

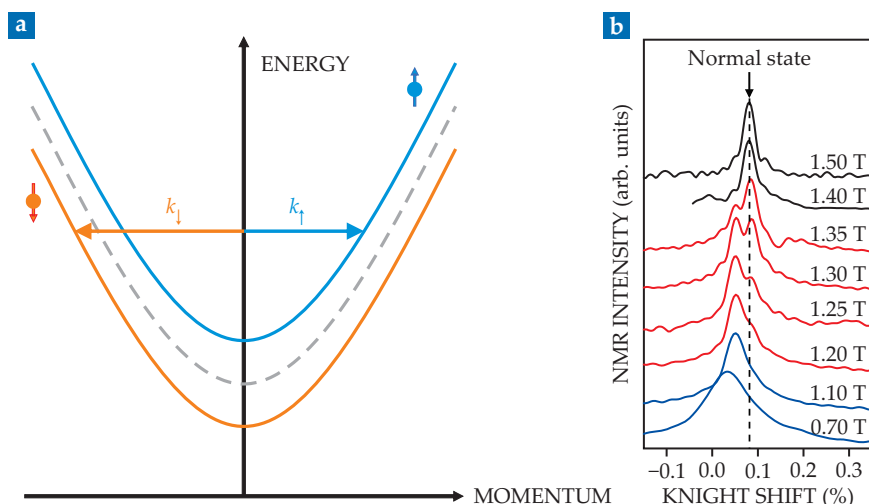


FIGURE 2. FFLO SUPERCONDUCTIVITY arises from Zeeman splitting. **(a)** In the absence of a magnetic field, spin-up and spin-down electrons have the same energies and momenta (gray dashed curve), so when the highest-energy electrons pair up in the superconducting state, the net momentum is zero. But in the presence of a magnetic field, spin-up (blue) and spin-down (orange) electrons take on distinct momenta k . When the highest-energy electrons pair to form an FFLO state, the pairs have nonzero net momentum and create spatial modulations in the spin density. **(b)** For strontium ruthenate at 70 mK, NMR measurements—given in terms of the Knight shift, which quantifies the NMR frequency shift—show the transition with increasing magnetic field from homogeneous superconductor (blue) to FFLO superconductor (red), characterized by double peaks, to nonsuperconducting (black). (Adapted from ref. 2.)

phases, with the FFLO occupying the high magnetic field, low-temperature region. The magnetic fields in their study were about a tenth of those necessary for previous FFLO candidates, which makes SRO a practical choice for future FFLO investigations.

Although encouraging, the new result isn't conclusive. The only definitive evidence would be an observation of spatial modulations in the superconducting order parameter through, for example, measurements of the superconducting gap—the small energy gap that opens when electrons pair up. That smoking gun could come in the future from scanning tunneling microscopy measurements.

Heather M. Hill

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Groundwater flows deep under Antarctic ice

Ice-dynamics models must be updated now that researchers have observed a thick layer of salty water in sediments beneath the West Antarctic Ice Sheet.

Some 70% of Earth's fresh water is stockpiled in Antarctica's ice. If it were all to melt, global sea level would rise by 58 m. Estimates of ice loss critically depend on such factors as the conditions at the base of an ice sheet and the stability of ice shelves that prevent the sheet from sliding into the ocean. (For more on Antarctica's ice shelves, see the article by Sammie Buzzard, *PHYSICS TODAY*, January 2022, page 28.)

Researchers have hypothesized that underground water may exist below the ice. If enough water melts at the ice sheet's bed, the friction between the ice and the land decreases, and the ice flows toward the ocean faster. For simplicity and with

just a few observations, most glaciology simulations have modeled the basal meltwater as a thin layer that's a few millimeters to a few meters thick with an impermeable mass of bedrock below.

