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Vostok Subglacial Lake: A Review of Geophysical Data Regarding Its Discovery and Topographic Setting

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Vostok Subglacial Lake is the largest and best known sub-ice lake in Antarctica. The establishment of its water depth (>500 m) led to an appreciation that such environments may be habitats for life and could contain ancient records of ice sheet change, which catalyzed plans for exploration and research. Here we discuss geophysical data used to identify the lake and the likely physical, chemical, and biological processes that occur in it. The lake is more than 250 km long and around 80 km wide in one place. It lies beneath 4.2 to 3.7 km of ice and exists because background levels of geothermal heating are sufficient to warm the ice base to the pressure melting value. Seismic and gravity measurements show the lake has two distinct basins. The Vostok ice core extracted >200 m of ice accreted from the lake to the ice sheet base. Analysis of this ice has given valuable insights into the lake's biological and chemical setting. The inclination of the ice-water interface leads to differential basal melting in the north versus freezing in the south, which excites circulation and potential mixing of the water. The exact nature of circulation depends on hydrochemical properties, which are not known at this stage. The age of the subglacial lake is likely to be as old as the ice sheet (~14 Ma). The age of the water within the lake will be related to the age of the ice melting into it and the level of mixing. Rough estimates put that combined age as ~1 Ma.

1. INTRODUCTION

The concept of liquid water beneath the ice sheets of Antarctica is, to those unfamiliar with glacial processes, somewhat incongruous [*Siegert*, 2005]. The surface air temperatures in central East Antarctica often reach below −60°C, and the coldest official temperature ever recorded on Earth, −89.2°C (−128.6°F), occurred at Vostok Station on 21 July 1983. Yet, a little less than 4 km below the ice

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surface at this Russian base, a huge body of water named Vostok Subglacial Lake exists.

Lakes beneath the Antarctic Ice Sheet were first reported from airborne radio echo sounding (RES) records in the late 1960s and early 1970s [*Robin et al.*, 1970; *Oswald and Robin*, 1973], and Vostok Subglacial Lake was first measured using this technique by *Robin et al.* [1977] on Christmas Eve in 1974. This lake is the largest of >380 known lakes that lay under the East and West Antarctic Ice Sheets [*Wright and Siegert*, this volume].

Temperatures can attain the melting value beneath an ice sheet because of three factors. First, the pressure beneath an ice sheet (i.e., the weight of ice) causes a reduction in the melting point, which beneath 4 km of ice is around −3.2°C. Second, the ice sheet insulates the base from the ultracold temperatures at the surface. Third, heat is transmitted to the base from deep within the lithosphere (geothermal heat). For an ice sheet 4 km thick in central East Antarctica, the heat required to melt basal ice is about 50 mW m^{-2}, which is roughly the background geothermal value [*Siegert and Dowdeswell*, 1996]. Thus, subglacial water, and lakes, can occur beneath the center of a large ice sheet without the need for unusual glacial or geothermal conditions.

Water flow beneath an ice sheet is controlled by the hydraulic potential (a combination of gravity and ice overburden). In simple terms, water may flow "uphill" if the slope of the ice surface exceeds about one tenth of the opposing slope at the ice sheet base. In other cases, subglacial water simply flows downhill. The production and flow of water at the ice sheet bed, through what glaciologists expect to be an organized subglacial drainage network [*Siegert et al.*, 2007], lead to its accumulation within topographic hollows and hence the formation of subglacial lakes.

There has been a huge level of scientific and media interest in Vostok Subglacial Lake (and subglacial lakes in general) following the discovery that the water depth of the lake was more than 500 m [*Kapitsa et al.*, 1996]. Discussion about whether to make in situ measurements of the lake has been driven by two scientific hypotheses. The first is that unique microorganisms inhabit the lake. The second is that a complete record of ice sheet history is available from the sediments that lie across the lake floor. Future exploration of Vostok Subglacial Lake, and other subglacial lakes, will be focused on testing these hypotheses [*Lukin and Bulat*, this volume; *Fricker et al.*, this volume; *Ross et al.*, this volume]. If the hypotheses are correct, future investigations of subglacial lakes could enable valuable insights into the history of Antarctica, detailing its response to and control on climate change, and our understanding of biological functioning within extreme environments.

This chapter presents an overview of geophysical and glaciological investigations of Vostok subglacial lake as an introduction to the lake and the processes taking place within it and other Antarctic subglacial lake environments.

2. DISCOVERY OF VOSTOK SUBGLACIAL LAKE, 1960s–1990s

The history of the discovery of Vostok Subglacial Lake spans 30 years between the 1960s and 1990s, involving scientists and research organizations from the United Kingdom, Russia, mainland Europe, and the United States (see *Zotikov* [2006]). The first person to mention lakes within central Antarctica was R. V. Robinson, the senior navigator of the fourth Soviet Antarctic Expedition, in 1959. *Robinson* [1961] explained, in a recorded radio broadcast from Mirny Station, that navigation of intracontinental flights utilized various ice-surface features, including discrete flat surfaces that appeared as "lakes" with apparent "shorelines." Unwittingly, Robinson may have been reporting the ice-surface manifestation of a subglacial lake several kilometers below. Subglacial lakes, especially large ones, are associated with an extremely flat and smooth ice sheet surface above them. This is because there is effectively zero friction between the ice sheet and the lake. However, a significant amount of friction occurs between ice and bedrock outside the lake margin. Such friction will lead to surface roughness and will be related to a noticeable slope of the ice sheet. Therefore, areas of low basal friction, such as Vostok Subglacial Lake, can be effectively "mapped" through detailed surveying of the ice surface. Of course, Robinson did not know this in 1961, and so no attempt was made to establish a relationship between Vostok Subglacial Lake and the ice-surface geomorphology until the 1990s and the advent of accurate satellite radar altimetry.

Russian and British scientists debated whether water might exist beneath the surface of the Antarctic Ice Sheet, using quite simple thermodynamic considerations [e.g., *Robin*, 1955; *Zotikov*, 1963]. While they predicted that basal water production in central regions of East Antarctica was likely, no specific mention of subglacial lakes was made.

In 1964, a team of Russian scientists, led by Andrei Kapitsa (Moscow State University), performed a seismic experiment on the ice surface over what is now known to be Vostok Subglacial Lake. Seismic data are useful in the examination of subglacial lakes because the compressional sound wave (P wave) will propagate as well through water as ice and reflect off boundaries where there is a significant density contrast. Records of the "two-way travel time" of the first-arrival P wave, multiplied by the velocity of sound waves in the propagating medium, yield the distance traveled. Thus, seismic sounding can provide information on

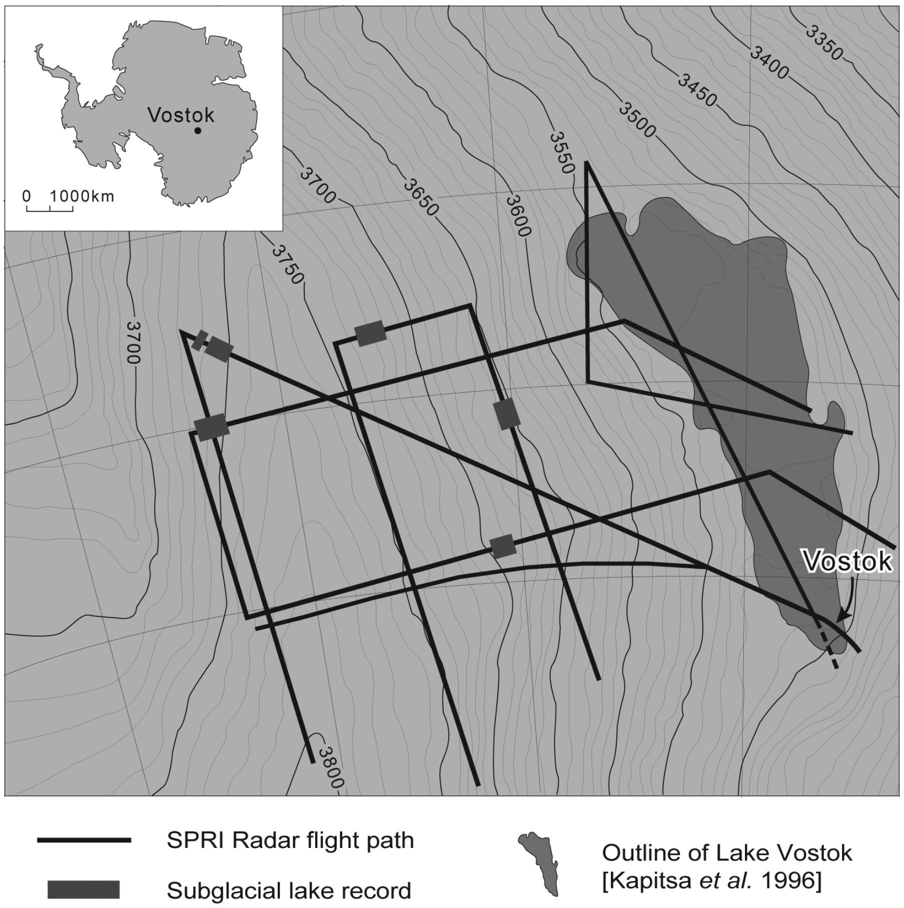


Figure 1. ERS-1 ice sheet surface elevation over, and upstream, of Vostok Subglacial Lake, with 1970s radio echo sounding (RES) transects illustrated, showing evidence of the lake itself, and a series of small lakes in the Ridge B locale.

