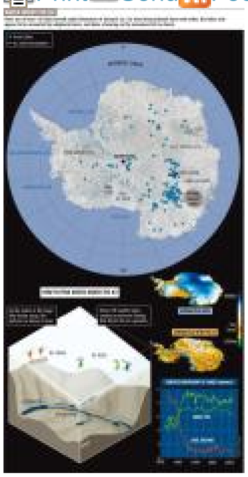

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Seen from the outside, Antarctica is a desert, frozen and all but lifeless. Dig below the surface, however, and you will find deep secrets. Thousands of metres beneath Antarctica's forbidding facade, at the place where ice meets rock, lies a land that is exotic, dynamic and above all, wet. Water courses around Antarctica's soft underside; it collects in deep, dark lakes, spills out into streams and rivers, and forms wetlands and marshes that have not seen the sun for millions of years.

"Antarctica has two faces," says geologist Robin Bell from Lamont Doherty Earth Observatory in New York. "It has the face it shows to the world and it has the one on the inside. And the inside face could be the one that really matters."

Where there is water, there is also - usually - life, so now that Antarctica is turning out to conceal the world's biggest wetland, it may harbour more living things than anyone had dreamed of. But there is also a darker side to this new view of Antarctica. Ice is slippery when wet; the more widespread the water, the more likely the ice is to slide into the sea. The hidden face of Antarctica's mighty ice sheets may determine their fate, and ultimately, therefore, the fate of us all.

In itself the idea of water under Antarctica is not new. Scientists have known for decades that the sheer weight of the overlying kilometres of ice causes some melting at its base, and that here and there the water has collected into lakes. Just as when the ice flows over deep mountains and valleys its surface becomes rucked and rumpled, where the ice crosses a large enough lake its surface can become flat and smooth, outlining the lake's hidden shores.

That's exactly how a satellite image taken in 1993 picked out the edges of what is now the most famous of Antarctica's deep lakes, Lake Vostok. Renowned for its astonishing size, Vostok is around the same area as Lake Ontario but twice as deep, making it one of the largest freshwater lakes in the world. Located in the very heart of Antarctica, it has been covered with ice for at least 15 million years.

It is also the only one of Antarctica's hidden lakes that researchers have come anywhere near penetrating. At 3439 metres below the surface, a Russian ice core that was being drilled to investigate the Earth's climate began bringing up lake ice that had frozen to the base of the ice sheet. Though researchers are still arguing about whether this accretion ice contains traces of life, many have speculated about the life forms that could be floating in the lake's dark interior (see *What lies beneath*).

Still, for many years Vostok was considered little more than a curiosity. It could perhaps give us some insight into what life might exist on other planets, or Jupiter's ice-covered moons, but few people thought that Vostok, or any other under-ice lakes, would have much to say about home.

Over the past few years, that has all changed. Researchers from several countries who have been flying over the continent with ice-penetrating radar, searching for telltale reflections from subglacial water, have raised the tally of Antarctic lakes to more than 100. The more lakes we find, the more importance they seem to hold for planet Earth. "Lake Vostok was nice," says glaciologist Slawek Tulaczyk from the University of California, Santa Cruz. "It started off the focus on under-ice lakes. But now we know there are many more of them, and we are starting to realise that they're connected to the outside world."

Buried rapids

While some geophysicists were spotting their new lakes from the air, others were punching holes through Antarctica's ice sheets to see what lay beneath, and almost everywhere they drilled, they found water. Still, they assumed that if this water flowed at all, it was just a painfully slow migration through the pores of the soft mud that underlies large parts of Antarctica's ice. "We had always suspected that the lakes were connected," says Martin Siegert of the University of Edinburgh, UK. "But we thought it would take thousands of years for water to get from one lake to another."

The first hint that this might be wrong came in 2005, when Tulaczyk and his colleagues saw something curious. They had been studying the Siple Coast, a region of West Antarctica where the ice sheet is particularly active. The area contains several giant glaciers called ice streams, which move at what, for ice, is a considerable pace. One of these had stopped moving just a hundred years earlier, while others seemed to show signs of speeding up over a timescale of centuries.

At the time, that pace of change was the fastest known for Antarctica, yet the researchers noticed that several parts of the ice streams seemed to have changed much, much more rapidly. Comparing satellite radar data taken on 26 September 1997 with another pass some three weeks later, they saw that an area of ice about 125 kilometres square seemed to have slumped downwards by at least half a metre. At the same time, other parts of an adjoining ice stream had lurched either upwards or downwards.