Reality, however, is most certainly different from those model assumptions. Take away the ice, and Antarctica has many of the same topographical features as any other continent, such as permeable valleys and impermeable rugged mountains. But the remote and harsh environment of Antarctica and the technical challenges of identifying water deep beneath the bed of the ice sheet have prevented glaciologists from observing any subglacial groundwater, aside from in a handful of nonglaciated regions at the ice's margins.¹

Now Chloe Gustafson of the University of California, San Diego, and her colleagues have conclusively observed groundwater under the Whillans Ice Stream—a river of ice flowing from the West Antarctic Ice Sheet on land to the

Ross Ice Shelf floating off the Siple Coast. Their new data indicate that the basin of groundwater contains an order of magnitude more water than previous estimates of subglacial hydrological systems.²

Into the field

To image subglacial groundwater, researchers have used seismometers and ground-penetrating radar. Although those methods have measured liquid water in the top few hundred meters, they aren't adept at observing the volume of water in deeper subterranean reservoirs. Radar signals attenuate because radio waves are easily absorbed by liquid water. And seismic-wave signatures are sensitive primarily to density variations, which limits how well those layers can be distinguished from one another.

In a 2017 feasibility study, two of Gustafson's coauthors—Kerry Key and Matthew Siegfried—found that a magnetotellurics (MT) approach should be capable of detecting groundwater more

than a few hundred meters below Antarctic ice sheets.³ Natural variations in electric and magnetic fields arise from the interaction of charged particles in the solar wind with Earth's conductive magnetosphere. Like all other time-varying electromagnetic fields, the ones in Antarctica are governed by Maxwell's equations and induce local secondary electromagnetic fields in ice, groundwater, rock, and other materials. MT sensors installed at the surface passively measure the resistivity of the secondary electromagnetic fields. High-resistivity glacier ice, for example, is easily distinguished from low-resistivity sediments whose pore space holds subglacial groundwater.

Although the MT approach is well established and has been used to study nonglaciated terrain over the past several decades, the method demanded some modifications for subsurface interrogations in Antarctica. Good measurements require electrodes to be well coupled to the surface. But snow on Antarctica's surface weakens that coupling, so Gustafson and her colleagues used temperature-insensitive titanium electrodes with a large surface area. On top of that, they applied an environmentally friendly buffer to the electrodes to amplify the resistivity signal further.

With their observational method in mind, Gustafson and her colleagues prepared for the fieldwork in West Antarctica. The area they visited is far from the permanent research stations in Antarctica, and the bitterly cold climate makes it and the rest of the continent accessible for just the three months of the Southern Hemisphere's summer. But measurements of the ice streams in West Antarctica would provide critical observations needed to accurately calculate ice velocities in models.

During the November 2018 to January 2019 field season in Antarctica, Gustafson and her colleagues installed a few dozen MT stations—one of which is shown in figure 1—on the Whillans Ice Stream. From the collected MT data and