(1) the ice thickness, (2) the depth of water within the lake, and (3) the thickness of any sediment at the base of the lake. In 1964, Kapitsa's team was interested in recording the thickness of ice and not aware of the lake, so the data collected from the lake itself were not interpreted until much later. After the field work, these seismic data were stored in Dr. Kapitsa's garden shed in Moscow, luckily surviving a fire that subsequently destroyed it. The tightly rolled seismic paper resulted in only the edges of the data being charred, a feature that is clearly visible in the original record.

A problem for using seismic techniques to establish the ice thickness around Antarctica is that the upper ~100 m of the ice sheet consists of snow that is not yet compressed enough to be classified as glacier ice. Sound waves do not travel well through snow, which acts like a sound-proofing blanket, and one has to drill down to at least 40 m into the dense glacier ice, where the seismic explosion and seismometers can be set. Thus, seismic investigations of ice sheets take a long time to perform and are not well suited to surveying at a continental scale.

During the 1970s, a United Kingdom-United States-Danish consortium led by Gordon Robin (Scott Polar Research Institute in Cambridge) performed a systematic airborne radar sounding survey of the ice sheet base. Radar works by the emission of a very high frequency VHF radio wave that is transmitted down into the ice sheet and is reflected off layers of contrasting electrical properties. Such boundaries are found between air and ice at the surface, internal ice sheet layers, and between ice and bedrock or water at the base of the ice sheet. As in seismic sounding, radar can be used to measure the thickness of ice by multiplying the two-way travel time by the velocity of radio waves in ice. By stacking the reflections from individual pulses of VHF radio wave reflections in a time-dependent manner as one traverses across the ice sheet, a pseudo-cross-section can be recorded. Since the equipment is mounted on an aircraft, information about the ice base is recorded along a flight line at a speed of ~300 km h^{-1}. Thus, airborne radar is a very efficient means of surveying the Antarctic ice base.

The radar reflections off a subglacial lake surface are easily distinguishable from those of the ice-bedrock interface [see *Wright and Siegert*, this volume]. Specifically, subglacial lake radar records are characterized by (1) very bright radar returns due to the high reflectivity of radio waves at an ice-water interface, (2) extremely constant reflected radar signal strength over horizontal distances (because the lake surface is very smooth, and therefore, the radio waves are not subject to scattering associated with a rough surface), and (3) a virtually straight and horizontal ice-water interface observed in the radar-derived cross-section. In contrast, ice-bedrock interfaces yield generally weak, variable radar reflections, which are observed in cross section to undulate beneath the ice sheet. Details of a number of small Antarctic subglacial lakes were first reported from analysis of airborne radar in 1973 by Oswald and Robin. Soon after, a large expanse of water was noticed in radar data close to Vostok Station and the existence of Vostok Subglacial Lake discovered [*Robin et al.*, 1977]. Scientific interest in Vostok Subglacial Lake did not follow its discovery, however. In fact, evidence of Vostok Subglacial Lake was lost by many within the glaciological literature for over a decade. For example, the Vostok ice core's depth-age chronology was first modeled assuming the ice rested on the bed, rather than in water; an issue that was corrected only in the late 1990s [*Petit et al.*, 1999].

Accurate mapping of the ice sheet surface through the altimeter of the European Space Agency's ERS-1 was undertaken in the early 1990s. Satellite altimetry provides very accurate measurements of the Earth's surface and is therefore useful for mapping the flat ice sheet regions that occur above subglacial lakes. *Ridley et al.* [1993] were able to use such data to establish the general shape of a very flat region above Vostok Subglacial Lake. The margins of the flat ice-surface corresponded extremely well with the edge of the lake identified from radar measurements. Ridley and other's investigation of satellite altimetry of the ice surface led to a reexamination of Kapitsa's seismic data at Vostok Station, the studying of Robin's radar data across Vostok Subglacial Lake, and, following this, an international conference on Vostok Subglacial Lake to discuss these data sets (held in Cambridge 1994), which in turn led to a seminal publication by *Kapitsa et al.* [1996]. From these investigations, the lake was shown to be 230 km in length, 50 km wide, and about 14,000 km^2 in surface area (Figure 1). Vostok Station was shown to lie over the southern extreme of the lake where the depth of the water is 510 m.

The water within Vostok Subglacial Lake has been shown to be extremely fresh. VHF radio wave penetration through even 10 m of water, as demonstrated by *Gorman and Siegert* [1999] in the shallow northern end of the lake, can be achieved only if the conductivity of the water is unusually low (i.e., very little salt content). Further, the manner in which the ice sheet floats in the lake water is also indicative of a water density consistent with fresh water (1000 kg m^{-3}) compared with salty water (density of sea water is 1025 kg m^{-3}) [*Kapitsa et al.*, 1996]. Small levels of salinity, especially at depth, cannot be ruled out from analysis of the radar data, however.

The age of Vostok Subglacial Lake can be thought about in three ways: the age of the subglacial lake itself, the age of any (preglacial) lake at the same site, and the age of the water within the lake. The age of the subglacial lake is likely to be the same as the age of the ice sheet, which could be as much as 14 million years [*Sugden*, 1992]. It is conceivable that a preglacial lake, occupying the same basin, originates from well before this time. The age of the lake water will be related to the age of the ice that melts into it. The base of the Antarctic ice sheet at Vostok Station is around 700,000 years old [*Petit et al.*, 1997]. Therefore, the age of water within the lake cannot be less than 700,000 years old. The mean age of the lake water will be controlled by how efficient the lake system is at replacing old water with new water. Several processes may occur that are important to this issue. First is the melting rate of basal ice into the lake. Second is the drainage of water out of the lake. Third is the rate of ice freezing to the base of the ice sheet from the lake water. Fourth is the flow of water from upstream regions into the lake. None of these processes, bar the location and degree of basal refreezing, are known with any certainty, however. We are left to estimate the minimum age of the lake, based on the calculated age of the ice sheet base, to be around 1 Ma [*Siegert et al.*, 2001].

3. RECENT GEOPHYSICAL CAMPAIGNS

In recent years, concerted efforts have been made to map the size and extent of Vostok Subglacial Lake. The results (discussed in Section 4) have allowed an enhanced appreciation of the lake's physiography and the physical, biological, and chemical processes that are likely to take place within it.

3.1. Italian Airborne Geophysics Campaign 1999–2000

In response to the enhanced scientific interest in Vostok Subglacial Lake generated by the discovery of its water depth [*Kapitsa et al.*, 1996], Italian geophysicists undertook the first radar sounding measurements of the lake and its surrounding since the Scott Polar Research Institute RES measurements in the 1970s [*Tabacco et al.*, 2002]. In the Austral summer of 1999–2000, 12 new RES transects were

