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LAKES BENEATH THE ICE SHEET: The Occurrence, Analysis, and Future Exploration of Lake Vostok and Other Antarctic Subglacial Lakes

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Key Words Antarctica, subglacial environments, exploration

■ **Abstract** Airborne geophysics has been used to identify more than 100 lakes beneath the ice sheets of Antarctica. The largest, Lake Vostok, is more than 250 km in length and 1 km deep. Subglacial lakes occur because the ice base is kept warm by geothermal heating, and generated meltwater collects in topographic hollows. For lake water to be in equilibrium with the ice sheet, its roof must slope ten times more than the ice sheet surface. This slope causes differential temperatures and melting/freezing rates across the lake ceiling, which excites water circulation. The exploration of subglacial lakes has two goals: to find and understand the life that may inhabit these unique environments and to measure the climate records that occur in sediments on lake floors. The technological developments required for in situ measurements mean, however, that direct studies of subglacial lakes may take several years to happen.

1. INTRODUCTION AND BACKGROUND

1.1. Conditions Beneath the Ice Sheet

The concept of liquid water beneath the ice sheets of Antarctica is, to those unfamiliar with glacial processes, somewhat incongruous. 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 the Russian Vostok Station on July 21, 1983. Yet, a little less than 4 km below the ice surface at Vostok Station, at the ice sheet base, a huge body of water named Lake Vostok exists. This lake is the largest (by an order of magnitude) of more than 100 known lakes that lay under the East and West Antarctic ice sheets. 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 temperature at which ice melts. Beneath 4 km of ice, this value is approximately −3°C. Second, the ice sheet insulates the base from the ultra cold temperatures at the surface. Third, heat is generated at the ice sheet base from the Earth (geothermal heat) and

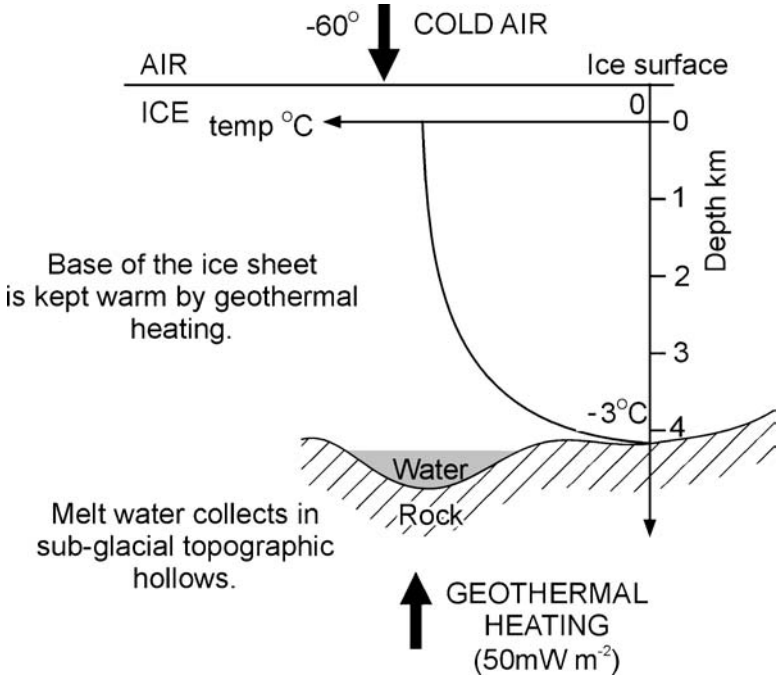

Figure 1 Ice sheet thermal conditions and the maintenance of warm subglacial conditions in East Antarctica owing to geothermal heating.

the ice sheet itself (friction heat owing to the deformation of ice and basal sliding). For an ice sheet 4 km thick, the heat required to melt basal ice is approximately 50 mW m^{-2}, which is the background geothermal value (Figure 1). Thus, subglacial water, and lakes, can occur beneath the center of a large ice sheet without the need for unusual geothermal conditions.

Water flow beneath an ice sheet is controlled by the water pressure gradient (a combination of gravity and ice overburden). In simple terms, water may flow uphill if the slope of the ice surface exceeds approximately 1/10 of the ice sheet base. In other cases, subglacial water flows downhill. The production and flow of water at the ice sheet bed lead to its accumulation within topographic hollows and, hence, the formation of subglacial lakes.

1.2. Identification of Subglacial Lakes

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 & Robin 1973). The technique of RES works through the issuing of VHF radio waves into the ice sheet, which reflect of boundaries of dielectric contrast (Figure 2). Such boundaries occur at the ice surface, within the ice sheet (internal

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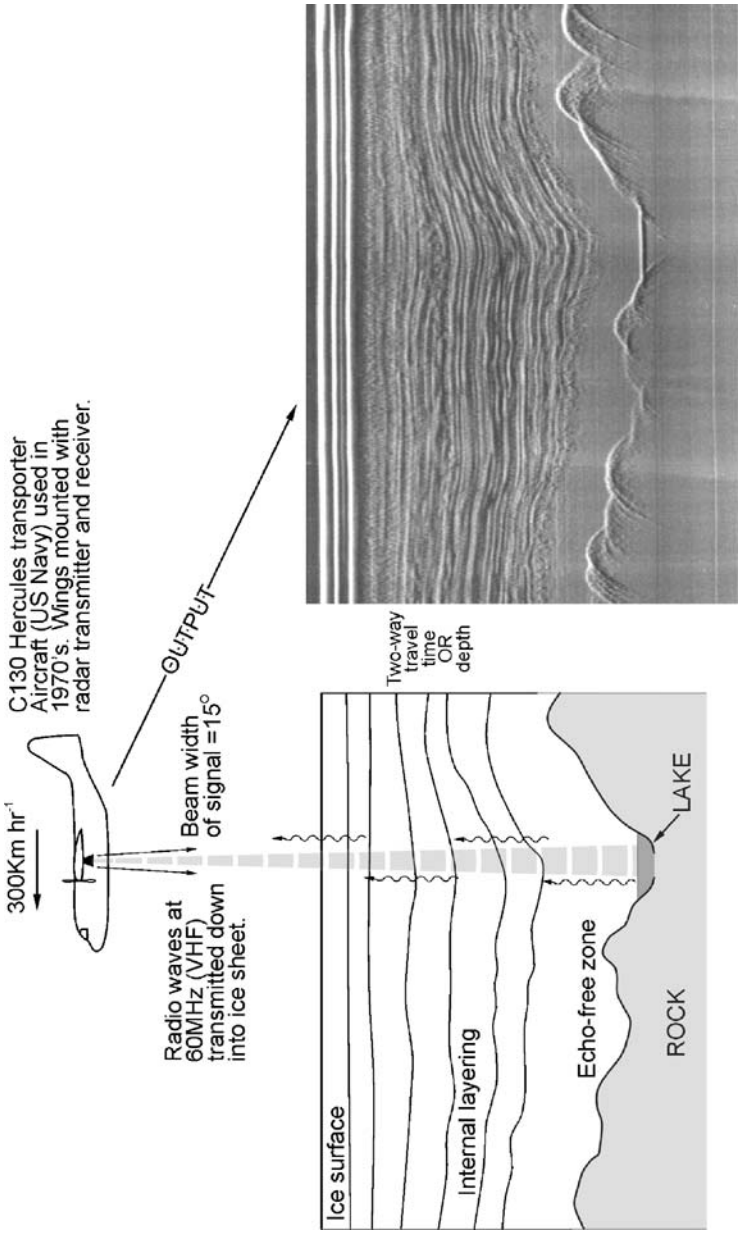

Figure 2 The technique of airborne radar sounding, and its application to identifying Lake Vostok and other subglacial lakes. In the 1970s, airborne radar surveys were undertaken with a C130 Hercules transporter aircraft, with the wings mounted with the radar transmitter and receiver. Aircraft navigation was accurate to approximately 5 km in the center of Antarctica. Today, most radar surveys use smaller aircraft and GPS to navigate. Subglacial lakes are easily identified on airborne radar records owing to their uniformly strong and flat appearance. Bedrock perturbations are recorded as hyperbolae in radar data.

layering), and from the ice sheet base. Airborne RES at 60 MHz is often used to penetrate to the base of ice more than 4 km thick in Antarctica (e.g., Robin et al. 1977, Drewry 1983, Morse et al. 2002, Studinger et al. 2003a). This is possible because ice is relatively transparent to radio waves at this frequency (Johari & Charette 1975), especially when it is several tens of degrees below freezing, as is the case for most of the Antarctic Ice Sheet. The strength of reflection from the bed depends to a first order on the difference between the dielectric properties of the ice (dielectric constant $\varepsilon = 3.2$) and the dielectric properties of the subice material. As the dielectric constant of water ($\varepsilon = 81$) is very different from typical bedrock ($\varepsilon = 4$ to 9), a much stronger reflection is obtained from an ice-water interface compared with an ice-rock interface. This difference is increased by the relatively rough character of an ice-bedrock interface, which scatters energy and further reduces echo strength. This makes RES an ideal technique for identifying water bodies beneath ice sheets. Subglacial lakes are identified on 60 MHz RES records by the presence of the following characteristics (Figure 3): (*a*) strong reflections from the ice sheet base, which appear bright on film records and are typically 10–20 dB stronger than adjacent ice-bedrock reflections; (*b*) echoes of constant strength along the track, indicative of an interface that is very smooth on the scale of the RES wavelength; and (*c*) a very flat and virtually horizontal character, with maximum slopes typically approximately -10 times the surface slope.

More than 100 lakes have now been identified beneath several regions of the Antarctic Ice Sheet (Siegert et al. 1996, 2005; Tabacco et al. 2003; Popov & Masolov 2004). Lakes range in size from less than a kilometer in length to Lake Vostok (the best known of the lakes), which is the largest by an order of magnitude (Kapitsa et al. 1996) (Figure 4, see color insert).

Figure 3 60 MHz RES data for 11 Antarctic subglacial lakes and their surrounding ice sheet bed topography. (*a*) Two lakes in the Dome C area (#33 and #34). The mean ice thickness above these lakes is ~4000 m. (*b*) Lake in the Ridge B area (#46). The mean ice thickness above the lake is ~3700 m. (*c*) Lake at Titan Dome near the South Pole (#52). The mean ice thickness above the lake is ~3070 m. (*d*) Lake in the Whitmore Mountains area (#68). The mean ice thickness above the lake is ~2900 m. (*e*) Two lakes in the Hercules Dome area (#72 and #73). The mean ice thickness above these lakes is 3200 m (#72, right-hand side of the image) and 2800 m (#73, left-hand side of the image). (*f*) Lake Vostok, East of Ridge B. The mean thickness at this part of the lake is ~4000 m. (*g*) Lake at the mouth of the Astrolabe Subglacial Basin (#30). The mean ice thickness above this lake is 4000 m. (*h*) Lake at the head of the Byrd Glacier (#61). The mean ice thickness above this lake is 2580 m. (*i*) Lake beneath the center of the West Antarctic Ice Sheet (#67). The mean ice thickness above this lake is 3200 m. (*a*)–(*f*) are adapted from Dowdeswell & Siegert (2002), (*g*)–(*i*) are from Siegert (2002). Lakes are located by a white letter "L" in each RES image. Numbers of subglacial lakes are as defined in Siegert et al. (1996).

