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The physiography of modern Antarctic subglacial lakes

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Abstract

The size and distribution of Antarctic subglacial lakes have been investigated using airborne radio-echo sounding (RES) and satellite radar altimetry. Over 70 lakes have been identified beneath the ice sheet from distinctive, mirror-like reflectors observed on RES records. Almost 60% of lakes are found within 200 km of an ice divide and only about 15% are located >500 km distant. The total volume of water stored in lakes beneath the Antarctic Ice Sheet is between 4000 and 12,000 km^3. The bedrock topography of the ice-sheet interior is characterized by large subglacial basins separated by mountain ranges. More than 60% of lake records have marginal bed gradients of < 0.1, implying that many Antarctic subglacial lakes are found in areas of relatively low bed relief, in and on the margins of subglacial basins. First, there are those lakes located where subglacial topography is relatively subdued, often towards the centre of subglacial basins. Secondly, some lakes occur in significant topographic depressions, closer to subglacial basin margins. Lakes are also found perched on the sides of subglacial mountains. Sixteen lakes are located close to the transition from slow to enhanced ice-sheet flow. Warm-based fast-flowing ice streams provide a possible route by which subglacial lakes may establish a hydrological connection with the ice-sheet margin. At a continental scale, the locations of Antarctic subglacial lakes match the modeled distribution of pressure melting at the ice-sheet bed.

Keywords: physiography; radio-echo sounding; subglacial lakes

1. Introduction

Large outburst floods, resulting from the rapid release of stored meltwater, have been observed at the margins of a number of modern glaciers (e.g. Björnsson, 1974; Clarke, 1982; Goodwin, 1988). Some large-scale geomorphic features in Quaternary mid-latitude landscapes have also been ascribed to huge releases of water from either ice-sheet marginal or subglacial sources (e.g. Baker, 1978; Shaw and Gilbert, 1990; Shaw, 1996). In the 1970s, the existence of large bodies of water beneath the modern Antarctic Ice Sheet was discovered (e.g. Oswald and Robin, 1973; Robin et al., 1977). It is only relatively recently, however, that the size and distribution of these subglacial lakes have been investigated systematically using geophysical instruments mounted on aircraft and satellite platforms (e.g. Ridley et al., 1993; Siegert et al., 1996; Dowdeswell and Siegert, 1999). In addition, the relationship between large subglacial lakes, ice flow and ice-sheet thermal structure is now being examined (e.g. Shoemaker, 1990; Siegert and Dowdeswell, 1996; Siegert et al., 2000; Kwok et al., 2000).

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In this paper, we review the methods used to identify and map large water bodies beneath the Antarctic Ice Sheet, and describe the distribution and size of these lakes. We then examine the ice-surface and bed-topographic settings in which Antarctic subglacial lakes are located and, finally, discuss briefly the links between subglacial lakes, ice-sheet dynamics and temperatures.

2. Identification of Antarctic subglacial lakes

2.1. Airborne radio-echo sounding

Lakes beneath the Antarctic Ice Sheet were first observed on airborne 60-MHz radio-echo sounding (RES) records as extensive areas of smooth and very strong returns from the glacier bed, below several thousand meters of ice (Oswald and Robin, 1973). These areas are specular or mirror-like reflectors (Fig. 2), with an echo strength that is 10–20 dB above the more usual values associated with an ice–rock interface. Such reflectors are characteristic of a water surface. Field experiments support this interpretation. Seismic investigations identified a lake-bed reflector at about 510 m beneath the subglacial surface of Lake Vostok in East Antarctica (Kapitsa et al., 1996). More recently, Gorman and Siegert (1999) have shown, from radio-echo returns which penetrate to a shallow lake-bottom reflector at several subglacial lake