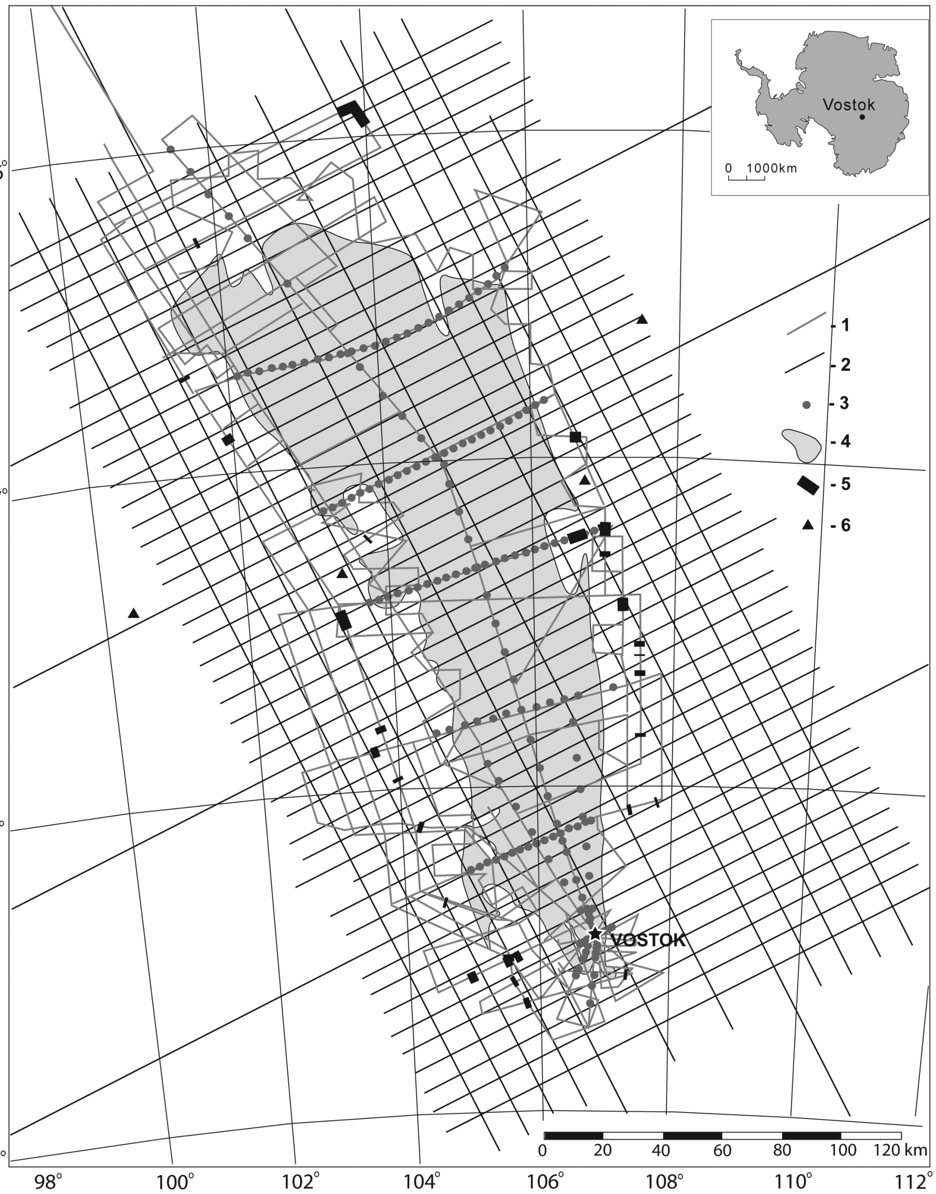


Figure 2. Location of geophysical investigations. The legend is coded as follows: 1, Russian RES profiles; 2, US RES flights; 3, Russian reflection seismic shots; 4, outline of the lake, based on Russian RES data; 5, subglacial lakes as given by *Siegert et al.* [2005]; 6, subglacial lakes as given by *Popov and Masolov* [2007].

collected over the lake, including one continuous flight across the long axis of the lake. The data were used to confirm the findings of *Kapitsa et al.* [1996] and to better define the aerial extent of the lake.

3.2. US Airborne Geophysics Campaign, 2000–2001

In order to further understand the physiographic setting, geological framework, and ice dynamics of the Vostok Subglacial Lake area, scientists from the U.S. Antarctic Program carried out an aerogeophysical survey during the 2000–2001 Antarctic summer (Figure 2). The survey was designed to simultaneously acquire laser altimeter, ice-penetrating radar, gravity, and magnetic data and was complemented by ground geophysical measurements of ice-surface velocities and seismic monitoring. More than 20,000 line-km of aerogeophysical data were acquired by the U.S. National Science Foundation's Support Office for Aerogeophysical Research during the 2000–2001 season with an instrumented De Havilland DHC-6 Twin Otter aircraft [*Studinger et al.*, 2003a; *Richter et al.*, 2001; *Holt et al.*, 2006]. The main grid covered an area of 157.5 × 330 km and was augmented by 12 regional lines, extending outside of the main grid between 180 and 440 km.

3.3. Russian Over-Snow-Based Geophysical Investigations, 1995–2008

Russian researchers began systematic investigation of Vostok Subglacial Lake almost immediately after its outline had been discovered [*Ridley et al.*, 1993]. During the 1995/1996 field season, the Polar Marine Geosurvey Expedition began to study the Vostok Subglacial Lake area by conducting reflection seismic sounding within the framework and under the auspices of the Russian Antarctic Expedition. Since 1998, this work has continued together with ground-based RES [*Masolov et al.*, 2001, 2006]. In 2008, an important stage of the Russian investigations was completed; seismic and radio echo studies aimed at mapping the lake bottom and its environment were finished. The resulting data set (Figure 2) was used to determine an appreciation of the bedrock landscape in the Vostok Subglacial Lake area. In total, 318 seismic reflection soundings were carried out, and 5190 km of RES were acquired.

4. GEOPHYSICS RESULTS

4.1. Ice-Penetrating Radar

The ice thickness above Vostok Subglacial Lake has been determined with unprecedented accuracy by combining radar data in the two major recent surveys (565,735 and 710,448 radar data points from the Russian and U.S. programs, respectively; Plate 1). By integrating information on ice thickness with that of surface elevation, an enhanced map of the bed elevation was also established. The result of this data amalgamation is the most complete depiction of the surface of Vostok Subglacial Lake and the surrounding topography, to date.

The extent of the lake is 15,500 km^2 (excluding 70 km^2 of "islands"), and the elevation of the lake surface varies between 800 m below sea level (bsl) in the south and 200 m bsl in the north. The coastline of the lake is 1030 km long and is complicated by numerous bays and peninsulas. Importantly, two islands were found in the south-western part of the lake. One is situated in 8 km south-westward from Vostok Station. Its size is about 15 × 3 km. The other one is situated 48 km away from the station and is about 11 × 4 km. The latter island deserves special attention as it is located directly on the ice flow line, which passes through borehole 5G-1. One explanation for the mineral inclusions found in the lower levels of the core is that they were captured by the glacier as it flowed over the island [*Jouzel et al.*, 1999] (see also Section 5.4).

Over the lake, the ice is thicker in the north (up to 4300 m) and thins to about 3700 m in the south. The 600 m change in thickness of the floating ice is associated with a 60 m change in ice-surface topography. On the southwestern shore of Vostok Subglacial Lake, a 10 km wide and 30 km long region with thicker ice and strong bright reflectors indicative of subglacial water has been identified as an embayment separated from the main lake by a narrow bedrock ridge.

The ice flowing into Vostok Subglacial Lake from Ridge B in the west (Figure 1) is characterized by large thickness variations along the western shoreline. In the north between 77°S and 76.5°S, the flank of the bounding topography is at an average elevation of around 200 m bsl, 500 m above the lake surface at 700 m bsl. In the south between 78°S and 77.5°S, a steep shoulder on the western side with average elevations around 400 m above sea level rests almost 1000 m above the lake surface at 550 m bsl.

The differences in surrounding topography and lake surface elevation result in variations to the thickness of ice flowing onto Vostok Subglacial Lake. This dominates the melting and freezing pattern within the lake. Melting occurs in regions with thicker ice, while accretion dominates in regions with thinner ice [*Tikku et al.*, 2004]. The thicker ice in the north enters the lake through a depression in the subglacial topography, while the thinner ice in the south flows over a region with elevated topography. The bounding topography on the eastern side is generally much steeper than on the western side. The eastern side forms a straight shoreline in contrast to the rugged western shoreline. The subglacial topography on the west is very rugged with large differences in elevation over short distances compared with the relatively smooth topography east of the lake. This change in roughness in the topography reflects a change in subglacial geology [*Studinger et al.*, 2003b]. The continuity of the eastern shoreline as a straight segment over more than 200 km indicates that the bounding topography is fault controlled.

4.2. Gravity

The free-air gravity anomaly reflects both the major geologic and topographic structures and changes in the water depth of Vostok Subglacial Lake. A pronounced north-south trending gradient dominates the free-air gravity field (Plate 2a). This gradient parallels the eastern shore of Vostok Subglacial Lake. The steep gradient separates an area of positive

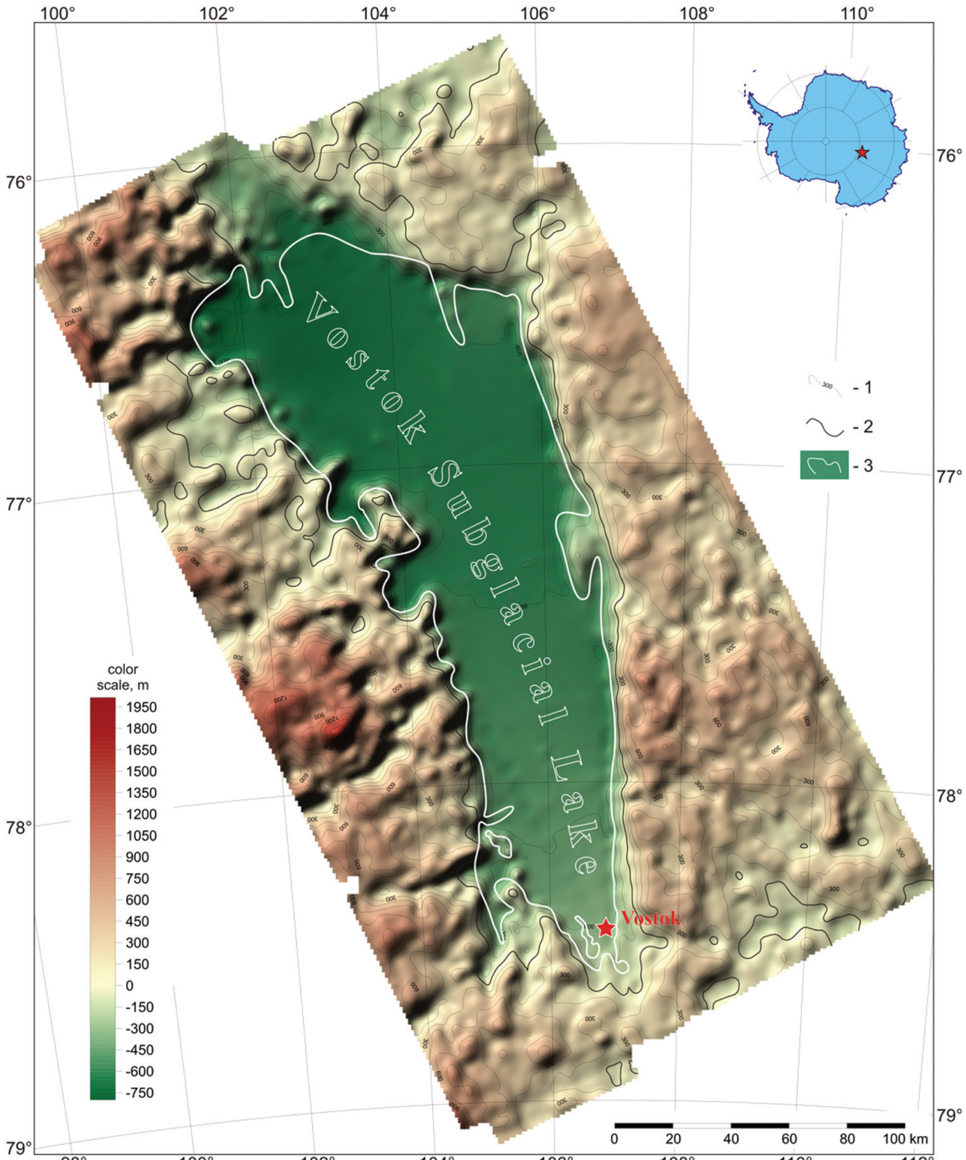


Plate 1. Detailed map of the lake surface and surrounding topography from a combination of Russian and U.S. geophysical data. The legend is coded as follows: 1, ice base, contours in meters; 2, sea level (WGS-84 surface); 3, outline of the lake, based on Russian RES data.