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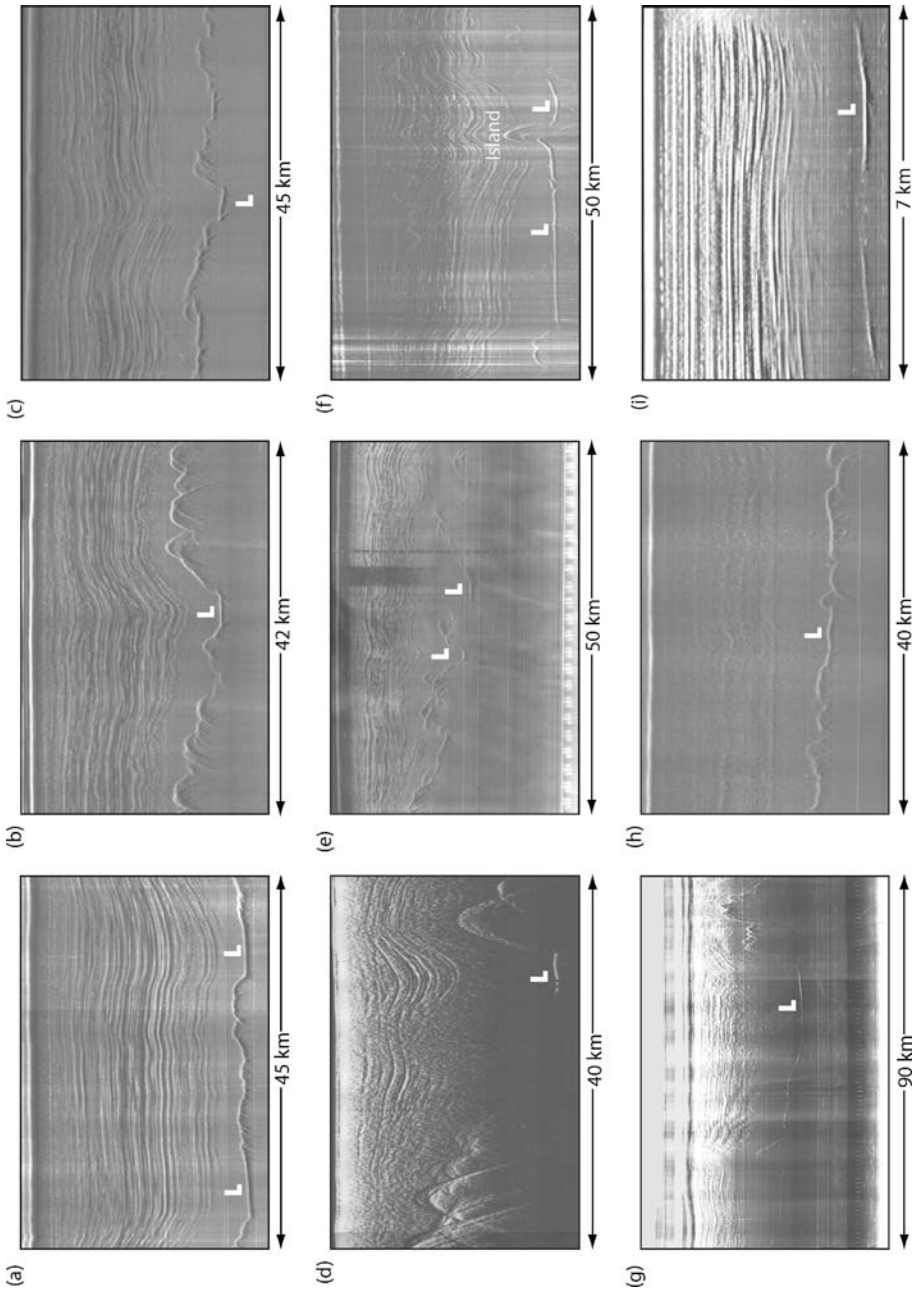

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1.3. Scientific Interest in Subglacial Lakes

There has been a huge degree of scientific and media interest in Lake Vostok (and subglacial lakes in general) following the discovery that the water depth of the lake was several hundred meters (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 subglacial lakes will be focused on testing these hypotheses. 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.

2. PHYSIOGRAPHY OF ANTARCTIC SUBGLACIAL LAKES

2.1. Locations of Subglacial Lakes

In general terms, there are two places beneath the Antarctic Ice Sheet where melting occurs. The first is beneath the center of the ice sheet, where ice is generally thickest and the ice sheet is warm-based across large regions. The second is closer to the ice sheet margin beneath warmed-based, enhanced ice flow units. Dowdeswell & Siegert (2002) identified 10 areas of Antarctica where subglacial lake-type reflectors occur: Dome C (where more than 40 lakes have been identified); Ridge B (including Lake Vostok), Dome A (where only two lakes have been found), Titan Dome, South Pole, Hercules Dome, the Whitmore Mountains, the Transantarctic Mountains (near Byrd Glacier), Oates Land, and George V Land (including a lake at the mouth of the Astrolabe Subglacial Basin). More recently, Tabacco et al. (2003) have identified a further 14 lakes across the Dome C region, and Popov & Masolov (2004) have found evidence of 16 lakes around the Dome A and Dome F regions (Figure 4).

2.2. Lake Surface Areas

Approximately 75% of lakes have observed lengths of less than 5 km. Only Lake Vostok is longer than 30 km. Lake Vostok is more than 250 km long and as much as 80 km wide, making it unique in terms of surface area (Tabacco et al. 2002, Studinger et al. 2003a). Around Dome C, Siegert & Ridley (1998) found that a number of lakes thought to be relatively small lay beneath a noticeably large flat ice surface. As is the case for Lake Vostok, Siegert & Ridley (1998) hypothesized that the spatial extent of these flat surface features mark the actual extent of the lakes beneath, which makes the size of the lakes much greater than had been first thought. New RES data from Dome C confirms that relatively large lakes (three of which are $\sim$1000 km^3 by area) exist between Dome C and Lake Vostok (Tabacco et al. 2002, Tikku et al. 2002).

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2.3. Lake Depths and Water Volumes

Only Lake Vostok has been sounded by seismic methods, which reveal a depth of between 510 m (Kapitsa et al. 1996) and ~1000 m (Siegert et al. 2001). Water depths for a number of other lakes have been inferred, however, from measurements of the surrounding bedrock topography. These measurements suggest that the depths of many lakes are between approximately 50 and 250 m (Dowdeswell & Siegert 1999). Indeed, several lakes may be much greater than this, judging by the side-wall slopes. According to Dowdeswell & Siegert (1999), more than 50% of the lakes are likely to contain less than 5 km^3 of water, and only 10% store more than approximately 100 km^3. Lake Vostok, by contrast, is thought to hold approximately 5000 km^3 of water (Studinger et al. 2004). Thus, Lake Vostok is unique in terms of its volume, but this may reflect the fact that it is large by surface area, rather than unusually deep compared with other subglacial lakes in Antarctica.

Recent inspection of aerogravity data collected over Lake Vostok reveals that its bathymetry may involve two discrete basins: a large southern basin and a smaller northern basin separated by a thin shallow zone (Studinger et al. 2004).

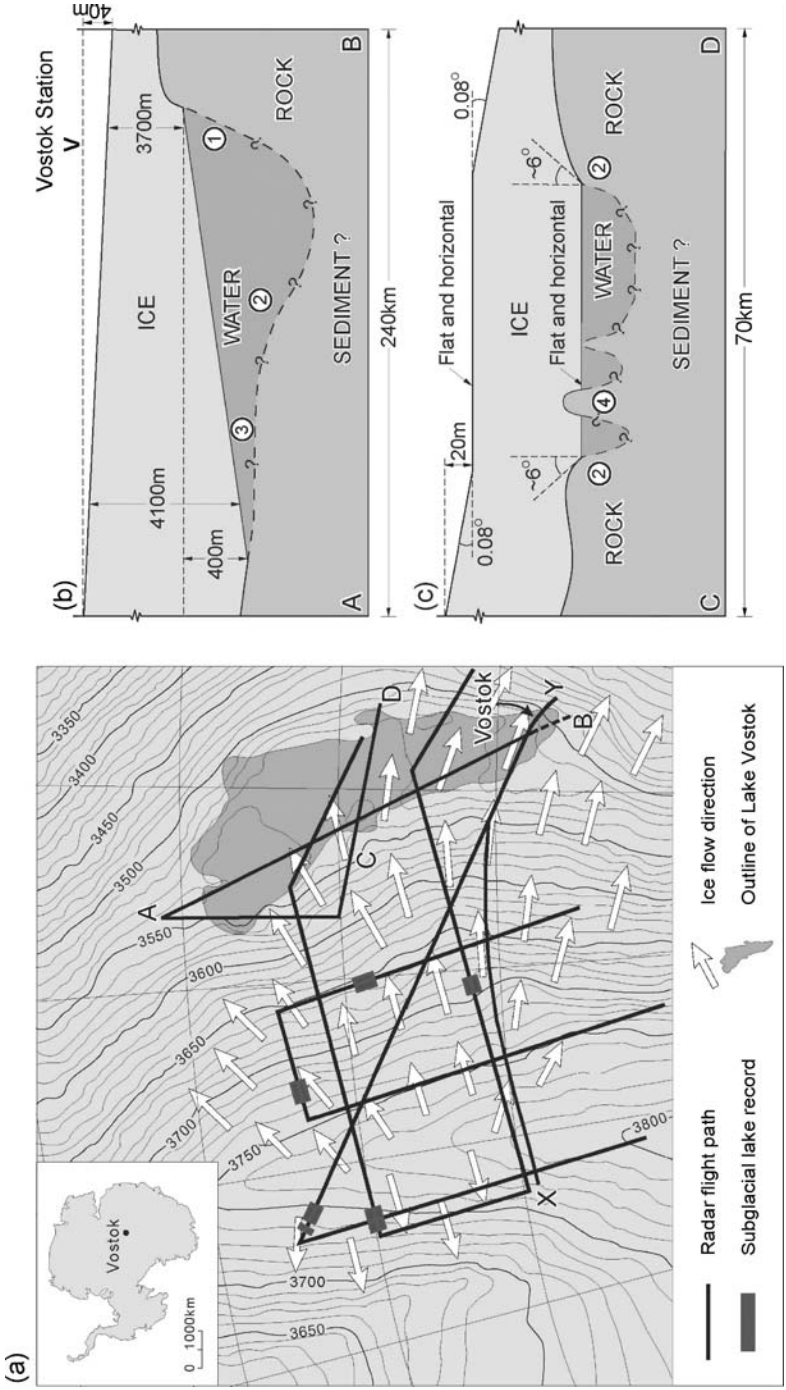
2.4. Slope of the Ice-Water Interface

RES data, combined with ERS-1 satellite altimetry, show that the ice sheet surface above Lake Vostok has an elevation change from one end to the other of only approximately 50 m. For the lake to be in hydrostatic equilibrium with the ice sheet above, the slope of the ice-water interface must be approximately ten times, and in opposite direction to, the ice surface slope (Figure 5). Thus, the ice thickness of the northern end of Lake Vostok is approximately 500 m greater than in the south. The relationship between ice and lake surface slopes is true for all subglacial lakes.