There aren't many things that can make ice do this. One possible explanation was the movement of water, so the researchers wondered if they were seeing the uppermost signs of several sudden under-ice floods (*Geophysical Research Letters*, vol 32, L03501). If so, the water might act as a lubricant to make the ice slide even more quickly. "Water lifts up the ice like the jack that you use to change your tyre," says Tulaczyk. "And then the ice slips." However, with only two snapshots in time, the researchers had no chance of tracing where the water might have come from or gone to, so the idea remained speculation.

Until, that is, a team of UK researchers caught some water in the act. Earlier this year, Duncan Wingham from University College London, working with Siegert and several others, reported satellite observations showing that the ice above a lake in East Antarctica had lurched suddenly downwards by a full 3 metres. At the same time as this lake was apparently losing water, several others downstream seemed to be filling up, each by around 1 metre. Over a period of about a year, Wingham and his colleagues watched the equivalent of a river the size of the Thames flow between these lakes beneath the ice (*Nature*, vol 440, p 1033). And this was surely not the only instance.

The sheer speed of these events has taken the rest of the science world by surprise. "Nothing should happen in ice sheets on such short timescales," says Don Blankenship, a geophysicist at the University of Texas, Austin. "This thing that takes millions of years to change is being tickled by a process that happens on a timescale of months. I don't think anyone has yet been able to swallow what that means."

Moreover, unlike Tulaczyk's Siple Coast slump, this one happened in the east of the continent. Antarctica's ice sheet is really two sheets that join like giant butterfly wings (see Map). The West Antarctic sheet is by far the smaller of the two, and most of the ice there sits on land that is below sea level. That makes it more vulnerable: if some of the ice sheet melts, the rest is exposed to relatively warm seawater and yet more melting. The western sheet is the one that has so far caused most worry. If it melted, it would raise the world's oceans by 5 metres, and leave nothing in western Antarctica but a few scattered islands.

By contrast, the vast East Antarctic sheet is mostly based on higher ground. Most of its drainage glaciers are frozen to their beds, and advance with the sluggish flow of plasticine. East Antarctica, so the theory went, is old and cold and set in its ways. That's just as well, because this is the ice sheet that holds most of the fresh water on planet Earth. If the eastern sheet melted, it would raise sea level by a staggering 70 metres.

"The west has the ice streams, and we've known for a long time that it's dynamic. Things are changing there all the time. But the east is so stable. In 15 million years it has hardly changed at all," says Siegert. And yet, the water there is also on the move. "Even in the east," he says, "it's not the ice doing the work. It's the water."

Strange world

East Antarctica may also hold more lakes than anyone has yet realised. The official tally of Antarctic lakes is 145 (*Antarctic Science*, vol 17, p 453), but Blankenship believes there could be more. The lakes his team submitted to the overall inventory had to fit three categories. First, they had to be "flat". This doesn't have quite its usual meaning in the strange world of Antarctica's underside, where water moves in mysterious ways. The weight of the ice squeezing downwards counts for much more than local hills and valleys in telling water where to go. "You can have lakes sloping down the sides of mountains, you can have uphill waterfalls, it's wacky," says Blankenship.

"You can have lakes sloping down mountains, you can have uphill waterfalls"

By calculating the ice thickness, Blankenship drew contours of a measure he called "hydraulic flatness" - in other words, the places where, given the overlying ice pressure, any water there would naturally lie. Hydraulic flatness therefore told Blankenship where, by rights, any lakes should be. Within the flatness contours he then looked for ice-penetrating radar reflections that were both bright - which means they are reflecting from water - and smooth, as you'd expect from a lake surface.

As well as the so-called Great Lakes - those that satisfied all three criteria, and thus made it into the official inventory - Blankenship found others. Some are flat and bright but not smooth; he has dubbed these "fuzzy lakes". Others are flat and smooth but not bright, and he calls these "dim".

Both types tend to be found near at least one Great Lake, and Blankenship believes they could be related. The fuzzy lakes, for example, could be like marshes: wet enough to be bright, but with patches of land poking through the water to prevent them being smooth. These under-ice wetlands could be regularly flooded by overflows from the Great Lakes, and then pass the water on down the line. Though he is less sure about what exactly the dim structures represent, Blankenship thinks they may also be some sort of lake.