free-air anomalies (up to 50 mGal) in the east from negative values (less than −120 mGal) over the lake. A gravity low in the northern part of the lake (−90 mGal) is separated by a saddle (−70 mGal) from the main gravity low over the southern part of the lake (−120 mGal). West of the lake, the free-air gravity field comprises positive anomalies ranging from −40 to +20 mGal. To remove the gravitational effect of the ice-bedrock density contrast, a complete Bouguer anomaly has been calculated using the ice surface and subglacial topography grids. East of the lake, the amplitudes reach −170 to −140 mGal, while west of the lake, the Bouguer gravity shows amplitudes around −200 mGal in the north and −220 mGal in the south. This step in Bouguer gravity over a short distance of less than 100 km reflects a significant change in crustal structure east and west of the lake that has been interpreted as a thrust sheet emplacement onto an earlier passive continental margin [*Studinger et al.*, 2003b]. Minor normal reactivation of the thrust sheet offers a simple

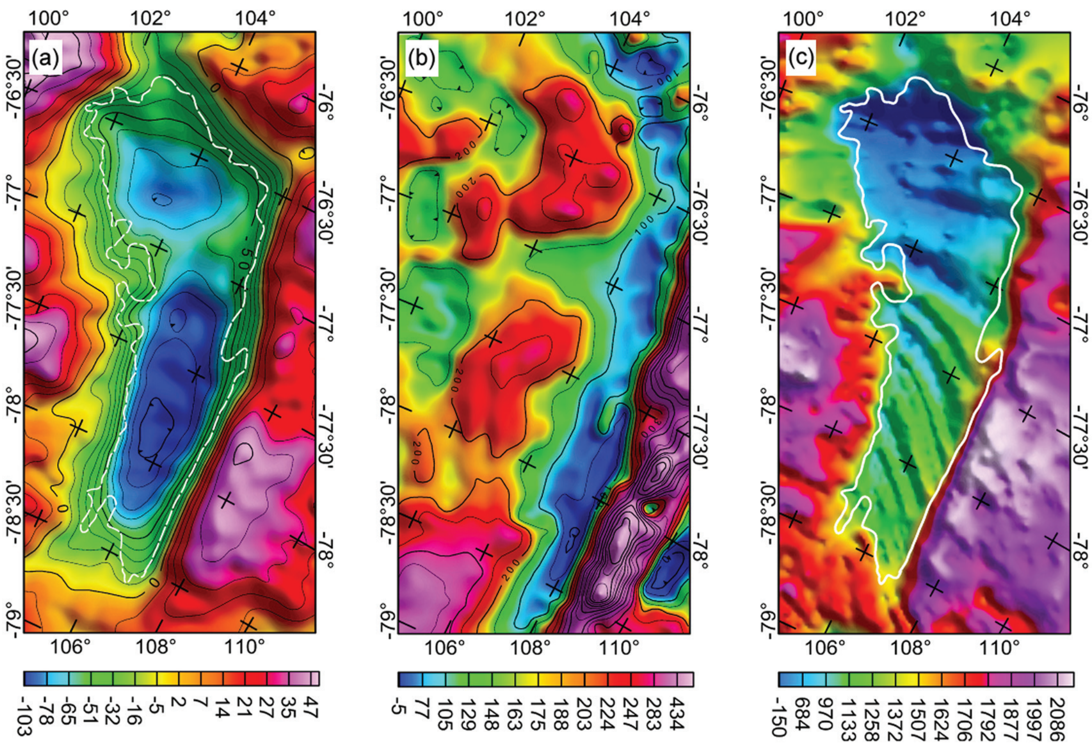


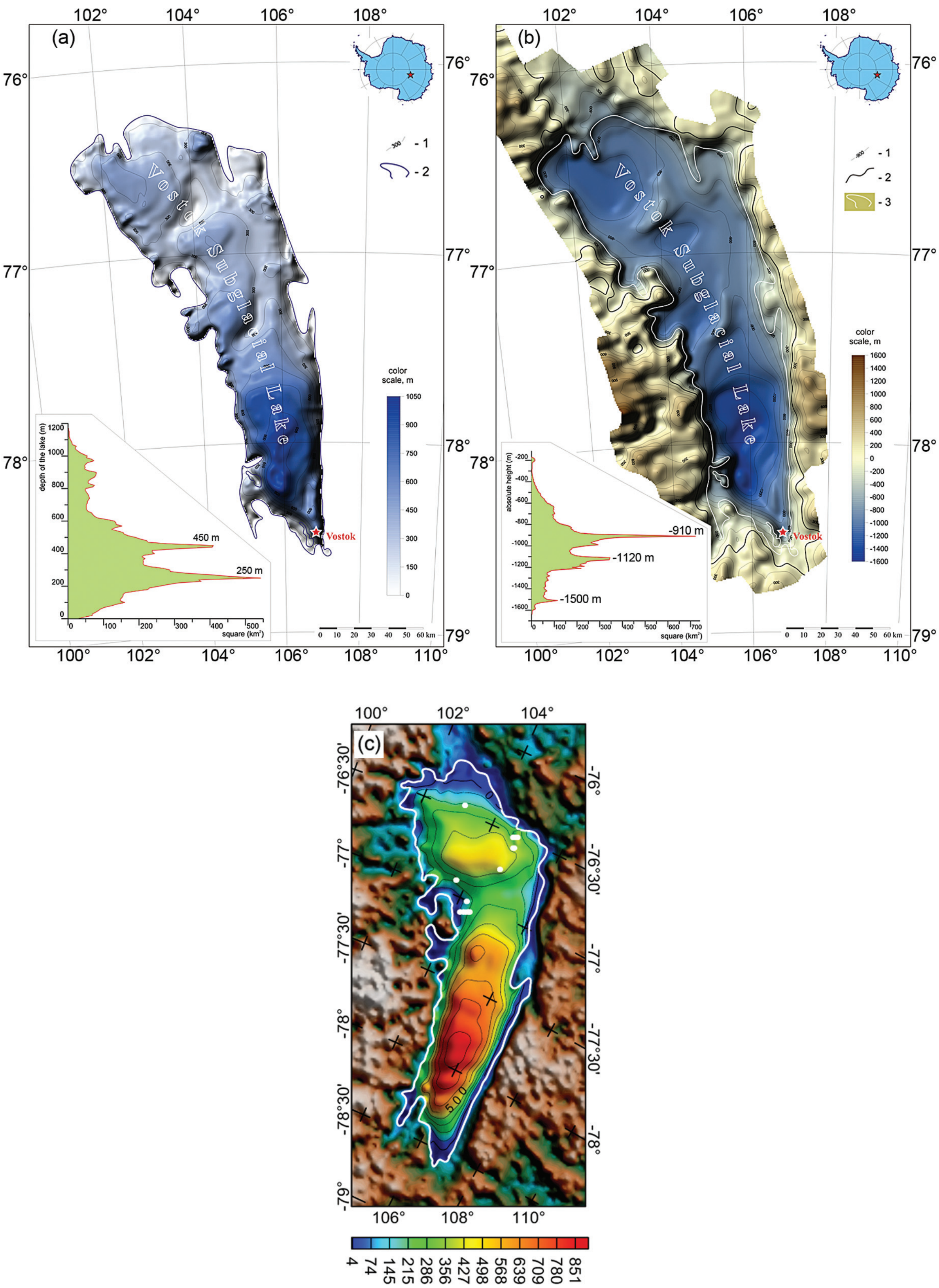
Plate 2. Gravity and magnetic fields, and internal layer structures, over Vostok Subglacial Lake. (a) Free-air gravity in mGal. Contour interval is 5 mGal (thin lines) and 10 mGal (thick, annotated lines). The data have been reduced from the flight elevation down to sea level (free-air correction), and the predicted gravity for the latitude on the Geodetic Reference System 1980 ellipsoid has been subtracted. (b) Total field magnetic anomaly (nT) in 3960 m elevation. Contour interval is 100 nT (thick, annotated lines) and 50 nT. (c) Depth of an internal layer in meters above sea level.

mechanism to explain the formation of the Vostok Subglacial Lake basin.