2.5. Types of Subglacial Lakes

Dowdeswell & Siegert (2002) characterized subglacial lakes into three main types as follows: (*a*) lakes in subglacial basins in the ice-sheet interior, (*b*) lakes perched on the flanks of subglacial mountains, and (*c*) lakes close to the onset of enhanced ice flow.

The majority of Antarctic subglacial lakes are located within 200 km of ice divides in the interior of the ice sheet (Figure 4). The bedrock topography of the ice sheet interior involves large subglacial basins separated by mountain ranges (Drewry 1983). The lakes in this category are those found in, and on the margins of, subglacial basins. These lakes can be divided into two subgroups. First, there are those located where subglacial topography is relatively subdued, often toward the center of subglacial basins (e.g., Figures 3*a*,*i*). Secondly, some lakes occur in significant topographic depressions, often closer to subglacial basin margins, but still near the slow-flowing center of the Antarctic Ice Sheet. Where bed topography is very subdued, deep subglacial lakes are unlikely to develop.



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Perched subglacial lakes are found mainly in the interior of the ice sheet, on the flanks of subglacial mountain ranges (Figure 3*d*). In several cases, small (<10 km long) subglacial lakes have been observed perched on the stoss face of large (>300 m high), steep (gradient >0.1) subglacial hills.

At least 16 subglacial lakes occur at locations close to the onset of enhanced ice flow hundreds of kilometers from the ice sheet crest (Siegert & Bamber 2000). An example is provided by three subglacial lakes near the onset of fast flow into Byrd Glacier (e.g., Figure 3*h*). Byrd Glacier is fast flowing and drains a very large interior ice sheet drainage basin into the Ross Ice Shelf (Drewry 1983). These subglacial lakes are similar in size and depth to the small and probably shallow lakes found in parts of major subglacial basins in the ice sheet interior.

2.6. Tectonic Setting of Lake Vostok

In recent years, a concerted effort has been made to map the size and extent of Lake Vostok. Studinger et al. (2003a) summarized the results from an extensive geophysical survey of the lake and its locale (Figure 6*a*, see color insert). The results confirmed the aerial extent of the lake, established previously from examination of ERS-1 satellite altimetry (Ridley et al. 1993, Kapitsa et al. 1996). A major new finding of this survey was that the western half of the lake has distinct gravity and magnetic anomaly compared to the eastern half. The border between the two anomalies is clear and linear along the eastern margin of the lake (Figure 6*b*).

←

Figure 5 The dimensions and topographic setting of Lake Vostok. (*a*) ERS-1 altimetry of the Antarctic Ice Sheet between Ridge B and Dome C. The location of Lake Vostok can be identified from the anomalous flat ice surface region. SPRI (Scott Polar Research Institute, University of Cambridge) radar flight lines and the location of all known subglacial lakes around Lake Vostok (denoted as *black squares*) are provided. The surface ice sheet elevation, derived from the ERS-1 altimeter, is also shown. The contour interval is 10 m. Arrows denote the direction of surface flow of ice over Lake Vostok calculated from InSAR (Interferometric Synthetic Aperture Radar) (Kwok et al. 2000). It must be noted that recent analysis of flow structures within the ice sheet suggests the InSAR data may be inaccurate across the south of Lake Vostok (Tikku et al. 2004). (*b*) Cross-section from north to south along the 200 km length of the lake. (*c*) Cross-section from West to East along the 50 km width of the lake. The depth of Lake Vostok can be estimated by (1) seismic information, which has revealed a water depth of >500 m beneath Vostok Station; (2) side-wall bedrock gradient adjacent to the lake of 0.1, which indicates several hundred meters of water depth in the center of the lake; (3) radio-wave reflections from the lake floor, showing the water depth to be between 10 and 20 m in the north of the lake; and (4) bedrock islands measured by radar.

Studinger et al. (2003b) analyzed aerogeophysical and seismological data to establish a "conceptual tectonic model" for Lake Vostok and its locale. They concluded that the tectonic framework around Lake Vostok involves a crustal boundary (the source of the linear magnetic anomaly). The cause of this boundary is likely to be associated with the emplacement of a thrust sheet onto a previously passive continental margin. The age of the thrusting has been estimated as Proterozoic (i.e., Precambrian, in excess of 600 million years). Subsequent normal reactivation of the thrust sheet then may have created the trough in which Lake Vostok is located (Studinger et al. 2003b). What remains unknown about Lake Vostok's trough is the extent to which subglacial erosion during the onset of glaciation contributed to its development.

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3. ORIGIN AND AGE OF LAKE VOSTOK

Much attention has been given to Lake Vostok as a possible habitat for life. Being an order of magnitude larger than any other subglacial lake, Lake Vostok has been viewed by many as the ultimate long-term target for exploratory research (Priscu et al. 2003).

3.1. Origin and Age of the Lake

The age and origin of Lake Vostok will be critical to the biota within the lake, and to the age and quality of the geological records on the lake floor. One published theory concerning the origin of Lake Vostok is unlikely (Duxbury et al. 2001). In this theory, the lake is assumed to have existed within its trough prior to glaciation, and remain intact as the ice sheet grew across the lake to its current relatively stable configuration. In fact, the region that is now Lake Vostok was probably occupied by grounded ice during ice sheet buildup, even if the trough and lake were present prior to glaciation. This is because the margin of the ice sheet would have been far closer to the position of the lake during the early stages of ice growth (e.g., DeConto & Pollard 2003). The surface slopes of the ice sheet over the region of Lake Vostok would, therefore, have been significantly greater than those at the center of today's ice sheet. In this situation, water would have been driven out of the trough to the ice sheet margin. A probable analogy to Lake Vostok during ice sheet buildup is the Astrolabe Subglacial Trough in Wilkes Land, which holds the thickest ice in Antarctica (4776 m). This trough has a small subglacial lake at its mouth, which indicates that the whole trough is subject to subglacial melting, and that water is driven out of the deepest parts of the trough. As the Astrolabe Subglacial Trough is unable to hold a large lake owing to the ice overburden, Lake Vostok would not have been resident in its trough during the early stages of ice sheet growth in Antarctica. Thus, the lake is most likely to postdate the formation of the current ice sheet. The exact age of the East Antarctic Ice Sheet has been strongly debated over the past few decades. Some believe that it has remained in

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its present form for the past 15 million years (e.g., Stroeven et al. 1998), which could make Lake Vostok nearly as old. Others claim that the ice sheet has undergone substantial modification in this time (e.g., Harwood & Webb 1998), which could make the age of the lake much younger. Although this fundamental problem remains to be solved (see Miller & Mabin 1998), its solution may exist within the geological record held in subglacial lake floor sediments. The extraction of lake floor sediments is, therefore, an important driver behind subglacial lake exploratory research.

3.2. Origin and Age of the Lake's Water

Regardless of the origin and age of Lake Vostok, the age of the water within the lake (and other lakes) is a function of the age of ice melting into the lake and its turnover time. The age of the basal ice in the Vostok ice core (located at the southern end of the lake) is an important constraint on the age of youngest water within the lake. Preliminary examination of the isotope record (Jouzel et al. 1999), estimates of the air-hydrate crystal growth rates (Lipenkov et al. 2000), and ice flow modeling (Parrenin et al. 2004) provide evidence that the basal glacier ice, 230 m beneath the 3310 m level, could be as old as one million years. This marks the maximum possible age of the youngest lake water. This also effectively marks the date at which Lake Vostok was last in direct contact with biotic and chemical constituents in Earth's atmosphere. The mean age of water within Lake Vostok is a function of the residence time of the water and how well the meltwater mixes with the existing lake water. We can speculate that if 20% of the annual meltwater mixes with the resident lake water before refreezing, then the residence time of Lake Vostok would be approximately 100,000 years (Mayer & Siegert 2000, Mayer et al. 2003). Hence the mean age of Lake Vostok's water is most probably of the order of one million years.

4. WHY IS LAKE VOSTOK UNIQUE?

Lake Vostok is unique because of its size. To understand why this subglacial lake is so much larger than any other, and therefore why it is unique, we must understand the subglacial morphology of the Antarctic continent and the way in which ice flows across this landscape.

4.1. Morphological Analysis of Subglacial Antarctica

There are several overdeepened troughs in Antarctica that, like Lake Vostok's, are more than 100 km in length and tens of kilometers wide (Figure 7, see color insert). The origin of these troughs is open to debate. Some may have formed through tectonic processes such as rifting and faulting prior to glaciation (as has been shown for Lake Vostok; Studinger et al. 2003b). All troughs are likely to have been affected by subglacial erosion at a time when they were occupied by

fast-flowing ice flow units. Although several troughs are likely to be actively eroding, as they are occupied by fast-flowing ice (such as in the Astrolabe Subglacial Trench), many must be relic features from an earlier, smaller phase of Antarctic glaciation (such as the Adventure Subglacial Trench in Dome C) (e.g., Drewry 1975).

Examination of the morphology of the seven largest troughs in Antarctica reveals that Lake Vostok's trough is not unique within subglacial Antarctica in terms of size (Figure 2). The longest is the Lambert trough; the Astrolabe Subglacial Basin is the widest, the deepest, has the steepest sides, and houses the greatest thickness of ice; and the largest by area is the Byrd Subglacial Basin in West Antarctica (Figure 1). The similarity between Lake Vostok's trough and other glacially derived overdeepened troughs (Figure 1) suggests that it too could be a glacially affected trench.