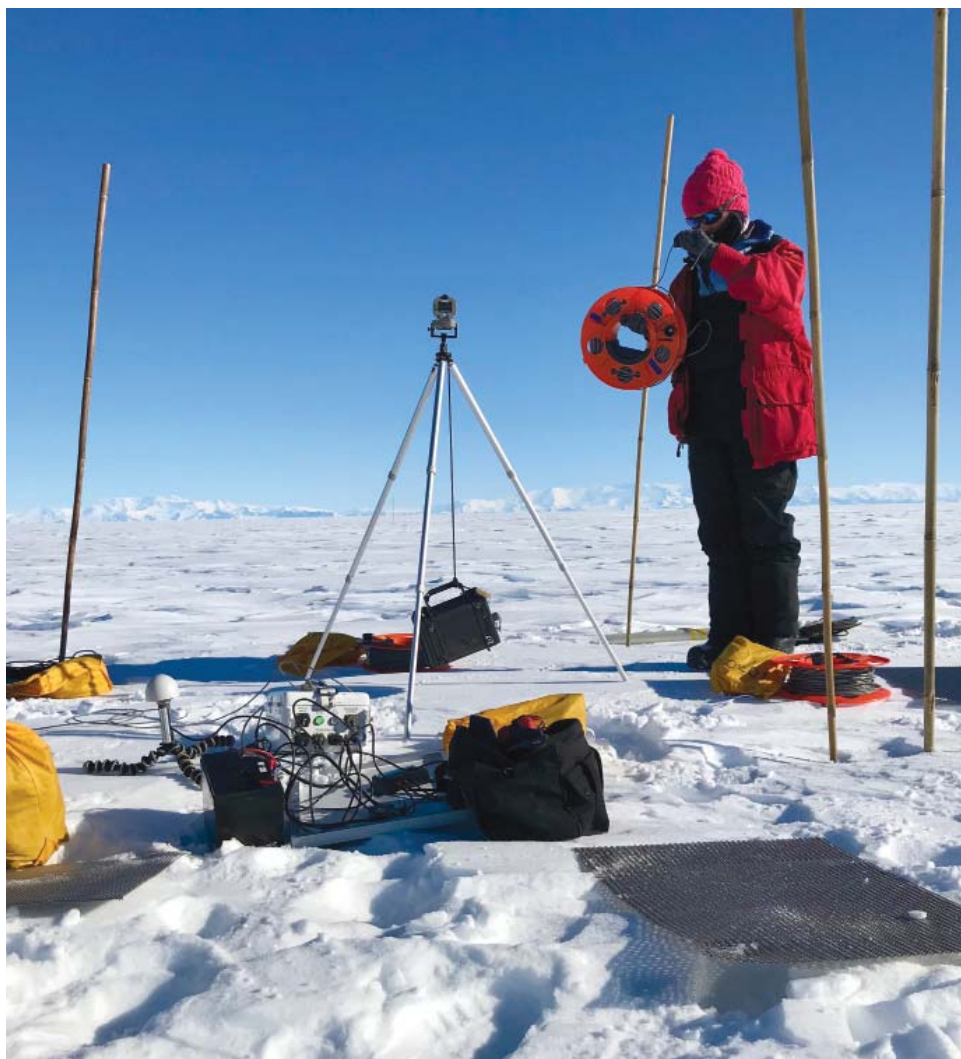


FIGURE 1. SEARCHING FOR GROUNDWATER. Chloe Gustafson sets up a magnetotellurics station for measuring the resistivity of the subsurface in West Antarctica. The dark titanium sheet in the foreground serves as an electrode: Its large surface area provides sufficient contact with the ground to measure the electrical resistivity of the land, ice, and groundwater. The instrumentation, installed during the 2018–19 field season, was placed inside a triple-walled box to protect it from snow drifts and ice accumulation. (Courtesy of Kerry Key.)

a passive seismic survey, the researchers discovered a sedimentary basin underneath some 800 m of ice.

An ocean of groundwater

In that deep basin, the researchers found a subglacial water system. Figure 2 shows

the electrical-resistivity results for the two regions of the ice stream that they focused on: the Whillans subglacial lake and the downstream area, known as the Whillans grounding zone, that connects to the ocean. In both locations, a layer of porous and permeable sediment extends



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some 2 km into the subsurface below the ice and is saturated with groundwater. All told, the volume of groundwater that Gustafson and her colleagues observed is at least an order of magnitude more than that found in the thin, shallow layer immediately below the ice stream's base.

To their surprise, the researchers learned that some of the groundwater was salty. The salinity increased with depth and had values approaching that of seawater. The MT measurements revealed that in the top few hundred meters of the basin below the ice sheet, fresh meltwater mixed with the saltier deep groundwater, a mixing whose existence had only been suggested theoretically.

The saltiness of the groundwater may be from seawater that infiltrated into the subglacial system 5000–7000 years ago when seawater advanced farther inland. Fresh water that subsequently melted from the glacier would have created the salinity gradient observed today.

Martin Siegert of Imperial College London says that the salty water could have also been added to the groundwater reservoir through a modern tidal-pumping mechanism. "We know that there are parts of the ice sheet in some parts of Antarctica with tidal ranges of six meters," he says. "The ice sheet gets lifted up and then slammed back down on its bed every single day because of the tides. So you've got all the water flowing in from underneath the ice shelves, the floating ice shelves, and then back out again. It's like a bellows effect." When asked about the tidal-pumping mechanism, Gustafson said, "It's certainly possible."

New observations, better models

Now that groundwater has been conclusively observed below the Whillans Ice Stream, the next step will be to incorporate the results into ice-flow models to determine to what extent the ice-sheet velocity is affected by subglacial groundwater. But how much the velocity would be affected by the groundwater is still an open question.