4.3. Magnetics

The magnetic anomaly map and the regional lines show a wide variety of characteristic wavelengths and amplitudes indicating changes in subglacial geology (Plate 2b). In the main grid, a pronounced north-south striking 900 nT anomaly dominates the magnetic field in the southeastern portion. This linear anomaly is about 30 km wide and can be traced outside the main grid on the two southern and four eastern regional lines. This anomaly is bounded on its western side by a linear low that follows closely the positive magnetic anomaly up to 76.5°S. North of 76.5°S, the trend of the magnetic low is oriented more to the west. The pair of linear highs and lows parallels the eastern shore line of Vostok Subglacial Lake. West of this structure, the magnetic field is very smooth and comprises long-wavelength anomalies on the order of 50 to 70 km and up to 350 nT with almost entirely positive amplitudes. The distinct change in magnetic character over Vostok Subglacial Lake from a short-wavelength, high-amplitude field in the east to a long-wavelength smooth field over the lake and the west is related to a change in subglacial geology and is not an artifact of the change in subglacial elevation. The long-wavelength anomalies in the western part of the grid reflect sources located between 10 km depth and the Curie Point isotherm, while the high-amplitude, short-wavelength anomalies in the eastern part are likely to be dominated by near-surface sources.

Plate 3. (opposite) Water depth of Vostok Subglacial Lake. (a) Water depth from seismic studies. The legend is coded as follows: 1, isobaths in meters; 2, outline of the lake, based on Russian RES data. (b) Bathymetry of Vostok Subglacial Lake. Hypsographic curves are depicted in the inserts. The legend is as follows: 1, bedrock contours in meters; 2, sea level (WGS-84 surface); 3, outline of the lake, based on Russian RES data. (c) Water depth of the cavity in meters determined from inversion of aerogravity data. White regions mark locations where grounding is observed in the ice-penetrating radar data.


(a)
Vostok Subglacial Lake
- 1
- 2
color scale, m
Vostok
depth of the lake (m)
450 m
250 m
square (km²)
(b)
Vostok Subglacial Lake
- 1
- 2
- 3
color scale, m
Vostok
absolute height (m)
-910 m
-1120 m
-1500 m
square (km²)
(c)
4 74 145 215 286 356 427 498 568 639 709 780 851

4.4. Flow Field Derived From Internal Structures

The complex topography along the upstream shoreline is preserved in the deep internal layers as the ice sheet traverses the lake. Topographic peaks are preserved as ridges in the internal layers, and topographic depressions are preserved as troughs (Plate 2c). As ice flows over a topographic peak along the shoreline, the silhouette of this peak is preserved as vaults in the topography of the lake surface because the lee side of such obstacles is filled with accreted lake ice, which prevents ice flowing from the sides of the peak to fill this cavity [*Tikku et al.*, 2004]. These structures are resolved in three distinct internal layers at depths between 900 and 3750 m. The flow field derived by structure tracking for Vostok Subglacial Lake displays a large but gradual rotation in the flow direction, from W-E in the northern end to NNW-SSE in the southern end (Plate 2c). The observed rotation is consistent with the general divergence associated with the ice divide over the lake. Accretion ice, lake water frozen to the bottom of the ice sheet, is preferentially imaged along flow lines emanating from topographic ridges [*Tikku et al.*, 2004]. The coincidence of the accretion ice reflector with the flow lines both provides independent support for the flow field and suggests focused accretion along the western shoreline. It also testifies that the flow of ice over the lake has remained largely unchanged for ~20,000 years (the approximate time taken for ice to cross the lake).

4.5. Bathymetry

As mentioned in section 2, the principal problem with reflection seismics in the interior of Antarctica concerns the thick snow-firn layer where acoustic wave attenuation occurs. During the 1995–1997 period, a new technique, using five to six 75 m lines of a detonating cord as a simple alternative to drilling a shot hole, was developed that ensured both efficiency and reliable data acquisition [*Popkov et al.*, 1998].

The seismic data reveal the average depth of Vostok Subglacial Lake to be about 410 m, and the volume of the water body is about 6350 km^3 (Plate 3a). Plate 3b shows the bathymetry is divided into two different-sized basins. The first (southern) part is the deepest (around 800 m). The second (northern) part is relatively shallow (at around 300 m) [*Masolov et al.,*, 2008].

While seismic information provides accurate measurements of the lake water depth, the results across the entire lake area remain subject to interpolations between data-free zones. The broad lake water depth can, however, be established well by inverting the dense aerogravity data [*Studinger et al.*, 2004]. The free-air gravity anomaly field reflects density variations related to both major geological and topographic structures including changes in the lake water depth. The influence of the regional subglacial topography and the geometry of the overlying ice sheet is well constrained from ice-penetrating radar measurements and can be removed from the observed gravity anomaly. The unknown parameter that dominates the remaining gravity anomaly is the lake water depth.

The estimated bathymetry of the gravity inversion is consistent with the seismic results; Vostok Subglacial Lake consists of two sub-basins (Plate 3c). The southern sub-basin is much deeper and approximately twice the spatial area of the smaller northern sub-basin. The two sub-basins are separated by a ridge with very shallow (~200 m) water depths.

The distribution of melting and freezing at the base of the ice sheet appears to be intimately linked to the two-basin structure. The regions with basal melting and freezing have been estimated from thickness changes between internal layers along ice flow. The same pattern is visible in characteristic signatures in the ice-penetrating radar data. The thin layer of accreted ice at the base of the ice sheet is imaged as a weak reflector in the radar data [*Bell et al.*, 2002; *Tikku et al.*, 2004]. Regions of melting correlate with a fuzziness of the ice-water interface in the radar data. Over the northern basin, basal melting is dominant, while over the southern basin, basal freezing characterizes the lake/ice interaction. The intimate link between the regions of melting and freezing and the bathymetric structure of the lake has important ramifications for the water circulation. If the lake water is fresh, basal meltwater in the northern basin would sink to the bottom (section 5.4) [*Siegert et al.*, 2001], and water exchange between the two basins will be limited. The two separate basins may, therefore, have different chemical and biological compositions. Furthermore, sediments released by basal melting are likely to accumulate in the northern basin, while preglacial sediments are more likely to be found in the southern, deeper basin. The sampling strategy for the future recovery of sediments from the lake bottom depends on the type of sediments targeted.

5. PHYSICAL PROCESSES IN THE LAKE

Having established Vostok Subglacial Lake's broad physiographical setting, we are now able to consider the likely chemical and physical processes within the lake. Vostok Subglacial Lake has two obvious advantages for evaluating such processes. First, it is a very large subglacial lake. Because of this, large-scale processes within it are likely to be more obvious and identifiable than in small subglacial lakes. For example, there have been several models of water circulation within Vostok Subglacial Lake, and these have been developed from large-scale ocean models, which have a resolution of the order of kilometers. Second, by chance, the Vostok ice core is located above the southern end of Vostok Subglacial Lake, and this contains at its base some ice that is refrozen from the lake water.

5.1. Details of Accretion Ice Acquisition

Several deep ice cores have been extracted from the ice sheet at Vostok Station (at the southern end of Vostok Subglacial Lake) since drilling began in the mid-1960s (the first 500 m deep dry borehole was extracted in 1965), providing important information about the climate during the last glacial cycle. The most recent and deepest (3623 m) ice core terminated ~130 m from the base of the ice sheet [*Masolov et al.*, 2001]. The upper 3310 m of the ice core provides a detailed paleoclimate record spanning the past 420,000 years [*Petit et al.*, 1997, 1999]. In addition, microbiological analysis of the ice core has revealed a range of microbiota, including bacteria, fungi, and algae, some of which have been reported to be culturable in the laboratory [*Abyzov et al.*, 1998; *Priscu et al.*, 1999; *Karl et al.*, 1999].

Typical glacier ice contains a record of gases and isotopes from which paleoclimate information is inferred. In the Vostok ice core, this type of ice exists to a depth of 3310 m. Lower layers of ice, between depths of 3310 and 3538 m, are reported to have been reworked, making the extraction of paleoclimate information difficult to establish. The basal 84 m of the ice core, from 3539 to 3623 m, has a chemistry and crystallography that are distinctly different from the "normal" glacier ice above. The basal ice has an extremely low conductivity, huge (up to 1 m) crystal sizes, and sediment-particle inclusions (in the upper half) [*Jouzel et al.*, 1999]. The mineral composition of ice-bound sediments below 3539 m is dominated by micas and is clearly different than typical crustal composition and particles within the overlying glacial ice [*Priscu et al.*, 1999]. Its isotopic composition, distinct from the "meteoric" ice above, suggests that it formed by the refreezing of lake water to the underside of the ice sheet. Thus, there is ~210 m of accreted Vostok Subglacial Lake ice beneath Vostok Station [*Jouzel et al.*, 1999].