4.2. Ice Flow and the Existence of Lake Vostok

Ice flows onto Lake Vostok from the Ridge B ice divide, located between 200 and 250 km from the lake's western margin (Kwok et al. 2000). ERS-1 satellite altimetry shows the ice sheet surface above Lake Vostok to be unusually smooth and virtually flat (Figure 5) (Kapitsa et al. 1996, Siegert & Ridley 1998, Rémy et al. 1999). This morphology is caused by the different dynamics of ice that is grounded compared with floating ice. The basal shear stress across the ice-water boundary above the subglacial lake is effectively zero, so the ice sheet should flow over the lake by vertically uniform longitudinal extension (Paterson 1994). However, numerical ice flow modeling shows that the effect of longitudinal extension is small owing to buttressing at the downstream lake shore (Mayer & Siegert 2000). Instead, the flow of the floating ice is controlled more by the base-parallel shear deformation of the adjacent grounded ice. Surface ice motion across Lake Vostok has been measured using repeat-pass InSAR from ERS-1 (Kwok et al. 2000). The regional flow of the ice sheet upstream of the lake is from west to east, perpendicular to the surface elevation contours. As the ice flows past the grounding line on the lake's western margin, a noticeable southward component is added to the ice velocity (Bell et al. 2002, Tikku et al. 2004). At Vostok Station, the surface ice velocity is measured at 4.2 m year^{-1} in the direction 130°N (Kwok et al. 2000), which compares with an astronomically based measurement of 3.7 ± 0.7 m year^{-1} toward 142 ± 10°N (Kapitsa et al. 1996).

The ice above the Lake Vostok trough is distinct in that it has the lowest surface gradient (0.0002, dipping from north to south), which is due to the ice shelf type flow that occurs over the lake (Pattyn 2003). This situation is controlled by the flow of grounded ice upstream of the lake. Currently, there is only 50 m worth of north-south slope in the grounded ice that flows across the trough's western margin, and this translates into the elevation change over the lake itself. If the slope of the grounded ice across the lake's western margin were changed, so too must the ice surface slope over the lake. For example, if there were 200 m of grounded ice elevation change across the western margin of the lake, the ice surface change over

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the lake itself must match this value, and the elevation of the ice-water interface would change by ∼2000 m. Thus, the reason that a lake exists within the Vostok trough, and that ice shelf flow is subsequently permitted, is due primarily to the flow direction of grounded ice, and the minimal surface elevation change that occurs across the lake's upstream margin. This is a fundamental concept about Lake Vostok, and one that can be used to assess the lake's time-dependent variability (see Section 6). In all other cases, ice flows across large subglacial troughs at an angle greater than 30° to their long axes (Figure 7), and this is why no large lakes can exist within these troughs.

Lake Vostok's physiography may be unique, therefore, as a consequence of the flow of grounded ice around the lake. This can explain why there is only one mega subglacial lake beneath the ice sheet, and suggests that the existence of Lake Vostok is a function of ice sheet flow direction rather than anything unique about the lake's trough. Under this explanation, the formation of Lake Vostok postdates that of the trough and the date at which the ice flow over the trough became approximately perpendicular to the trough's long axis.

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5. PHYSICAL PROCESSES WITHIN LAKE VOSTOK

Our knowledge of physical processes within subglacial lakes has been developed almost exclusively from investigations of Lake Vostok for two reasons. First, it is a very large subglacial lake. Because of this, large-scale processes within it are more obvious and identifiable than in small subglacial lakes. For example, there have been several models of water circulation within Lake Vostok, and these have been developed from large-scale ocean models that have a resolution of the order of kilometers. Such a model is applicable to Lake Vostok, which is more than 250 km in length, but not to smaller lakes that are less than 10 km because the model simply cannot function adequately at such a small scale. Second, by chance, the Vostok ice core is located above the southern end of Lake Vostok.

5.1. Vostok Ice Core Studies

Several deep ice cores have been extracted from the ice sheet at Vostok Station (at the southern end of Lake Vostok) 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 ∼120 m from the base of the ice sheet. The upper 3310 m of the ice core provides a detailed palaeoclimate 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, some of which have been reported to be culturable in the laboratory (Abyzov et al. 1998, Karl et al. 1999, Priscu et al. 1999).

Typical glacier ice contains a record of gases and isotopes from which palaeoclimate 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 palaeoclimatic information difficult to establish (Figure 8). The basal 84 m of the ice core, from 3539 to 3623 m (Figure 8), 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 Lake Vostok ice beneath Vostok Station (Jouzel et al. 1999) (Figure 8). The accreted ice below 3608 m (and presumably extending to the ice-water interface) contains no sediment-particle inclusions, implying that it formed over the lake proper rather than along the shoreline.

Ice flows from west to east across Lake Vostok, and the accreted ice containing sediment particles must have formed across the western side of the lake at the first contact between ice and water. Airborne radar and seismic data suggest that the lake may be shallow across the western side compared to the 510–1000 m water depth recorded beneath the Station (Kapitsa et al. 1996, Lukin et al. 2000). There are two ideas linking water depth to the entrainment of material into the accreted ice. The first is that the basal ice scrapes against the shallow floor of the lake across the western side, picking up debris as it does so (Jouzel et al. 1999). The second is that the lake water is turbulent enough for fine sediment to be held in suspension and incorporated within the formation of accreted ice (Royston-Bishop et al. 2005).

5.2. Rates of Subglacial Melting and Freezing

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 $\sim 0.02^\circ$C m^{-1}, which relates to a heat flux through the ice from the lake ceiling of 46 mW m^{-2}, indicating that rates of subglacial freezing above Lake Vostok are most likely to be ∼4 mm year^{-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 approximately 11 mm year^{-1} (Salamatin 2000).

Figure 8 (*a*) Ice stratigraphy of the basal 550 m of ice beneath Vostok Station determined from analysis of the Vostok ice core (after Souchez et al. 2000). (*b–d*) Chemical records of the basal 90 m of the ice core. (*b*) δD with the frequency of rock particle inclusions, (*c*) δ^{18}O, (*d*) deuterium excess (Souchez et al. 2000). Adapted from Souchez et al. (2000).

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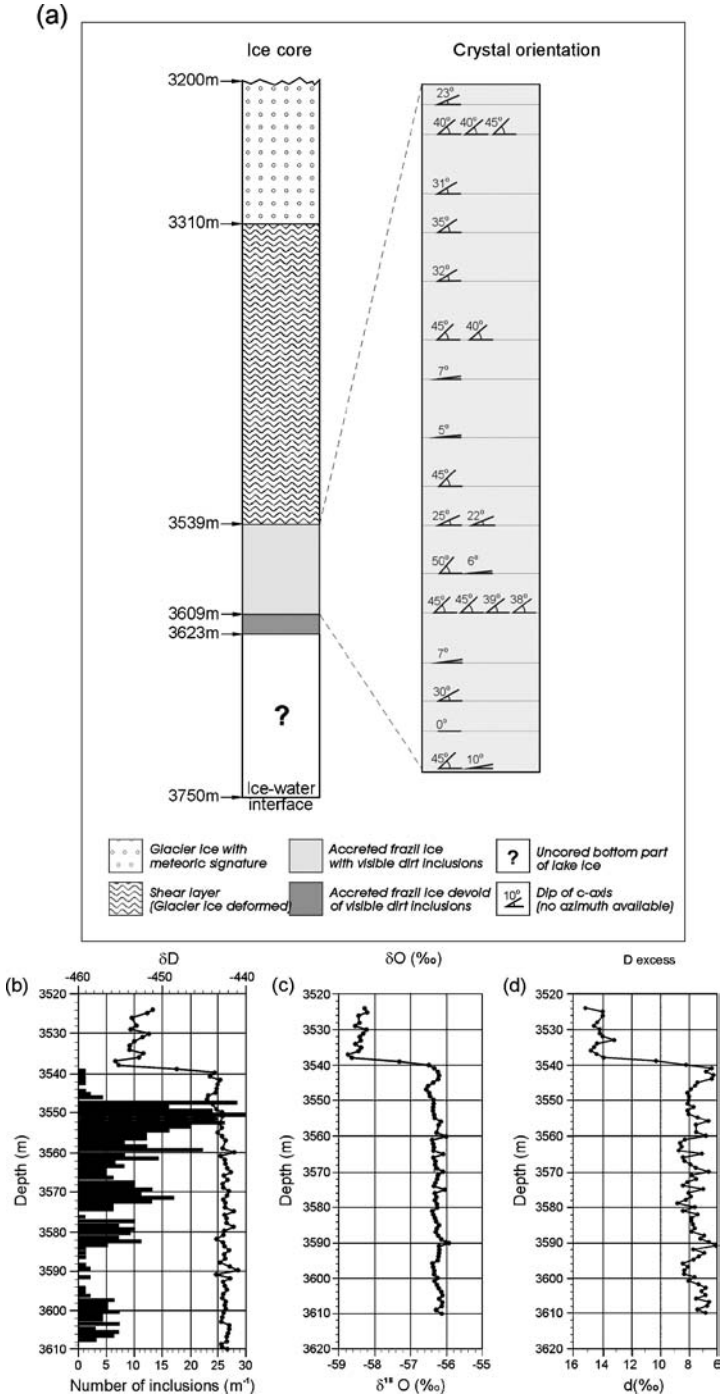

The spatial distribution of subglacial melting and freezing can be estimated theoretically from isochronous internal radar layering by observing the loss or gain of basal ice along a flowline. Using this technique, it has been shown that subglacial melting occurs in the north of Lake Vostok (Siegert et al. 2000), and freezing (accretion) takes place in the south (Bell et al. 2002, Studinger et al. 2004) (Figure 9, see color insert). 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.

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5.3. Water Circulation Models

The zones of subglacial melting in the north and freezing in the south of Lake Vostok are thought to be controlled by the slope of the ice-water interface because the thickness of ice dictates the pressure melting temperature and the density of meltwater. As a consequence of subglacial melting and freezing, circulation is induced in the lake.

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

Because the surface of Lake Vostok is inclined, the pressure melting point in the south will be slightly ($\sim$0.3°C) less than that in the north. The circulation of pure (non-saline) water in Lake Vostok 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 Lake Vostok is in a high-pressure environment, resulting in an unstable water column (Wüest & 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 (Figure 6*a*). 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 & 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 three models from which the circulation of pure water in Lake Vostok can be evaluated (Mayer et al. 2003, Wüest & Carmack 2000, Williams 2001) (Figure 6*a*). The models indicate that meltwater will be colder and denser in the northern area of Lake Vostok, where the ice is thickest, than in 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 Lake Vostok will include horizontal transfer and, to a lesser extent, 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 (Figure 6*a*).

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 (Figure 6*b*). 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 (*a*) the melting-freezing rates, (*b*) the rates of mixing between the fresh ascending meltwater layer and the underlying saline water, and (*c*) 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 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 & 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.