Some ice-sheet modeling on time scales of thousands of years has shown that as an ice sheet thins, the pressure release on the groundwater reservoir reverses the flow of water from a net-downward direction to net upward.⁴ Evidence of overpressure has been observed before as unique seismic-wave signa-

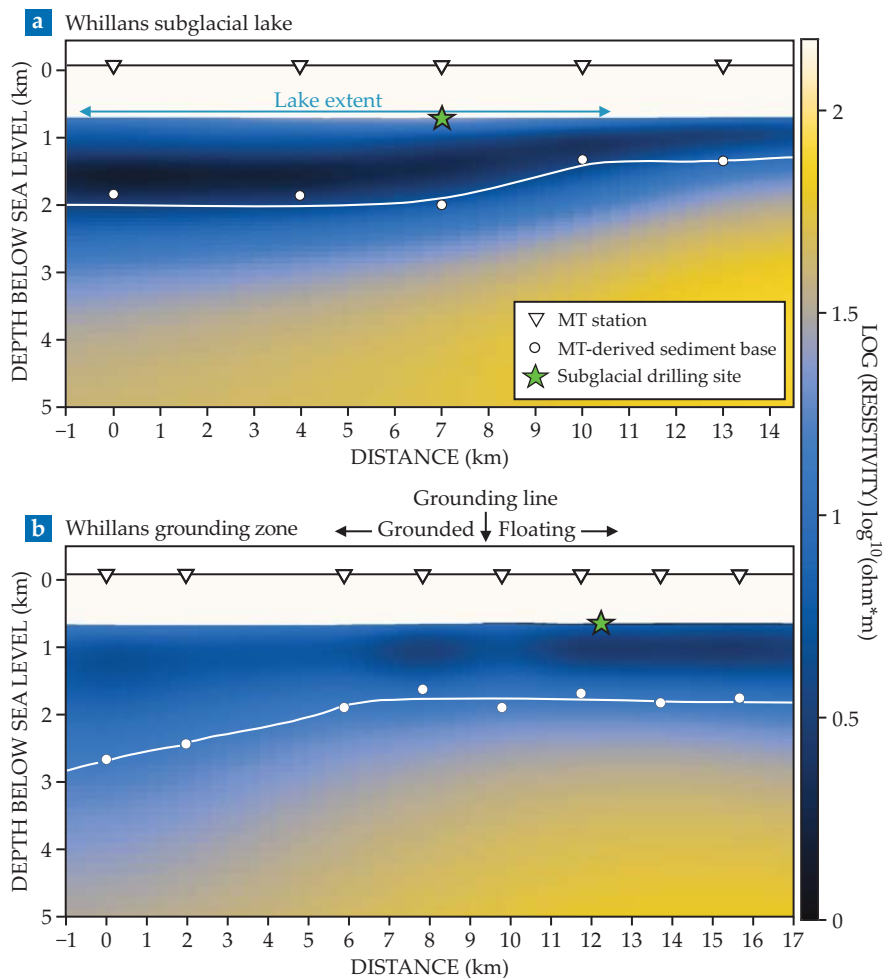


FIGURE 2. RESISTIVITY VARIATIONS measured by magnetotellurics (MT) stations were used to identify subglacial groundwater in West Antarctica. **(a)** The Whillans subglacial lake (dark blue) resides in the porous and permeable sediment beneath the ice (white) and above impermeable bedrock (yellow). The base of the sedimentary basin (white line) was estimated from the newly acquired MT data. **(b)** The downstream Whillans grounding zone contains the grounding line—the boundary between land and ocean. Previous studies that collected drill cores in the region (green stars) only recovered sediment from the top few meters below the ice. (Adapted from ref. 2.)

tures in bedrock off the coast of Martha's Vineyard. The observations likely originate from the retreat of the Laurentide Ice Sheet in North America as early as 2.5 million years ago. Gustafson says, "It can take thousands of years for the sediments to fully readjust to the pressure differential. So that's going to be something interesting to play around with in models of modern Antarctica."

Measurements of subglacial groundwater and their incorporation into ice-flow models will likely address some of the outstanding challenges in climate science (see the article by Tapio Schneider, Nadir Jeevanjee, and Robert Soclow, *PHYSICS TODAY*, June 2021, page 44).

The Whillans and other ice streams make up some 5% of Antarctica's surface area but are responsible for 90% of the ice flow. Tighter controls on the speed of ice streams will improve the estimates of ice mass balance and future loss.

Alex Lopatka

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