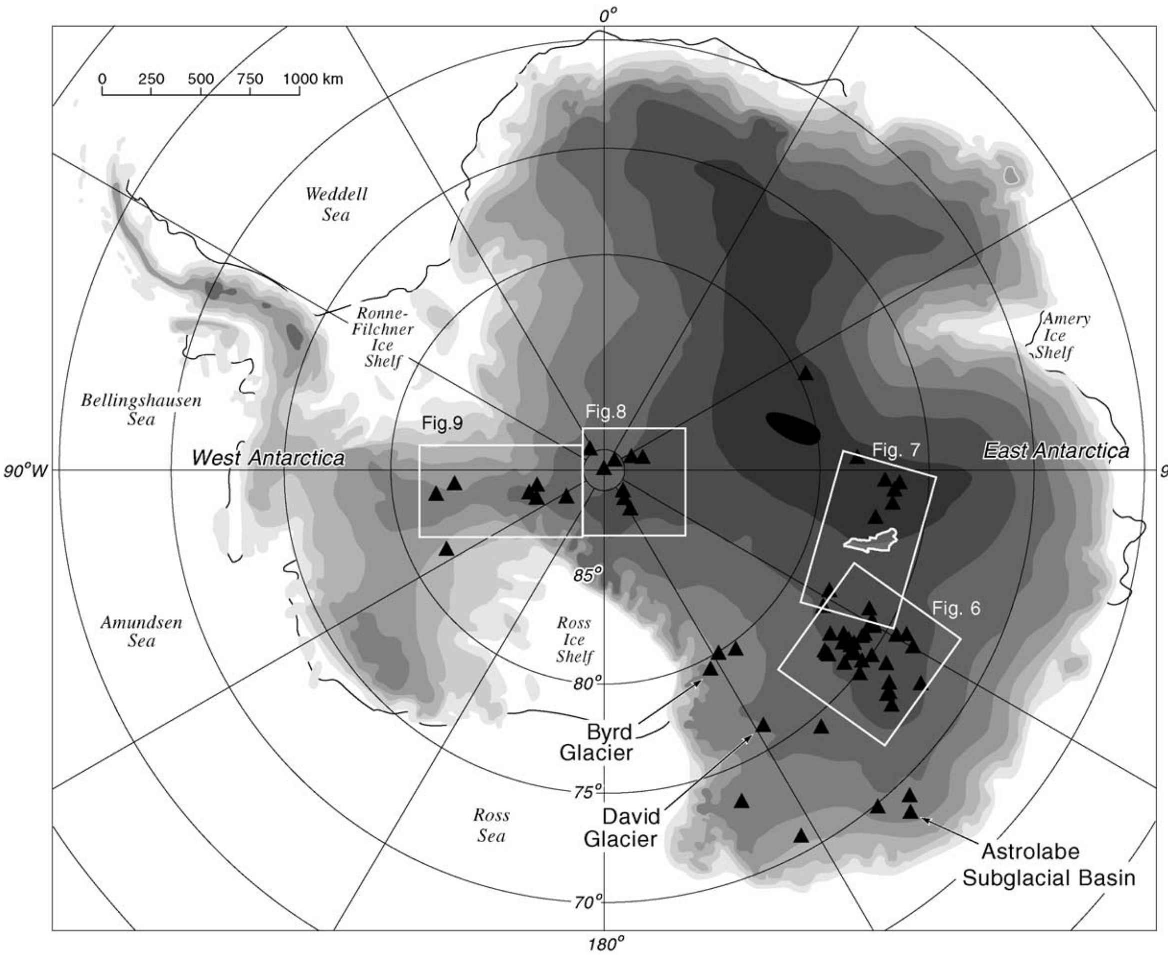


Fig. 1. Map of the Antarctic Ice Sheet showing the locations of Antarctic subglacial lakes (shown as triangles except Lake Vostok which is outlined). The ice-sheet surface is contoured at 500-m intervals (after Drewry, 1983). The boxed areas are enlarged in subsequent figures.

margins, that the lakes are indeed bodies of fresh water and are not simply very flat areas of saturated basal sediment.