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5.4. Storage of Gas Hydrates (Clathrates)

Dissolved oxygen will be found in the Lake Vostok water column because gas hydrates are released from the melting glacial ice. Gas hydrates (or clathrates) are crystal lattices formed by water molecules around gas molecules under conditions of low temperatures and high pressures. High pressures result in substantial volumes of gas being compressed and trapped within these lattice structures. Air hydrates are known to be present in the glacial ice above Lake Vostok (Uchida et al. 1994). This is because gases cannot dissolve in the solid ice, and hence all of the air is subject to the confining pressure of the ice. Some of the gases in the air clathrates that enter the lake can dissolve in water, and hence the air clathrate may completely or partially dissolve, dependent on the concentration of dissolved gases already present in the lake water. Lipenkov & Istomin (2001) calculate that the minimum oxygen concentration in Lake Vostok waters is $\sim$17 μM, just under twice that of water saturated with oxygen at the surface, whereas the maximum concentration is $\sim$850 μM. The oxygenation of lake water by dissolution of the clathrate will most likely occur near the surface of the lake, proximal to the supply of hydrates from the melting ice sheet base. Water circulation will then allow the transfer of oxygenated water to other parts of the lake, including the southern side, where subglacial freezing occurs, and deeper regions. It is also

likely that the concentration of dissolved oxygen will decrease with distance from the source of hydrates, if there is microbial respiration in the lake water and if there is oxidation of sulphides, ammonium, or other metabolic electron donors in the glacial debris. This may mean that some regions, such as the floor of the lake and the lake floor sediments, may be depleted in dissolved oxygen, potentially making the environment there anoxic.

Clearly, the oxygen concentration in the lake water is a function of the magnitude of the oxygen source (from clathrate dissolution) and oxygen sinks (oxidation of reduced compounds and incorporation in refrozen meltwater). Anoxia will occur in regions of the lake where the flux of oxygen is less than the potential oxygen demand. A third factor that may control oxygen concentrations, if the oxygen source exceeds the oxygen sink, is the saturation limit. The oxygen concentration of the lake water will gradually increase over time until the maximum oxygen concentration is reached. Additional oxygen is then retained as clathrate, which may effectively buffer variations in oxygen concentrations in the water column against short-term variations in oxygen supply and sinks. Oxygen concentrations are calculated to reach saturation levels in a minimum of 0.2–1.6 million years if there are no sinks of oxygen from the lake (Lipenkov & Istomin 2001). The timescale of nitrogen (N_2) saturation is of a similar magnitude, and it is likely that nitrogen clathrates will be found in the lake given the age of the lake and the lack of obvious N_2 sinks. A current lack of an oxygen mass balance for the lake prevents scientists from an unequivocal position on both the distribution of oxygen concentrations throughout the lake and the presence or absence of oxygen clathrates.

McKay et al. (2003) cite the lack of clathrates in the Vostok ice core's accreted ice as evidence in support of clathrates sinking to the lake floor owing to the incorporation of CO_2 (making the clathrates heavier). They calculate that the concentration of N_2 and O_2 in the water is approximately 2.5 liters kg^{-1}. Such an amount of gas is enough to cause serious problems with degassing and expansion if the water were to be brought to the surface. Hence, plans to extract samples of water from Lake Vostok, especially deep water, should make allowances for the likely gas concentrations within the water.

5.5. Implications for Other Subglacial Lakes

The water circulation predictions for Lake Vostok are based on large-scale ocean models that cannot be readily used for smaller subglacial lakes (as the single cell width in such models is often the size of a small lake). However, the processes identified for Lake Vostok through these modeling initiatives have important consequences for other subglacial lakes. This is because the models show that the driver of water circulation is the sloping ice roof of the lake. As all lakes have this characteristic, it should be expected that all lakes should undergo circulation of the lake water in response to the differential temperatures and pressures, and rates of melting and freezing, at their surfaces. In fact, some subglacial lakes have a noticeably higher surface slope than Lake Vostok, which may permit a dynamic

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response more vigorous than anticipated thus far. Such dynamic flow of water can be modeled using numerical fluid dynamics tools, and these are currently employed to study the hydrodynamics of small lakes.

6. SENSITIVITY OF LAKE VOSTOK TO ICE SHEET CHANGES

A reasonable understanding of the modern glaciological setting of Lake Vostok has been established, and some idea about the physical and chemical dynamics of this uniquely pristine lake has been developed (Siegert et al. 2001, Studinger et al. 2003a), yet there has been little discussion as to how these processes change over time. Today, Lake Vostok is in relative hydrostatic equilibrium with the overriding ice sheet (i.e., the lake surface slope is about ten times, and in opposite direction to, the ice surface slope) (Figure 10*a*). Under changes to the ice sheet, for hydrostatic equilibrium to be maintained, the lake must adjust accordingly.

Processes in Lake Vostok are likely to change as a consequence of ice sheet variations, such as those occurring over glacial-interglacial cycles (see Royston-Bishop et al. 2004 for evidence in support of variations in the size of Lake Vostok). The ice sheet in central Antarctica will change over this timescale in two ways: (*a*) by change to the ice thickness and ice surface elevation and (*b*) by migration of ice divides and alteration in the grounded ice flow direction. The possible effects of these processes on the extent and volume of water in Lake Vostok are discussed below.

6.1. Lake Response to Variations in Ice Thickness

Today, Lake Vostok is most likely to be in a contained, pressurized environment, which means the ice sheet response to small changes in ice surface elevation will be distinct from those that will occur over an ice shelf. For ice shelves, a small change in the surface elevation of the ice sheet will be associated with a much larger (∼10 times) change to the draft of the ice. For Lake Vostok, however, this is very unlikely. Instead, a small increase in the ice surface elevation will lead to either (*a*) an increase in the level of the lake or (*b*) an increase in the effective depth of the lake for a steady ice sheet profile over the lake to be maintained.

If the thickness of grounded ice surrounding Lake Vostok is increased by 10 m, the lake level, actual or effective, will also rise by 10 m. If the actual level of the lake increases, the lake extent will also increase and no ice thickness change is required (Figure 10*b*). Rates of subglacial melting and freezing are maintained in this situation. On the other hand, if the effective lake level increases, this will have no effect on the ice surface elevation, and so ice thickness must instead increase by 10 m. In this case, melting rates are likely to be increased as the pressure melting point is reduced and temperatures increased beneath thicker ice. Hence, effective lake surface change is unlikely to occur on its own; instead, both processes will

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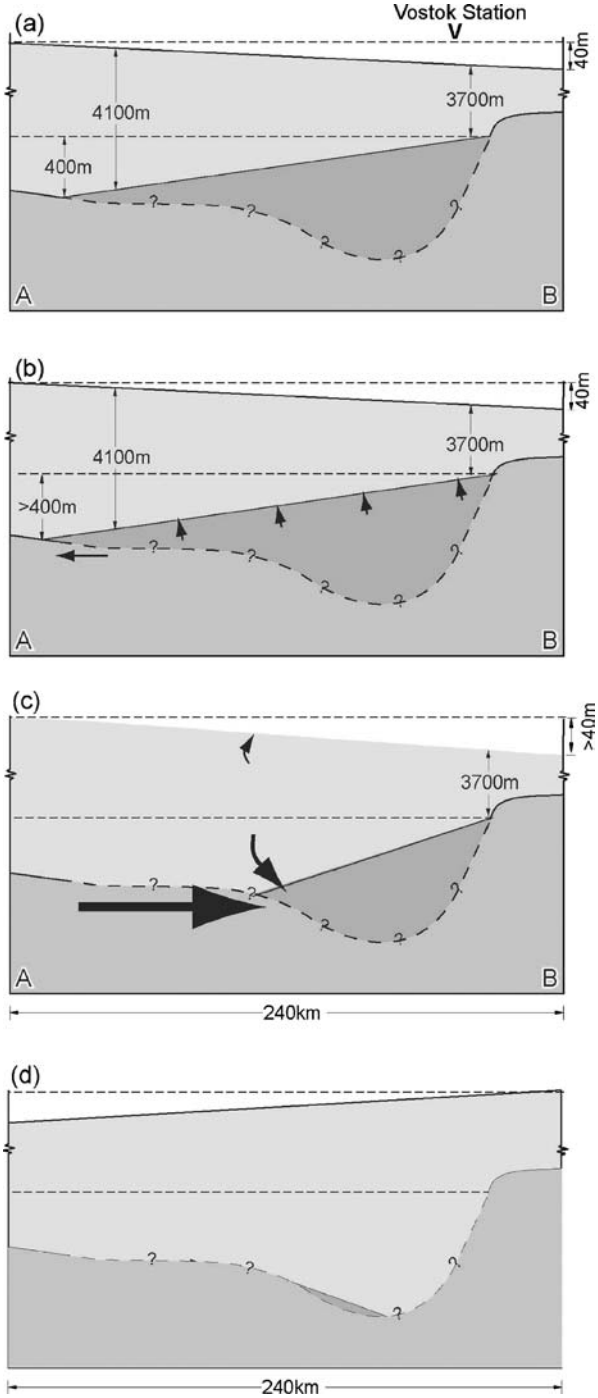

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contribute. The net effect of an increase in the grounded ice thickness is, thus, an increase in the volume and extent of the lake.

Evidence in support of ice thickness changes over Lake Vostok comes from calculations of former ice accumulation rates and numerical modeling of the ice sheet during the last glacial cycle. During the last interglacial, ice accumulation rates at Vostok Station (>2.5 cm year^{-1}) were greater than at present (~2.3 cm year^{-1}) (Siegert 2003). The grounded ice thickness in central East Antarctica is likely, therefore, to have been greater during the Eemian than at present. Conversely, during periods of full glaciation, the accumulation rate of ice in East Antarctica is only approximately 1.2 cm year^{-1}, which is compatible with a reduction in ice sheet elevation. According to the numerical modeling study of Huybrechts (2002), the surface elevation at Vostok Station varies from the present value by between +50 m (during interglacials) and –150 m (in periods of full glaciation) over the last four glacial cycles.

6.2. Lake Volume and the Direction of Ice Flow

Ice currently flows onto Lake Vostok approximately orthogonal to the axis of the lake (the lake axis is parallel to the grounded surface contours). There is consequently very little change in ice surface elevation across the western margin of the lake, and, hence, the ice surface over the lake is extremely flat (owing to ice shelf type flow; Pattyn 2003). The response of Lake Vostok to changes in surface slopes is assessed through examination of two end member situations.

First, if the grounded ice upstream of the lake flowed in a more north-south direction, there would be an increase in the number of contours crossing the western lake margin and, so, the ice surface over the lake would be steeper (Figure 10*c*). This would cause the lake surface gradient to increase and, hence, the lake will shrink to the south (albeit the lake could be deeper in the south under this scenario) (Figure 10*c*). Second, just a subtle change to the grounded flow direction west of the lake northward would reverse the ice profile gradient over the lake's western

←

Figure 10 Ice sheet processes affecting the volume of Lake Vostok. (*a*) Contemporary morphology of Lake Vostok, as estimated by Siegert et al. (2001). (*b*) Ice elevation change owing to variations in the depth of the lake. Assuming a closed system, if the water depth of Lake Vostok increased by 10 m, the ice surface elevation would also increase by 10 m. The consequence of this process is that the lake's volume increases with increase in ice surface elevation. (*c*) Changes to the ice surface slope over lake. Small changes to the surface elevation will result in much larger changes to the slope of the ice-water interface. The lake responds to this change by growing when the ice slope decreases, and shrinking under a steeper ice profile. (*d*) Change in subglacial conditions that may be expected by a reversed ice surface slope. In this case, the ice-water interface will slope in the opposite direction to at present, potentially forcing water out of Lake Vostok to the north and into the Aurora Subglacial Basin.