Does all this water really have an effect on the ice above? Blankenship thinks so. He has mapped the lakes to see how they relate to ice flow, and sure enough, most of the lakes occur just beneath the "ice divides", the places where ice has to decide whether to flow this way or that way. "The ice might be telling the lakes where to go, or the lakes might have some control on where the ice divides. As yet we don't know which," he says. "But there does seem to be some magic combination of ice sheet and lakes that causes ice to divide where the lakes form."

Putting all these findings together, many researchers now believe that Antarctica's hidden water could be crucial in determining the fate of its ice sheets. "Remember, this is the lubricant that's moving around," says Blankenship. "If it's down there it's slippery, and we don't know where the ice sheet's ticklish spots are." That's a worrying thought. Depending on where the water moves, it might have no effect on the overlying ice, or it might set a whole region sliding. Blankenship fears that warming since the end of the last ice age has melted the base of the ice, and this may already be priming some parts of the ice sheet to slip. East Antarctica could be ready to open its floodgates.

"Antarctica's hidden water could determine the fate of its ice sheets"

David Marchant from Boston University believes this may have happened before. He has spent decades tramping over the few exposed rocks in an arid, ice-free region of East Antarctica known as the Dry Valleys. And he keeps returning to one place in particular: a tortured landscape of channels and pits known as the Labyrinth.

Normally, if you see rock channels in Antarctica you would expect that they would have been gouged out by a passing glacier. This doesn't fit the Labyrinth's channels: they are strangely sinuous, whereas glaciers tend to plough straight. Moreover, where two of its channels meet, there are often potholes. That's the classic sign, says Marchant, of a turbulent whirlpool focusing its energy and eroding the rock in a giant swirl. There are also some channels that stop abruptly for no apparent reason, as if the agent that created them had lost interest. That's just what you'd expect if they had been made by water that then flowed off down a different path, says Marchant, or plunged into cracks in the overlying ice.

He became convinced that the Labyrinth had been carved by a massive under-ice flood, and he published his ideas in July (*Geology*, vol 34, p 513). However, his flood was vastly greater than the small-scale shifts that Wingham and his colleagues found. "We were finding potholes that are 200 metres across and 50 metres deep," says Marchant. "They are just enormous features. They're the largest potholes in the world." The water quickly stripped away all sedimentary rocks, and then lifted blocks of granite bedrock more than 2 metres wide and casually flung them out of the way. At its peak, Marchant estimates, the swirling flow of this mighty inundation would have been enough to drain the whole of Lake Vostok in less than a week.

From volcanic deposits above and below the Labyrinth rocks, Marchant has managed to date exactly when this giant flood took place. It flowed some 13 million years ago, during a period of gradual global cooling when the eastern part of Antarctica's ice was just becoming cold enough to freeze to its bed. Marchant believes that this initial freezing trapped water behind a dam. "You're ponding and ponding and ponding, and then when you break the dam it's very hard to stop."

There are also signs that other similar floods may have happened elsewhere in Antarctica. For instance, the ocean floor off Pine Island Bay in West Antarctica, which has been repeatedly covered with ice, most recently during the last ice age, is now gouged and scoured with channels just like the Labyrinth. Marchant believes there could be much more evidence still buried under ice. And there is no reason, he says, why such a massive flood couldn't happen again. All you'd have to do is tap into the water from several large lakes. "Once you start to find lakes that are interconnected, the entire ice sheet opens up."

Switching off the current

In principle, even a large flood like this wouldn't be big enough to have much direct effect on the global sea level. However, a sudden influx of fresh water might well have the power to change ocean circulation. Some have postulated that a similar massive flood disrupted the circulation of the North Atlantic during the last ice age, and the seas around Antarctica have their own share of pivotal spots, where cold, dense water sinks and helps to drive the oceanic conveyor belt. "The meltwater from these systems is flowing into one of the most sensitive areas of ocean on the planet," says Marchant.

There is also evidence that large-scale flooding may have happened more recently in Antarctica. Bell points out that, even through the ice, you can trace how a lake's shoreline has changed over time. When the ice flows over rock and onto water, it sags, leaving gaps that rapidly fill with snowdrifts. Using radar, you can track this pulse of snow through the ice sheet. Bell says that this method shows that Lake Vostok has probably not emptied in the past 100,000 years. "It may have gone up and down a little but it has stayed in its bowl," she says.