5.2. Microbiology

The accreted ice offered the first opportunity for aquatic biologists and geochemists to investigate material derived from a subglacial lake. Two recent independent studies of accreted ice subsampled from different depths (3590 and 3603 m) near the base of the Vostok ice core (maximum depth, 3623 m) have shown that these samples contain both low numbers and low diversity of bacteria [*Karl et al.*, 1999; *Priscu et al.*, 1999]. The low diversity (seven phylotypes) may reflect the small sample size analyzed (~250 mL of melt) and should be considered as a lower limit. Low concentrations of "growth nutrients" and evidence of mineralization of ^{14}C-labeled organic substrates were also found, although activity was measured under potentially more benign laboratory conditions of +3°C and 1 atm pressure [*Karl et al.*, 1999]. Since the accreted ice has been frozen from Vostok Subglacial Lake water, the inference is that these microbes were present in the lake water, at some point, and viable prior to freezing. *Priscu et al.* [1999], using ice-water partitioning coefficients from the permanently ice-covered lakes in the McMurdo Dry Valleys, estimated that the bacterial density within Vostok Subglacial Lake's water column could be on the order of 10^6 mL^{-1}. Microbiological analyses from the Vostok accreted ice are discussed in more detail by *Skidmore* [this volume].

5.3. Geochemistry

Solutes are added to the lake water during ice melt and via chemical weathering of debris in and around the base of the lake. The average chemistry of the meltwater entering Vostok Subglacial Lake can be inferred from *Legrand et al.* [1988], assuming that ice from glacial periods makes up 85% of the melt and that from interglacials makes up 15%. The average initial meltwater is equivalent to a very dilute mix of marine-derived aerosol, Ca-rich dust, and strong acids (i.e., HNO_3 and H_2SO_4). Solutes are rejected from the ice lattice during refreezing [*Killawee et al.*, 1998]; hence, there should be an accumulation of nutrients, gases, and solutes in the lake water over time. The isotopic and major ion composition of Vostok Subglacial Lake has been inferred from the composition of the accreted basal ice in the Vostok ice core. The accreted ice is enriched in ^{18}O and ^{2}H compared to the Vostok precipitation line [*Jouzel et al.*, 1999; *Priscu et al.*, 1999]. This is because there is isotopic fractionation during water freezing, but none during melting [*Souchez et al.*, 1988, 2000]. The accreted ice has values of δ^{18}O and δD that differ from the time-averaged melting ice by only 60% of the theoretical fractionation, and it has been suggested that 30% to 58% of unfractionated lake water is entrained in the accreted ice during freezing, so helping to maintain less extreme values of δD and δ^{18}O [*Souchez et al.*, 2000].

Royston-Bishop et al. [2004] inspected the δD and δ^{18}O data to explore whether Vostok Subglacial Lake is in isotopic steady state. A simple box model showed that the lake is likely to be in steady state on timescales on the order of 10^4 to 10^5 years (three to four residence times of the water in the lake), given our current knowledge of north-south and east-

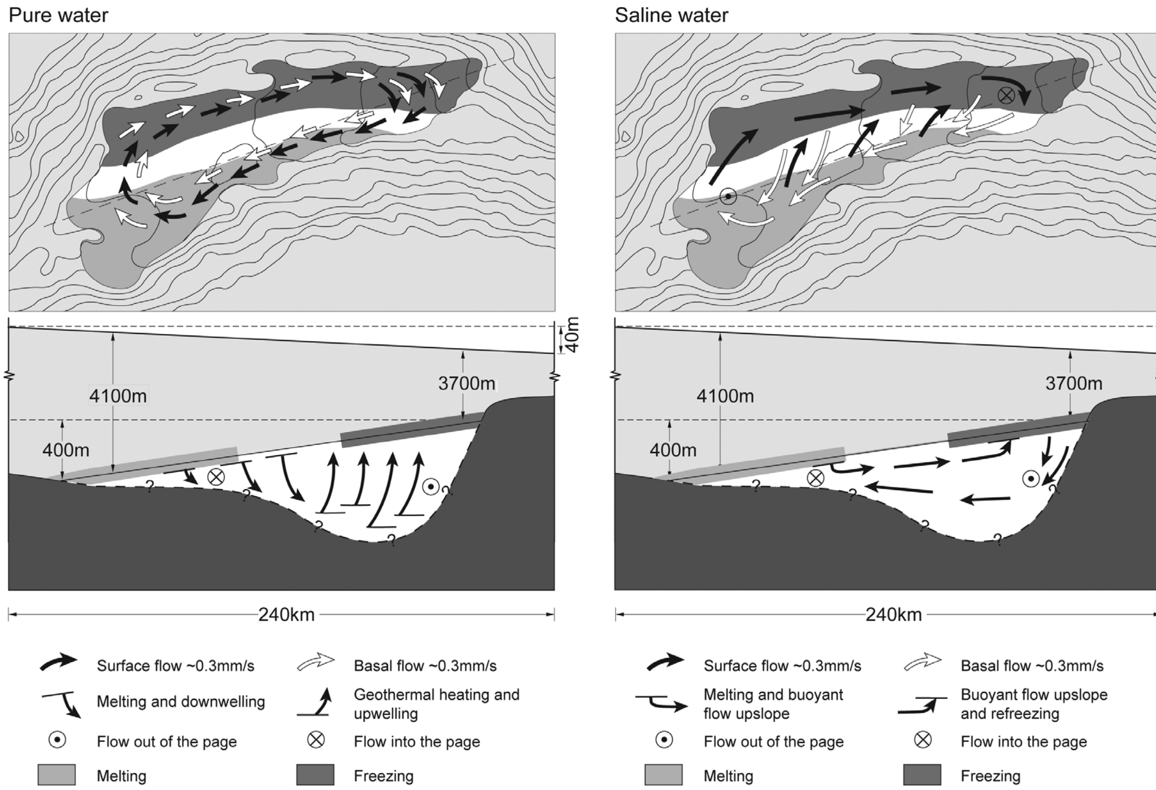


Figure 3. Water circulation within Vostok Subglacial Lake. (a) Circulation assuming that the water is pure. The white arrows show the bottom water circulation, and the black arrows denote the higher level circulation close to the ice base. Dots refer to upwelling of lake water; crosses denote downwelling. Dark gray shading refers to predicted zones of subglacial freezing; light gray shading indicates subglacial melting. (b) Circulation of Vostok Subglacial Lake thought to occur as a result of saline conditions (i.e., 1.2‰–0.4‰). Adapted from *Siegert et al.* [2001].

west gradients in the stable isotopic composition of precipitation in the vicinity of Vostok Station and Ridge B (where the deepest ice originates from the surface). This suggests that the lake has not been subject to any recent major perturbations, such as volume changes. However, they also showed that the lake may not be in perfect steady state, depending on the precise location of the melting area, which determines the source region of inflowing ice, and on the magnitude of the east-west gradient in isotopic compositions in the vicinity of Vostok Station and Ridge B.

5.4. Water Circulation and Water Balance

Borehole temperature measurements along the full length of the Vostok ice core have been used to establish the energy balance between the ice sheet and the lake [*Salamatin et al.*, 1998; *Salamatin*, 2000]. The mean basal temperature gradient is ~0.02°C m^{-1}, which relates to a heat flux through the ice from the lake ceiling of 46 mW m^{-2}, indicating that the rates of subglacial freezing above Vostok Subglacial Lake are most likely to be ~4 mm yr^{-1} [*Salamatin et al.*, 1998]. In the extreme case where ice at −10°C flows over the western lake margin, rates of melting and freezing beneath Vostok Station will probably not be higher than about 11 mm yr^{-1} [*Salamatin*, 2000].

The spatial distribution of subglacial melting and freezing can be estimated theoretically from isochronous internal radar layering, by observing the loss or gain of basal ice along a flow line. Using this technique, it has been shown that subglacial melting occurs in the north of Vostok Subglacial Lake [*Siegert et al.*, 2000], and freezing (accretion) takes place in the south [*Bell et al.*, 2002]. Rates of melting and freezing calculated from radar layering have been much higher (of the order of centimeters) than those from the ice core's temperature record. It is possible that heat used for melting can be taken from the lake water, but this requires a dynamic water circulation system.

The zones of subglacial melting in the north and freezing in the south of Vostok Subglacial Lake are thought to be controlled by the slope of the ice-water interface, since the thickness of ice dictates the pressure melting temperature and the density of meltwater. Melting and freezing induce circulation in the lake, which itself will be influenced heavily by the lake hydrochemistry.

There are two possible ways in which water within Vostok Subglacial Lake could circulate (Figure 3). One is if the lake contains pure water; the other is if the lake water is slightly saline. These two end-member possibilities are detailed below. In the first instance, circulation of pure water is discussed.

Since the surface of Vostok Subglacial Lake is inclined, the pressure melting point in the south will be slightly (~0.3°C) less than that in the north. The circulation of pure (nonsaline) water in Vostok Subglacial Lake will be driven by the differences between the density of meltwater and lake water. Geothermal heating will warm the bottom water to a temperature higher than that of the upper layers. The water density will decrease with increasing temperature because Vostok Subglacial Lake is in a high-pressure environment, resulting in an unstable water column [*Wüest and Carmack*, 2000]. This leads to convective circulation conditions in the lake in which cold meltwater sinks down the water column and water warmed by geothermal heat ascends up the water column. However, a pool of slightly warmer and stratified water may occur below the ice roof in the south, where the ice sheet is thinner and subglacial freezing takes place [*Wüest and Carmack*, 2000]. Here, the water would not be involved in convective motion as heat is transferred from the ice toward the lake (i.e., the temperature will decrease with depth). There have been four models from which the circulation of pure water in Vostok Subglacial Lake can be evaluated [*Mayer et al.*, 2003; *Wüest and Carmack*, 2000; *Williams*, 2001; *Thoma et al.*, 2010]. The models indicate that meltwater will be colder and denser in the northern area of Vostok Subglacial Lake, where the ice is thickest, than both the surrounding lake water and meltwater in areas with thinner ice cover. It appears therefore that this region is the main zone of downwelling of pure water. However, the circulation is complicated by the geometry of the lake cavity and the Coriolis force. This means that circulation in Vostok Subglacial Lake will include horizontal transfer and vertical overturning. The models agree that northern meltwater will sink and be transported horizontally to the south, via a clockwise circulation system, to a region where the pressure melting point is higher, allowing refreezing to occur.