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margin and, thus, over the lake itself. This would reverse the slope of the ice-water interface and force water to the north of the lake. In this situation, water would be evacuated from the lake if the basal slopes were <10 times the surface slope (Figure 10*d*). The flowpath of such water would be toward the Aurora Subglacial Basin to the northeast of Lake Vostok. This is an important concept to realize, as it suggests that conditions in Lake Vostok could change with only small adjustment to the grounded ice flow pattern upstream.

Evidence in support of a change to the ice flow direction over the lake comes from internal radar layer structures that have been mapped out across the southern end of Lake Vostok (Bell et al. 2002). These structures are evidence of the flow direction when the ice sheet passed across the western margin of the lake. They are, at least in part, indicators of former ice flow paths. The orientation of these structures is at a significant angle to the current surface velocities measured by InSAR (Kwok et al. 2000, Bell et al. 2002). Specifically, the InSAR velocity vector is approximately 30° south of that identified from internal ice structures. There are two possible explanations for this mismatch. The first is that the InSAR data are inaccurate (Bell et al. 2002, Tikku et al. 2004). The second is that at least part of the difference between the two vectors is due to changes in the surface velocity. Given that the surface elevation at Vostok Station changes over glacial-interglacials cycles it is highly likely that the ice sheet surface contours (and velocity vectors) were affected to some degree during such periods.

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6.3. Consequences for Lake Circulation and Physical Processes

As the driver for water circulation in Lake Vostok is its sloping ice roof, any change to this slope is bound to have an impact on the water circulation. An increase in the gradient may lead to greater variation in the basal temperature at one end of the lake compared with the other and, hence, enhanced rates of subglacial melting and freezing. The heat produced and released by melting (beneath thicker ice) and freezing (beneath thinner ice), respectively, will excite circulation of the lake water. In this way, steeper ice-water interfaces may be linked to more dynamic subglacial lakes. Conversely, a perfectly horizontal lake surface may not experience significant spatial change in the basal ice temperatures. Consequently, the circulation that results will not necessarily be driven from one end to the other and so would be organized differently. Numerical modeling of water circulation may allow us to better understand the link between the slope of the ice water interface and lake flow processes.

7. FUTURE EXPLORATION OF SUBGLACIAL LAKES

Following the realization that Antarctic subglacial lakes may house unique forms of life and hold detailed records of past climate change, the Scientific Committee on Antarctic Research (SCAR) published recommendations for their future

exploration (Kennicutt 2001). The report listed three specific scientific goals that such exploration should address, and put forward advice as to how site selection could be achieved. The first goal concerned the identification of life in the lake waters and lake floor sediments. The second involved the extraction of palaeoclimate records from the ice overlying the lakes and from the sediments across their floors. The third related to the origin and evolution of the lakes themselves, as this knowledge would be essential in interpreting information for the first two goals. A group of specialists was set up by SCAR to "consider and recommend mechanisms for the international coordination of a subglacial lake exploration program" (Kennicutt 2001, Priscu et al. 2003).

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7.1. Which Are the Most Suitable Lakes?

No single subglacial lake is currently known to be best suited to attain the SCAR scientific goals. Because of the surveying undertaken to date, however, only Lake Vostok is known to be a viable location for exploration. It is, therefore, appropriate that plans be made to study this lake further to attain SCAR's first goal concerning the identification of life. Further, although the goal is to find life, the ambition is to discover endemic ancient life. To realize this ambition a lake of substantial age and depth is required. Lake Vostok is thought to be such a candidate.

In terms of establishing records of past change in Antarctica (SCAR's second goal), examination of more than one lake would be preferred. All lakes may potentially record glacial-interglacial changes to the ice sheet, and some located in potentially sensitive regions such as Dome C may record more significant changes from early in Antarctica's glacial history. Ideally, sediment from the floors of several lakes aligned along a transect from the ice margin across Dome C to the Vostok Highlands and the Gamburtsev Mountains would enable an appropriate spatial appreciation of glacial history. Sampling from just one lake, although useful, would cause a restriction in the spatial interpretation of information. One key issue that lake floor sediments could address is the whether the ice sheet has remained stable for the past 15 Ma or whether it was more dynamic over this period (Miller & Mabin 1998). As the most sensitive region of East Antarctica to change is likely to be Dome C (much of the bed here is below sea level), examination of at least one lake from this location would be needed to address this issue.

Exploration of lakes at the center of the ice sheet from Dome C, Lake Vostok, and Ridge B would allow the first two of SCAR's goals for subglacial lake exploration to be addressed. Such work would also help to ascertain the origin and evolution of these lakes. This would leave two types of lake (perched lakes and lakes found at the onset of enhanced flow) unexplored. Hence, examination of these two types of lakes may occur at a time after lakes at the center of the ice sheet, and after the attainment of the SCAR-defined research goals.

A distinction should be made about the scientific merits of West Antarctic subglacial lakes, compared with those in East Antarctica. Whereas the East Antarctic Ice Sheet is expected to have been stable for several millions of years, causing the

lakes at its base to be of a similar age, the West Antarctic Ice Sheet has most likely fluctuated in size over this time. However, the exact nature of the fluctuation has yet to be deciphered from the geological record. Sediments across the floors of West Antarctic subglacial lakes may hold such a record, and it is this that makes their exploration particularly exiting.

7.2. Specific Plans for Lake Exploration—Lake Vostok, Russian Plan

In June 2003, the twenty-sixth annual Antarctic Treaty Consultative Meeting, held in Madrid, discussed the Comprehensive Environmental Evaluation (CEE) of a Russian plan to extract a sample from Lake Vostok. The plan is to use the existing Vostok ice core (about 150 m above the lake surface), and drill down through the lake's ice roof. Just before penetration of the ice ceiling, drilling fluid will be extracted from the core. Thus, as the core breaks through into the lake, it will be underpressurized compared to the ice overburden, and so instead of drilling fluid entering the lake, lake water will rise up the core 50 m or so. The core will be extracted quickly, and the Lake Vostok water within the ice core will be left to freeze. The core will then mine through the newly frozen ice and return it to the surface for analysis. Thus, samples of Lake Vostok surface water can be extracted from the lake without the need for in situ observation.

Critics of this plan argue that entering the lake without an ice barrier between the lake and the ice sheet surface is potentially dangerous, given the unknown levels of gas hydrates within the lake. One argument against the plan is that decompressing the core could encourage the lake water to degas with potentially catastrophic consequences. McKay et al. (2003) predict there to be large concentrations of hydrates within the lake water, but hypothesize that these are located at depth in the lake, rather than at the surface. Such a hypothesis could be used to argue in favor of the Russian plan. The only problem they would face is the decompression and expansion of solid ice as it returns to the surface; a scientific problem certainly, but not necessarily a catastrophic one.

Another critical issue that the planned sampling must deal with concerns the rates of freezing that can be expected in the ice core. Maximum rates of subglacial freezing beneath Vostok Station are of the order of several centimeters per year (Siegert et al. 2000, Bell et al. 2002). Even at this high rate, which is much higher than the Vostok ice core temperature profile suggests (e.g., Salamatin et al. 1998), it would take more than a year for lake water within the lower part of the ice core to freeze fully and allow subsequent recoring.

7.3. Other Plans for the Exploration of Lake Vostok

In 1996, when Lake Vostok was brought to the world's attention (Kapitsa et al. 1996), scientists began questioning whether unique microorganisms existed within the lake. Appetites were whetted by the discovery of microbes within the Vostok ice core accreted ice (Karl et al. 1999, Priscu et al. 1999). To answer this question

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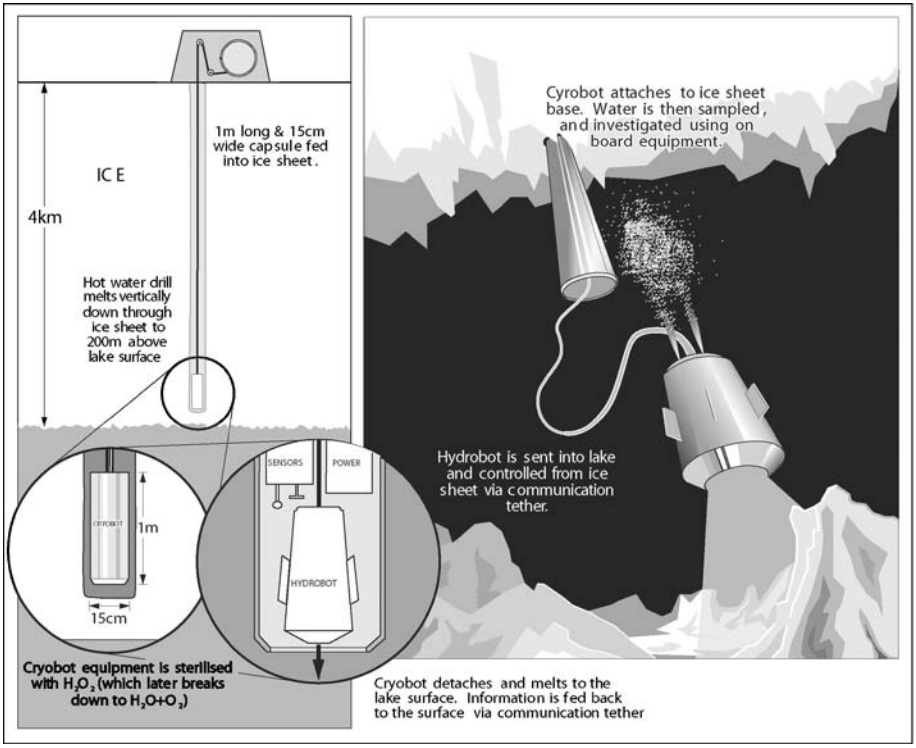

Figure 11 Experimental design to enable the in situ exploration of Antarctic subglacial lakes. The issue of how the hydrobot moves about the lake is important to the lake environment. It is shown here to use a water jet propulsion system that may result in mixing of the lake water. If the lake is stratified, such mixing must be avoided. A less invasive approach is to simply drop a string of instruments vertically down the water column and take a series of measurements and samples without lateral navigation.

unequivocally, however, requires in situ observations (Figure 11). Several plans were made to explore the lake, and all of them require the sampling strategy to be as sterile as possible. As such conditions preclude the use of drilling fluids, hot water drilling to the lake surface appears to be the only plausible way down. Of the plans made so far, most of them revolve around using hot water drilling to a stage above the lake ceiling. The hot water drill is removed and a tethered thermo-probe is inserted into the hole. It then melts down into the ice, which freezes above it. Unreeling a tether to the surface as it goes down, the sterile thermo-probe works its way to the lake ceiling, whereupon it deploys a hydrobot to sample and measure the environment of the lake (lake water and sediment). This plan has a far greater potential for truly understanding the lake system than its Russian counterpart, as it could record temperatures, flowrates, and stratification/gradients that would not be possible from a refrozen sample. Of course it would not be possible to

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return samples to the surface under this proposal, so the thermo-probe or hydrobot would have to include all the necessary equipment. As a consequence, the scheme is ambitious and requires considerably more technological development than the Russian plan.