It's a different story for Lake Concordia, which although only a tenth the size of Vostok is still a substantial body of water. Sometime in the past few hundred thousand years, Concordia's shoreline shifted dramatically. Bell says this surely means that water has been on the move.

For the moment, researchers are still digesting the implications of Antarctica's hidden face. The results are too fresh for us to be sure what they truly mean, but what is certain is that in the past few years the story of the icy continent has changed dramatically. "The surface may be old, cold and dry, but the bottom is warm and wet and changing," says Blankenship. "From the top down we thought we understood Antarctica. But from the bottom up it's a whole different world."

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It came from outer space

As well as life, Antarctica's ice might also be concealing signs of death on a massive scale. In May this year, geophysicists Ralph von Frese and Laramie Potts from Ohio State University in Columbus reported what they believe to be a gigantic crater, caused, they say, by a meteorite strike. Their findings have yet to be confirmed by other scientists, but if von Frese and Potts are right, this crater dwarfs the one at Chicxulub in Mexico, which has been fingered for the death of the dinosaurs. It may even have been responsible for the most deadly mass extinction the Earth has ever witnessed.

It's no easy task to spot a crater that has been swamped by several kilometres of ice. "Normally, you have to go to a site, pull up rocks and go through a checklist," says von Frese. However, he and Potts have worked extensively on identifying craters elsewhere in the solar system, and they used their expertise to explore Antarctica's hidden face.

The trick is to use gravity measurements to study the density of the underlying crust. When a meteorite strikes, it blasts away relatively light crustal material. Dense rock then flows in from the mantle beneath to fill the gap, and the result is a dense "plug". When they studied the measurements of Antarctica's underside from NASA's GRACE gravity probe, that's exactly what von Frese and Potts saw, in a region known as Wilkes Land. What's more, when they checked the topography of the region, the team found a giant basin that fitted neatly over the gravity anomaly, and was a whopping 500 kilometres across. If this truly is a meteorite crater, it's the biggest in the world. "You could fit the entire state of Ohio into it," says von Frese.

The size of the original meteorite is harder to estimate, since nobody knows exactly what the rocks at the impact site were made of, and thus how easy they would have been to shift. But von Frese believes it would have been roughly 41 kilometres across, which is four times the size of the object that devastated the dinosaurs.

Signs of youth

Judging the age of the strike is still more difficult, though it must be relatively young in geological terms, because the plug of mantle material is still there. In the heat of the deep crust, rock is soft enough to gradually flow to even out any weight imbalances, so in time the mantle rock will simply sink back again. That's what has happened at the Vredefort crater in South Africa, which at 300 kilometres across is the largest undisputed impact crater on Earth, and is about 2.5 billion years old. The sizeable Sudbury crater in Canada is 1.8 billion years old and has also lost its plug. Since the Antarctic plug is intact, von Frese says, the crater is probably less than a billion years old.

He also believes it's significant that - if you "rewind" the positions of the continents - the crater was diametrically opposite a series of massive lava flows that occurred in Siberia some 250 million years ago in the Permian. Some geophysicists think that a huge meteorite strike on one side of the planet will create reverberations that trigger volcanic outpourings on the other. "I don't think it's an accident that the Siberian traps are sitting exactly at the other side of the planet," says von Frese. "You're talking about a very precise hit."

That date is significant because it is also when some 95 per cent of marine life and 75 per cent of terrestrial life disappeared from the face of the Earth. This was the most devastating of all the Earth's mass extinctions, and though there have been many theories, nobody has come up with a conclusive explanation of why it took place. "For a spectacular extinction like that one, you'd expect to have a spectacular event," says von Frese. "And this seems to fit the bill."

The connection between von Frese's crater and the Permian extinctions remains little more than a leap of faith and is still to be published. Yet von Frese is hoping to go to Antarctica soon and test his theory. More detailed aerial studies of the gravity and magnetism may confirm or refute his idea. Though he would love to get his hands on some rocks to know for sure, von Frese admits that drilling is unlikely any time soon because the site is so inaccessible and smothered in several kilometres of ice. And the ice, at least in this part of Antarctica, looks set to stick around. "This place has been covered up for all of human history, and it doesn't look like it will be uncovered for the rest of human history," he says. "It's as remote from us right now as any place in the solar system.