An alternate point of view is that the lake is saline to a small extent [*Souchez et al.*, 2000]. The fresh glacier meltwater will, therefore, be buoyant compared with the resident, more saline lake water. The northern meltwater likely spreads southward and upward, traveling into regions of progressively lower pressure and displacing lake water in the south if the horizontal salinity gradient (north-south) is high enough to compensate for geothermal warming. The possibility of such a regime is controlled by (1) the melting-freezing rates, (2) the rates of mixing between the fresh ascending meltwater layer and the underlying saline water, and (3) vertical free convection driven by the geothermal heating of water at the lake bottom. The cold northern water will eventually enter a region where its temperature is at, or below, the pressure melting point, if the heat flux from the basal water is not sufficiently high. The water will then refreeze back onto the ice sheet base some distance away from where it was first melted into the lake. In this case, a conveyor of fresh cool meltwater is established, which migrates from north to south immediately beneath the ice sheet, which causes displacement of warmer dense lake water from south to north. In contrast, if the bulk salinity is not high enough, a stable stratification will develop in the upper water layers below the tilted lake ceiling, with more saline warmer water in the south and fresher, cooler water in the north [*Wüest and Carmack*, 2000]. The deep-water stratum will be subject to vertical thermal convection because, for any reasonable level of salinity, the temperature at the lake bottom will be high enough to start the convection.

Royston-Bishop et al. [2005] studied the size-frequency distribution of the microscopic particulates in accreted ice from the Vostok ice core. They demonstrated that the particles have similar distributions of major axis lengths, surface areas and shape factors (aspect ratio and compactness) irrespective of ice core depth, suggesting a common single process is responsible for their incorporation in the ice. In addition, *Royston-Bishop et al.* [2005] calculated Stokes settling velocities for particulates of various sizes and showed that 98% could float to the ice-water interface with upward water velocities of only 0.0003 m s^{-1}. This is well within the range of water flow speeds predicted by circulation models of Vostok Subglacial Lake [*Mayer et al.*, 2003]. The presence of larger particles in the ice (2%) and the uneven distribution of observed particulates in the core suggest that periodic perturbations to the lake's circulation, involving increased velocities, may have occurred in the past and are likely now.

Early models of water circulation in Vostok Subglacial Lake have been mostly conceptual in nature owing to a lack of observation to constrain the models. The models aimed at understanding the basic physics of water circulation and interaction between the lake water and the overlying ice sheet. The definition of the lake cavity and distribution of melting and freezing from geophysical soundings have enabled the next generation of numerical models with realistic constraints on bathymetry, melting and freezing rates, and other critical parameters. These models are coupled ice sheet and water circulation models and attempt to realistically predict not only the water circulation in the lake, but also the pattern of melting and freezing, the rates of melting and freezing, and the interaction between ice flow and water circulation in the lake (see *Thoma et al.* [2010], and references therein).

6. SUMMARY

Vostok Subglacial Lake is the largest of more than 380 subglacial lakes in Antarctica, being more than 240 km in length and 80 km wide. While its discovery, through airborne RES in the 1970s, was forgotten by many for more than a decade, scientific interest was suddenly generated following the discovery, in 1996, of its water depth being more than 500 m. This led microbiologists to hypothesize that Vostok Subglacial Lake is a viable habitat for life and that such life may have developed in isolation from the rest of the planet for as much as 14 million years [see *Skidmore*, this volume]. This hypothesis received widespread media and public interest, as well as further interest from scientists aiming to undertake the geophysical and, ultimately, direct exploration.

The first stage in the process of exploration was to conduct a comprehensive survey of the lake, given that the data collected in the 1970s comprised a mere handful of radio echo transects. The first airborne geophysical reconnaissance of Vostok Subglacial Lake since the 1970s was undertaken by the Italian Antarctic Research Programme. Several RES lines were flown, revealing the limits of the lake shoreline and enhanced definition of the lake surface.

In the Austral summer of 2000–2001, U.S. geophysicists acquired more than 20,000 line-km of data. Radio echo sounding revealed detailed information about the lake surface and its surrounding topography. These data were also used to show that large-scale melting occurs in the north of the lake and to reconfirm that freezing takes place in the south, resulting in more than 200 m of ice accreted to the underside of the ice sheet (as discovered in the ice core extraction of accreted ice a year or two earlier). Magnetic data revealed important information regarding the tectonic structure in which the lake lies, and gravity data were used to model the bathymetry of the lake, showing it to comprise two discrete basins.

The distinction between northern melting and southern freezing leads to circulation of the lake water, in a manner dependent on the salinity of the water. For pure water, the circulation behaves as in the very deep ocean, with cold water descending and rising up the column after heating from geothermal sources. For slightly saline water, melted ice will be lighter than the lake water and so will rise up the inclined ice-water interface. Both cases can account for the large-scale freezing that takes place in the south, as cold water will be transferred from north to south regardless of salinity. There has been much speculation about the hydrochemistry of Vostok Subglacial Lake. Clearly, direct access and sampling of the lake water will resolve this speculation.

While airborne geophysical data are essential for defining the ice sheet above the lake and its surface characteristics, its bathymetry can be measured only by ground-based seismic measurements. Russian scientists have been collecting such data since the mid-1990s. These data were used in conjunction with the U.S. bathymetry data to first reveal, and later to better define, the bathymetry of the lake. In addition, Russian geophysicists have acquired more than 5000 km of radio echo data of the ice sheet and lake surface. In combination with U.S. data, we now have an excellent understanding of Vostok Subglacial Lake's physiographical setting and of the physical processes operating within it.

As a consequence of the geophysical data collected to date, the direct measurement and sampling of Vostok Subglacial Lake can now be contemplated.

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REFERENCES

Abyzov, S. S., I. N. Mitskevich, and M. N. Poglazova (1998), Microflora of the deep glacier horizons of central Antarctica, *Microbiology*, *67*, 66–73.

Bell, R. E., M. Studinger, A. A. Tikku, G. K. C. Clarke, M. M. Gutner, and C. Meertens (2002), Origin and fate of Lake Vostok water frozen to the base of the East Antarctic ice sheet, *Nature*, *416*, 307–310.

Fricker, H. A., et al. (2011), Siple Coast subglacial aquatic environments: The Whillans Ice Stream Subglacial Access Research Drilling project, in *Antarctic Subglacial AquaticEnvironments*, *Geophys. Monogr. Ser.*, doi: 10.1029/2010GM000932, this volume.

Gorman, M. R., and M. J. Siegert (1999), Penetration of Antarctic subglacial water masses by VHF electromagnetic pulses: Estimates of minimum water depth and conductivity of basal water bodies, *J. Geophys. Res.*, *104*(B12), 29,311–29,320, doi:10.1029/1999JB900271.

Holt, J. W., et al. (2006), Airborne gravity over Lake Vostok and adjacent highlands of East Antarctica, *Geochem. Geophys. Geosyst.*, *7*, Q11012, doi:10.1029/2005GC001177.

Jouzel, J., J. R. Petit, R. Souchez, N. I. Barkov, V. Y. Lipenkov, D. Raynaud, M. Stievenard, N. I. Vassiliev, V. Verbeke, and F.

Vimeux (1999), More than 200 meters of lake ice above subglacial Lake Vostok, Antarctica, *Science*, *286*, 2138–2141.

Kapitsa, A. P., J. K. Ridley, G. D. Robin, M. J. Siegert, and I. Zotikov (1996), A large deep freshwater lake beneath the ice of central East Antarctica, *Nature*, *381*, 684–686.

Karl, D. M., D. F. Bird, K. Bjorkman, T. Houlihan, R. Shackelford, and L. Tupas (1999), Microorganisms in the accreted ice of Lake Vostok, Antarctica, *Science*, *286*, 2144–2147.

Killawee, J. A., I. J. Fairchild, J.-L. Tison, L. Janssens, and R. Lorrain (1998), Segregation of solutes and gases in experimental freezing of dilute solutions: Implications for natural glacial systems, *Geochim. Cosmochim. Acta*, *62*, 3637–3655.

Legrand, M. R., C. Lorius, N. I. Barkov, and V. N. Petrov (1988), Vostok (Antarctica) ice core: atmospheric chemistry changes over the last climatic cycle (160,000 years), *Atmos. Environ.*, *22*, 317–331.

Lukin, V., and S. Bulat (2011), Vostok Subglacial Lake: Details of Russian plans/activities for drilling and sampling, in *Antarctic Subglacial Aquatic Environments*, *Geophys. Monogr. Ser.*, doi: 10.1029/2010GM000951, this volume.

Masolov, V. N., V. V. Lukin, A. N. Sheremetyev, and S. V. Popov (2001), Geophysical investigations of the subglacial Lake Vostok in Eastern Antarctica (in Russian), *Dokl. Akad. Nauk*, *379* (5), 680–685. (*Dokl. Earth Sci.*, *379A*(6), 734–738.)