7.4. Exploration of West Antarctic Subglacial Lakes

Lake Vostok is not the only subglacial lake worthy of exploration. In East Antarctica there are over 90 known subglacial lakes that could contain unique life and hold records of past climate change. As these lakes could be several millions of years old, the requirement for their preservation as unique ecosystems makes their exploration challenging. The same is not necessarily true in West Antarctica, where there are several known subglacial lakes (Figure 4). The exploration of West Antarctic subglacial lakes has three advantages over the exploration of their East Antarctic counterparts.

The first advantage concerns the age of West Antarctic subglacial lakes. As the West Antarctic Ice Sheet probably decayed a number of times during the Quaternary, West Antarctic subglacial lakes must be considerably younger than those in East Antarctica. The lakes will not, therefore, be ancient systems as is anticipated for Lake Vostok. Nevertheless, the lakes comprise the same environment as in any subglacial lake (they are under the same boundary conditions), which means that biological selection processes are as likely to occur in West Antarctic subglacial lakes as they are anywhere else.

The second relates to environmental considerations and the preservation of ancient environments. The base of the East Antarctic ice sheet has never been reached by drilling (although the EPICA ice core in Dome C plans to), and this makes the planning of East Antarctic lake exploration particularly difficult in terms of environmental conservation. However, there have been numerous occasions when the base of the WAIS has been reached, sampled, and measured. In particular, wet ice-bed contacts have been observed several times on the Siple Coast (e.g., Gow et al. 1968, Kamb 2001). Hence, although the environmental issues relating to West Antarctic subglacial lake exploration are important, they may not be as insurmountable as the issues relating to East Antarctic subglacial lake exploration.

The third advantage relates to the elevation of the ice surface above subglacial lakes. The ice sheet surface in West Antarctica is no higher than 2400 m above sea level, which is over a kilometer lower than the ice surface over most East Antarctic subglacial lakes. Altitude-related problems encountered by scientists at the center of the East Antarctic Ice Sheet will not, therefore, be as much of an issue during the study of West Antarctic subglacial lakes.

These advantages have led a U.K.-U.S. consortium to propose the exploration of a 10-km-long West Antarctic subglacial lake, named Subglacial Lake Ellsworth (79.5°S, 90°W) (Siegert et al. 2004). Geophysical surveying of Lake Ellsworth is planned for 2006-7, with direct measurement and sampling to take place during the period of the forthcoming International Polar Year (IPY, 2007–2009). In

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fact, the IPY may witness a considerable advance in our understanding of subglacial lake environments in both East and West Antarctica, as several international teams have proposed scientific programs on a variety of subglacial lakes for this period.

7.5. Extraction of Sediment from Subglacial Lakes

The acquisition of climate records from subglacial lake floor sediments represents a significant challenge. No one has yet designed a drilling system capable of coring and retrieving material beneath several kilometers of ice and a water column potentially hundreds of meters deep. Knowledge of how to do this is being gained, however, by the ANDRILL (ANtarctic DRILLing) program, which over the next few years will drill through the Ross Ice Shelf in a number of locations and extract the sea floor sediment beneath to get a record of Cenozoic climate and ice sheet variability. Use of a traditional drilling rig, as in ANDRILL, is likely to be disruptive to the lake environment to some degree, as sediment will be disturbed and forced into the water column. If the sediment is fine, as is expected, it may take some time to settle out completely. Consequently, investigations focused solely on lake floor sediments (other than the thin layer of material that could be analyzed by a hydrobot) may have to take place after biological investigations or, at the very least, a sufficient distance away.

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8. SUMMARY

Approximately ten years ago, an inventory of Antarctic subglacial lakes was published, detailing the size of more than 70 lake-type features (Siegert et al. 1996). The water depth of the largest of these lakes, Lake Vostok, was discovered to be more than 500 m deep (Kapitsa et al. 1996). This information led biologists to regard the lake as a potential habitat for unique microorganisms, and led geologists to suggest that sediments across the floor of the lake will hold important environmental records. In the past decade there has been a concerted international scientific effort to understand Antarctic subglacial lakes and to plan the exploration of these unique environments.

- More than 100 subglacial lakes have now been identified from data collected from radar sounding of the ice base and satellite altimetry of the ice surface. They exist at the ice sheet base owing to geothermal heating, which at a background level is enough to maintain melting beneath several kilometers of ice. Meltwater produced at the ice base collects in topographic hollows to form pools of water.
- Lake Vostok, the largest subglacial lake, is more than 250 km long, more than 50 km wide, and, in at least one place, is more than 1 km deep. It resides beneath 3.7 and 4.2 km of ice in central East Antarctica. The lake occupies a huge subglacial trough, which, interpretation of geophysical data suggests,

may have been developed by faulting in preglacial times and subsequent glacial erosion.

- There are several large troughs beneath the Antarctic ice sheet, but only one is occupied by a large subglacial lake (Lake Vostok). This is because grounded ice flows approximately perpendicular to Lake Vostok trough's long axis, which permits an extremely low ice-surface gradient to exist and subglacial water to pond. In all other cases, ice flows at an angle ($>30°$) to the trough axis, which causes enhanced water pressure gradients at the ice base and the evacuation of water in even the deepest trough (the Astrolabe Subglacial Basin). Thus, Lake Vostok may be unique as a consequence of the ice flow around it, rather than its surrounding topography.
- The ceiling of Lake Vostok slopes by ten times the ice surface above it (to be in hydrostatic equilibrium). This causes the pressure and temperature at one end of the lake to be different to the other, which results in differential rates of melting and freezing and, in turn, water circulation.
- Even small changes to the ice surface that occur over glacial-interglacial timescales may have potentially significant consequences for the ceiling gradient over Lake Vostok. Thus, water circulation may be affected by changes to the ice sheet that occur over glacial cycles.
- All subglacial lakes have a sloping ice roof. Thus, the processes identified thus far for Lake Vostok that are driven by the differential conditions across the lake roof are likely to be applicable to other, smaller subglacial lakes.
- The exploration of subglacial lakes has two science goals. The first is to identify and understand the microorganisms that live in these extreme environments. The second is to extract and measure the climate record that will be held in the sediments across the floors of subglacial lakes.
- In terms of the first goal, plans to explore Lake Vostok range from a relatively simple experiment involving the trapping, freezing, and mining of lake water in the Vostok ice core's borehole, to highly sophisticated in situ measurement of the lake system using apparatus aboard remote vehicles. Plans are also being developed to explore other subglacial lakes, including Lake Ellsworth in West Antarctica, for the period of the IPY.
- The extraction of sediments from a subglacial lake is also some way off. However, relevant experience is being gained by geologists who are coring through sea floor sediments beneath sea ice and ice shelves in the Ross Sea (in the ANDRILL program). The technology developed in these investigations could one day be used to retrieve sediments from a subglacial lake.

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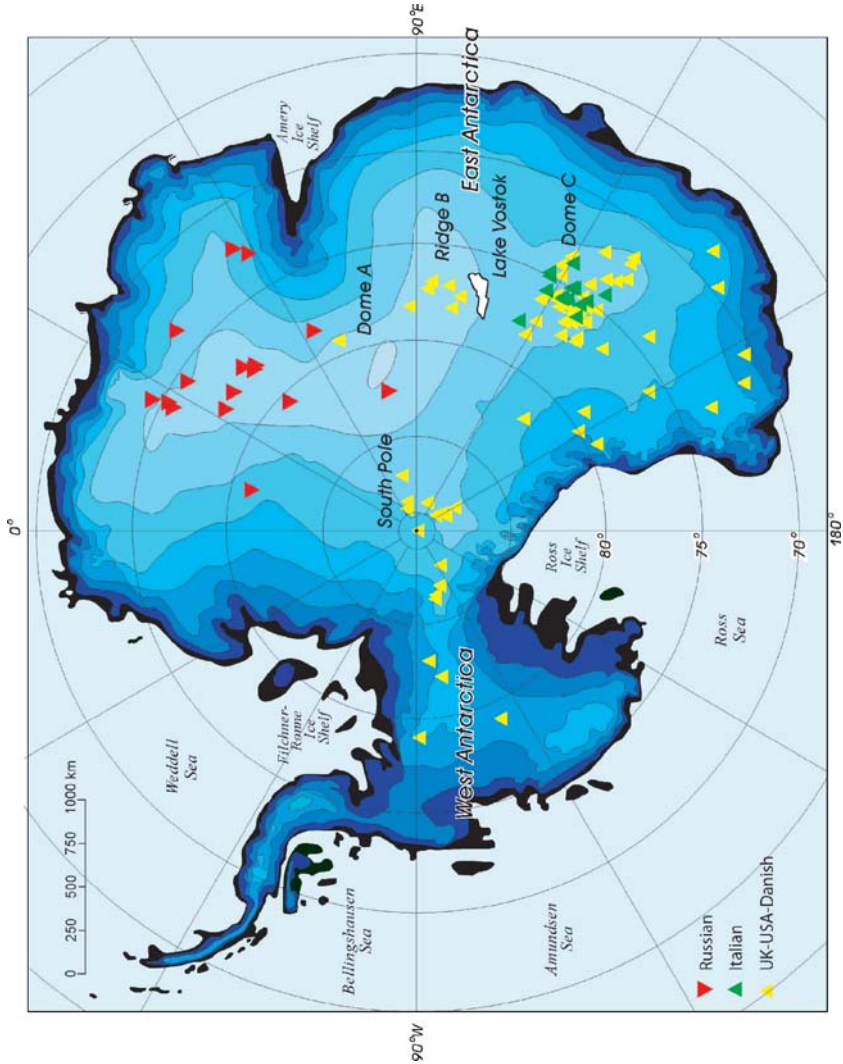

Figure 4 Map of the Antarctic Ice Sheet showing the locations of Antarctic subglacial lakes (*triangles*). The ice sheet surface is contoured at 500 m intervals (after Drewry 1983).

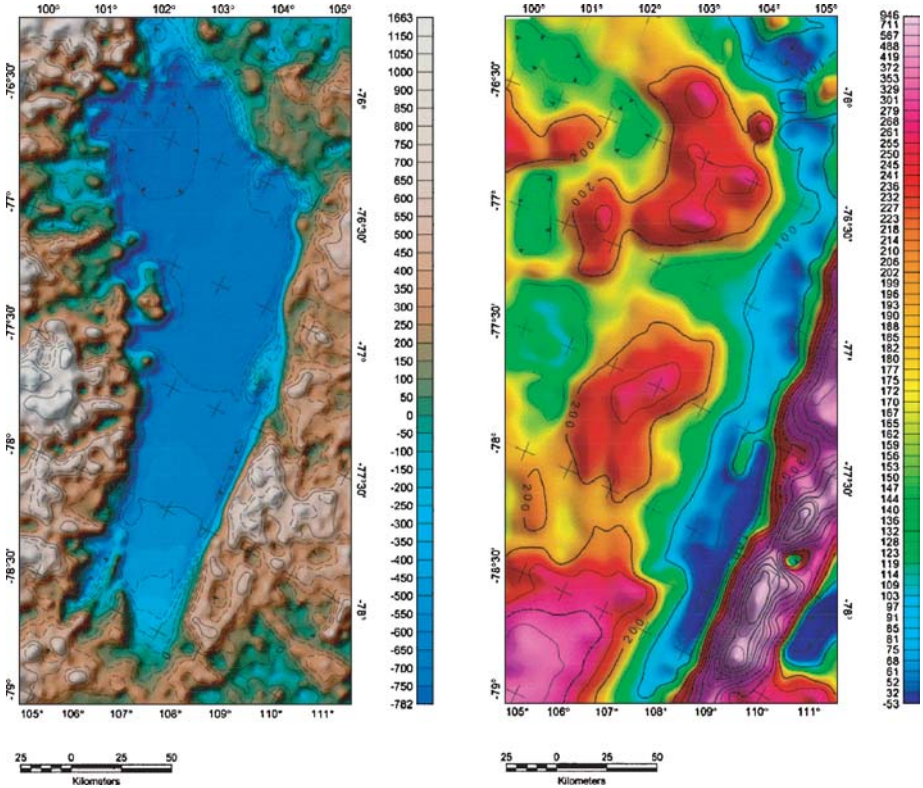

Figure 6 The tectonic setting of Lake Vostok. (*a*) The subglacial elevation of Lake Vostok. (*b*) The magnetic field anomaly across the Lake Vostok region. Reprinted from Studinger et al. 2003a, with permission from Elsevier.

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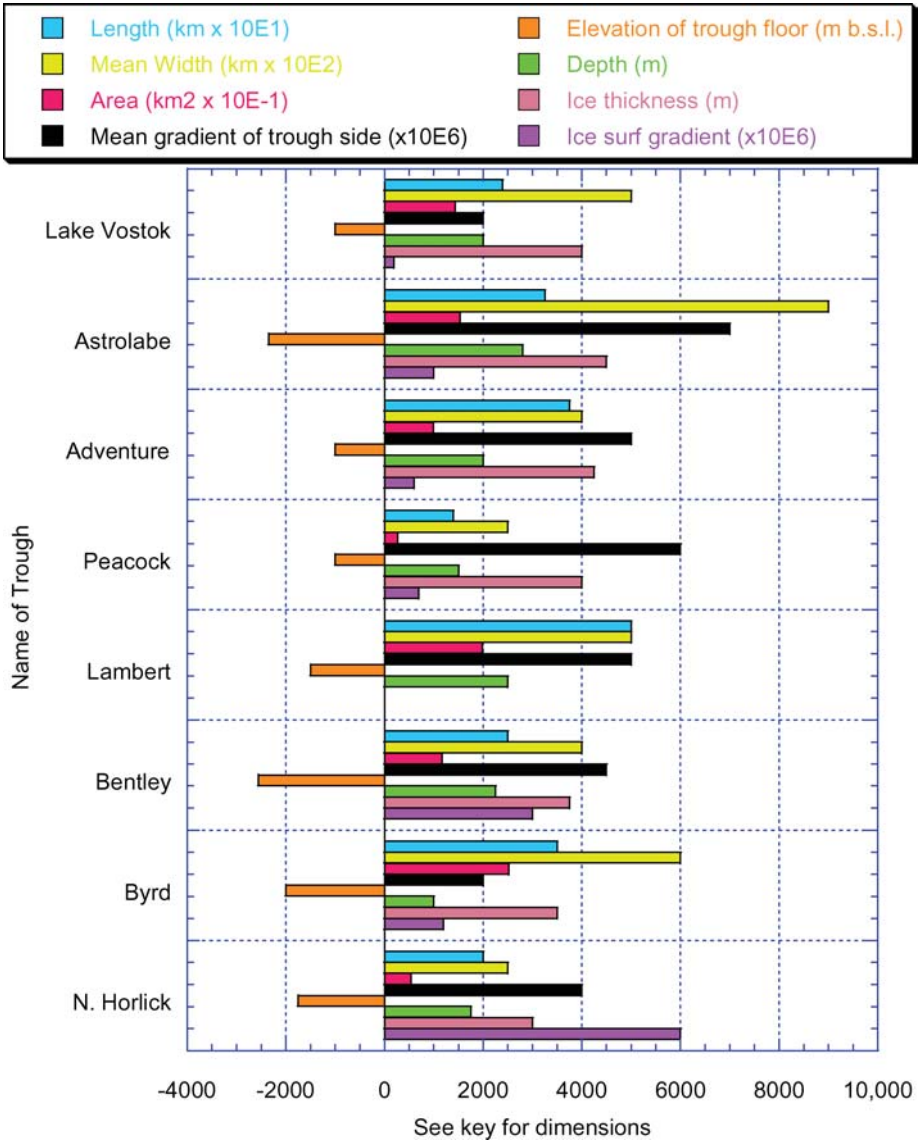

Figure 7 Physiography of Antarctic subglacial trenches as denoted in the bed map of Antarctica (Drewry 1983). The lengths, mean widths, shapes, and areas of troughs were calculated from a contour that depicts the shape of the trough, namely the –1000 m contour (for Astrolabe, Adventure, and Lambert), –750 m (for Peacock), and –1500 m (for Bentley, Byrd, and north of the Horlick Mountains). Side slopes were calculated from the lowest point in the trough (assumed to be –1000 m beneath Vostok Station), and the nearest topographic high point (i.e., the top of the head wall).

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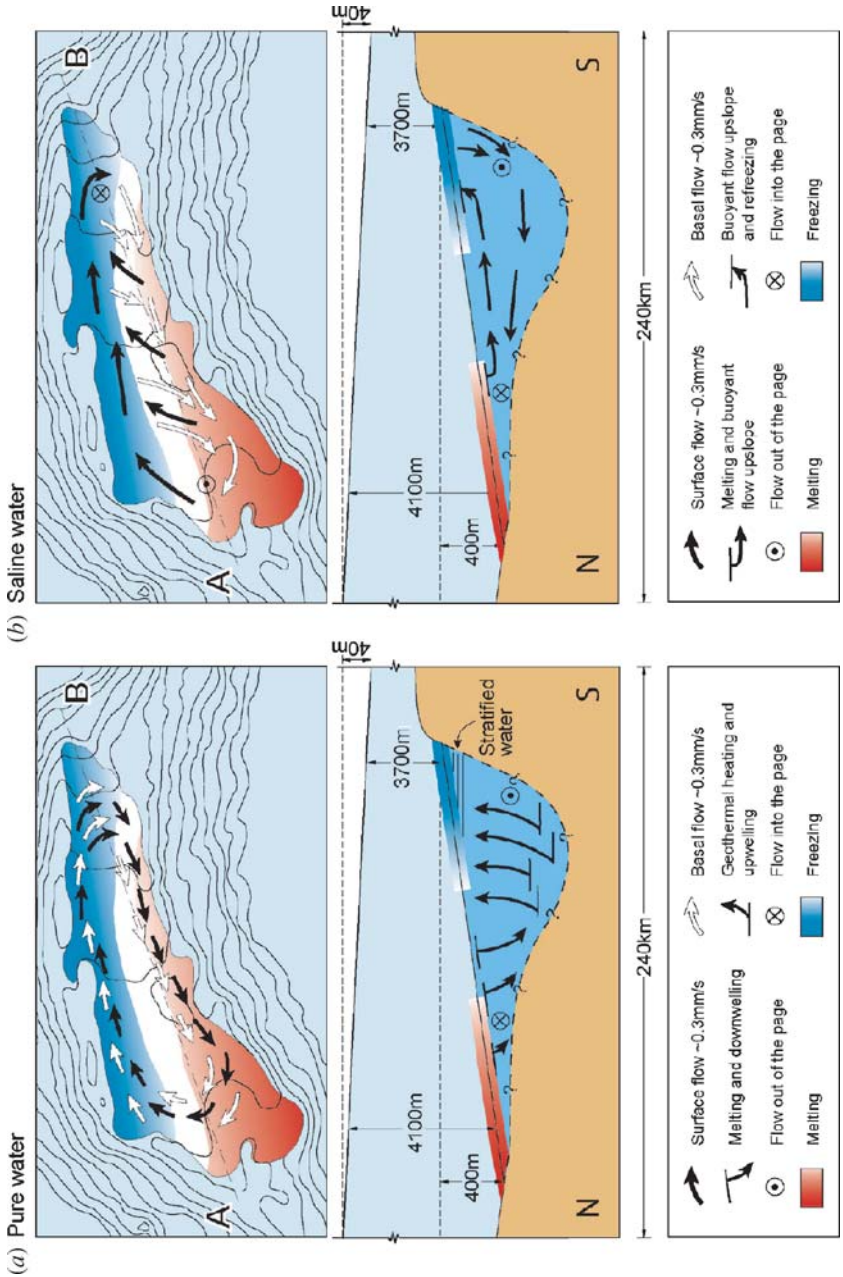

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Figure 9 Water circulation patterns within Lake Vostok under fresh and saline conditions. (*a*) Circulation calculated by numerical modeling, assuming that the water is pure (Williams 2001, Mayer et al. 2003). The white arrows show the bottom water 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. There are two clockwise circulation paths in the upper and lower regions of the lake. Most of the vertical mixing takes place in the southern two thirds of the cavity, but this exchange is rather limited. Blue shading refers to predicted zones of subglacial freezing, red shading indicates subglacial melting. (*b*) Circulation of Lake Vostok thought to occur as a result of saline conditions (Mayer et al. 2003) (i.e., 1.2–0.4‰). It should be noted that understanding Lake Vostok's water circulation may be complicated by the discovery of a distinct bathymetric basin beneath the "freeze zone" (Studinger et al. 2004). Numerical modeling that may uncover the bathymetric influence on water flow has yet to be undertaken, however. Adapted from Siegert et al. (2001).

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