Masolov, V. N., S. V. Popov, V. V. Lukin, A. N. Sheremet'ev, and A. M. Popkov (2006), Russian geophysical studies of Lake Vostok, Central East Antarctica, in *Antarctica—Contributions to Global Earth Sciences*, edited by D. K. Fütterer et al., pp. 135–140, Springer, New York.

Masolov, V. N., V. V. Lukin, S. V. Popov, A. M. Popkov, A. N. Sheremetyev, U. A. Kruglova (2008), Seabed relief of the subglacial lake Vostok, in *Abstract Volume, SCAR/IASC IPY Open Science Conference "Polar Research—Arctic and Antarctic perspectives in the International Polar Year", St. Petersburg, Russia, July 8–11, 2008*, edited by A. Klepikov, S3.1/P08.

Mayer, C., K. Grosfeld, and M. J. Siegert (2003), Salinity impact on water flow and lake ice in Lake Vostok, Antarctica, *Geophys. Res. Lett.*, *30*(14), 1767, doi:10.1029/2003GL017380.

Oswald, G. K. A., and G. D. Robin (1973), Lakes beneath the Antarctic Ice Sheet, *Nature*, *245*, 251–254.

Petit, J. R., et al. (1997), Four climate cycles in Vostok ice core, *Nature*, *387*, 359–360.

Petit, J. R., et al. (1999), Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica, *Nature*, *399*, 429–436.

Popkov, A. M., G. A. Kudryavtsev, V. A. Shumilov, and N. V. Kondratiev (1998), Methodological features of seismic studies in the region of the Russian station "Vostok" in Lake Vostok Study: Scientific Objectives and Technological Requirements, paper presented at International Workshop, Arct. and Antarct. Res. Inst., St. Petersburg, Russia, 24–26 March.

Popov, S. V., and V. N. Masolov (2007), Forty-seven new subglacial lakes in the 0°–110°E sector of East Antarctica, *J. Glaciol.*, *53*(181), 289–297.

Priscu, J. C., et al. (1999), Geomicrobiology of subglacial ice above Lake Vostok, Antarctica, *Science*, *286*, 2141–2144.

Richter, T. G., et al. (2001), Airborne Gravimetry over the Antarctic Ice Sheet, in *International Symposium on Kinematic Systems in Geodesy, Geomatics and Navigation*, edited by M. E. Cannon and G. Lachapelle, pp. 576–585, Univ. of Calgary, Calgary, Alberta, Canada.

Ridley, J. K., W. Cudlip, and S. W. Laxon (1993), Identification of subglacial lakes using ERS-1 radar altimeter, *J. Glaciol.*, *39*, 625–634.

Robin, G. D. (1955), Ice movement and temperature distribution in glaciers and ice sheets, *J. Glaciol.*, *3*, 589–606.

Robin, G. D., C. W. M. Swithinbank, B. M. E. Smith (1970), Radio echo exploration of the Antarctic ice sheet, in *International Symposium on Antarctic Glaciological Exploration (ISAGE)*, *IAHS Publ.*, *86*, 97–115.

Robin, G. D., D. J. Drewry, and D. T. Meldrum (1977), International studies of ice sheet and bedrock, *Philos. Trans. R. Soc. London, Ser. B*, *279*, 185–196.

Robinson, R. V. (1961), Experiment in visual orientation during flights in the Antarctic, *Sov. Antarct. Exped. Inf. Bull.*, *18*, 28–29.

Ross, N., et al. (2011), Ellsworth Subglacial Lake, West Antarctica: Its history, recent field campaigns, and plans for its exploration, in *Antarctic Subglacial Aquatic Environments*, *Geophys. Monogr. Ser.*, doi: 10.1029/2010GM000936, this volume.

Royston-Bishop, G., M. Tranter, M. J. Siegert, V. Lee, and P. Bates (2004), Is Lake Vostok in chemical and physical steady-state?, *Ann. Glaciol.*, *39*, 490–494.

Royston-Bishop, G., J. C. Priscu, M. Tranter, B. Christner, M. J. Siegert, and V. Lee (2005), Incorporation of particulates into accreted ice above subglacial Lake Vostok, Antarctica, *Ann. Glaciol.*, *40*, 145–150.

Salamatin, A. N. (Ed.) (2000), *Physics of Ice Core Records*, edited by T. Hondoh, pp. 243–282, Hokkaido Univ. Press, Sapporo, Japan.

Salamatin, A. N., V. Y. Lipenkov, N. I. Barkov, J. Jouzel, J. R. Petit, and D. Raynaud (1998), Ice core age dating and paleothermometer calibration based on isotope and temperature profiles from deep boreholes at Vostok Station (East Antarctica), *J. Geophys. Res.*, *103*(D8), 8963–8977, doi:10.1029/97JD02253.

Siegert, M. J. (2005), Lakes beneath the ice sheet: The occurrence, analysis and future exploration of Lake Vostok and other Antarctic subglacial lakes, *Annu. Rev. Earth Planet. Sci.*, *33*, 215–245.

Siegert, M. J., and J. A. Dowdeswell (1996), Spatial variations in heat at the base of the Antarctic Ice Sheet from analysis of the thermal regime above sub-glacial lakes, *J. Glaciol.*, *42*, 501–509.

Siegert, M. J., R. Kwok, C. Mayer, and B. Hubbard (2000), Water exchange between the subglacial Lake Vostok and the overlying ice sheet, *Nature*, *403*, 643–646.

Siegert, M. J., et al. (2001), Physical, chemical and biological processes in Lake Vostok and other Antarctic subglacial lakes, *Nature*, *414*(6864), 603–609.

Siegert, M. J., S. Carter, I. Tabacco, S. Popov, and D. Blankenship (2005), A revised inventory of Antarctic subglacial lakes, *Antarct. Sci.*, *17*(3), 453–460.

Siegert, M. J., A. Le Brocq, and A. Payne (2007), Hydrological connections between Antarctic subglacial lakes and the flow of water beneath the East Antarctic Ice Sheet, in *Glacial Sedimentary Processes and Products*, edited by M. J. Hambrey et al., *Spec. Publ. Int. Assoc. Sedimentol.*, *39*, 3–10.

Skidmore, M. (2011), Microbial communities in Antarctic subglacial aquatic environments, in *Antarctic Subglacial Aquatic Environments*, *Geophys. Monogr. Ser.*, doi: 10.1029/2010GM000995, this volume.

Souchez, R., R. Lorrain, J. L. Tison, and J. Jouzel (1988), Co-isotopic signature of two mechanisms of basal ice formation in Arctic outlet glaciers, *Ann. Glaciol.*, *10*, 163–166.

Souchez, R., J. R. Petit, J. L. Tison, J. Jouzel, and V. Verbeke (2000), Ice formation in subglacial Lake Vostok, central Antarctica, *Earth Planet. Sci. Lett.*, *181*, 529–538.

Studinger, M., et al. (2003a), Ice cover, landscape setting, and geological framework of Lake Vostok, East Antarctica, *Earth Planet. Sci. Lett.*, *205*(3–4), 195–210.

Studinger, M. (2003b), Geophysical models for the tectonic framework of the Lake Vostok region, East Antarctica, *Earth Planet. Sci. Lett.*, *216*(4), 663–677.

Studinger, M., R. E. Bell, and A. A. Tikku (2004), Estimating the depth and shape of subglacial Lake Vostok's water cavity from aerogravity data, *Geophys. Res. Lett.*, *31*, L12401, doi:10.1029/2004GL019801.

Sugden, D. E. (1992), Antarctic ice sheets at risk?, *Nature*, *359*, 775–776.

Tabacco, I. E., C. Bianchi, A. Zirizzotti, E. Zuccheretti, A. Forieri, and A. Della Vedova (2002), Airborne radar survey above Vostok region, east Antarctica: Ice thickness and Lake Vostok geometry, *J. Glaciol.*, *48*, 62–69.

Thoma, M., K. Grosfeld, C. Mayer, and F. Pattyn (2010), Interaction between ice sheet dynamics and subglacial lake circulation: A coupled modelling approach, *Cryosphere*, *4*, 1–12.

Tikku, A. A., et al. (2004), Ice flow field over Lake Vostok, East Antarctica inferred by structure tracking, *Earth Planet. Sci. Lett.*, *227*(3–4), 249–261.

Williams, M. J. M. (2001), Application of a three-dimensional numerical model to Lake Vostok: An Antarctic subglacial lake, *Geophys. Res. Lett.*, *28*, 531–534.

Wright, A., and M. J. Siegert (2011), The identification and physiographical setting of Antarctic subglacial lakes: An update based on recent discoveries, in *Antarctic Subglacial Aquatic Environments*, *Geophys. Monogr. Ser.*, doi: 10.1029/2010GM000933, this volume.

Wüest, A., and E. Carmack (2000), A priori estimates of mixing and circulation in the hard-to-reach water body of Lake Vostok, *Ocean Modell.*, *2*, 29–43.

Zotikov, I. A. (1963), Bottom melting in the central zone of the ice shield of the Antarctic continent and its influence upon the present balance of the ice mass, *Bull. Int. Assoc. Sci. Hydrol.*, *8*(1), 36.

Zotikov, I. A. (2006), *The Antarctic Subglacial Lake Vostok: Glaciology, Biology and Planetology*, 139 pp., Springer-Praxis, Chichester, U. K.

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