Over 400,000 km of RES data, acquired in analogue form at a frequency of 60 MHz, were collected over an area of about 7 million km^2, or about half of

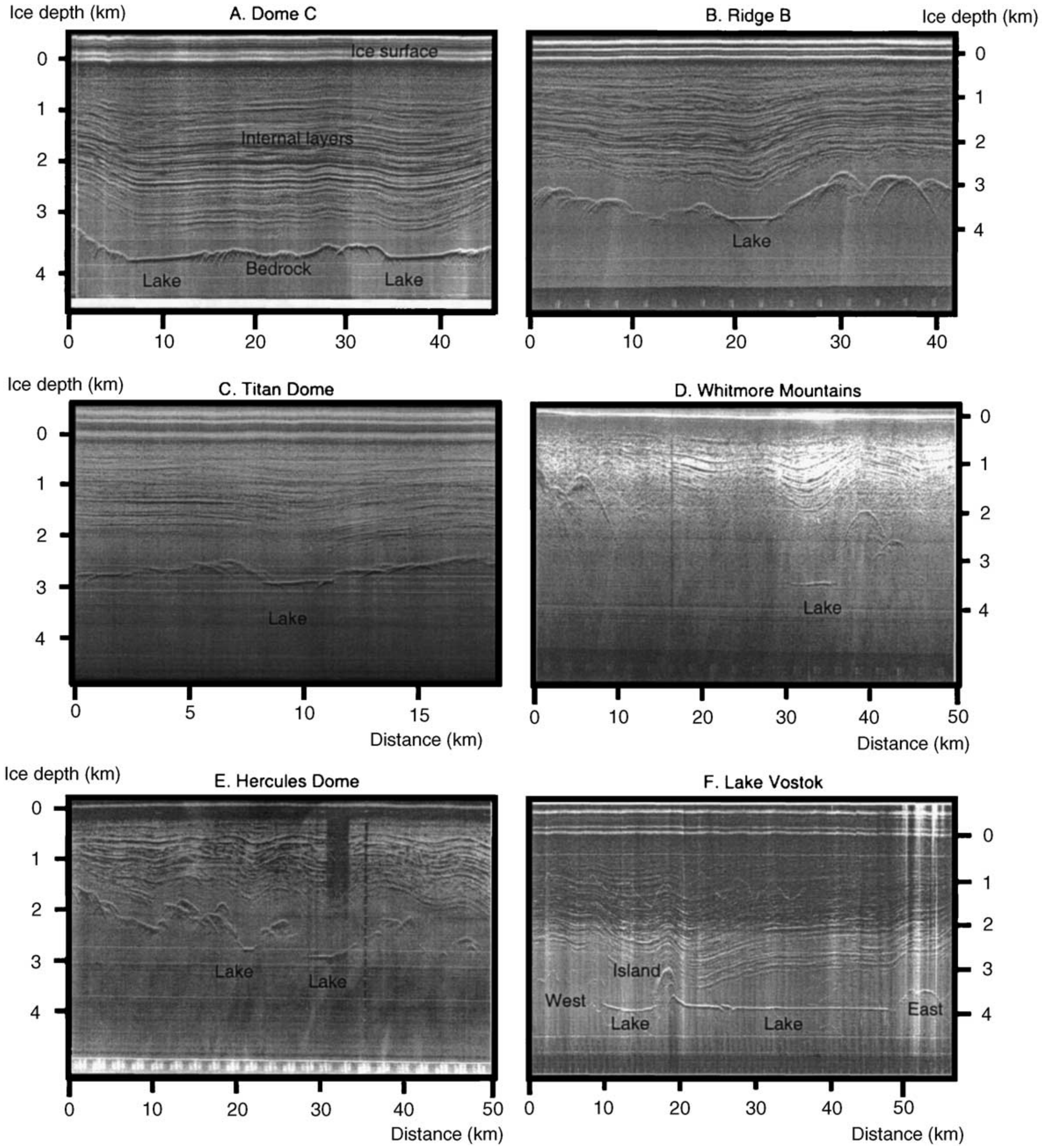


Fig. 2. 60-MHz RES data for eight Antarctic subglacial lakes and their surrounding ice-sheet bed topography. (A) Two lakes in the Dome C area (located in Fig. 6C). (B) Lake in the Ridge B area (located in Fig. 7C). (C) Lake at Titan Dome near the South Pole (located in Fig. 8B). (D) Lake in the Whitmore Mountains area (located in Fig. 9B). (E) Two lakes in the Hercules Dome area located in (Fig. 9B). (F) Lake Vostok, east of Ridge B. Note that, on this flight line over the lake, a bedrock hill protrudes through the lake waters (located in Fig. 7C).

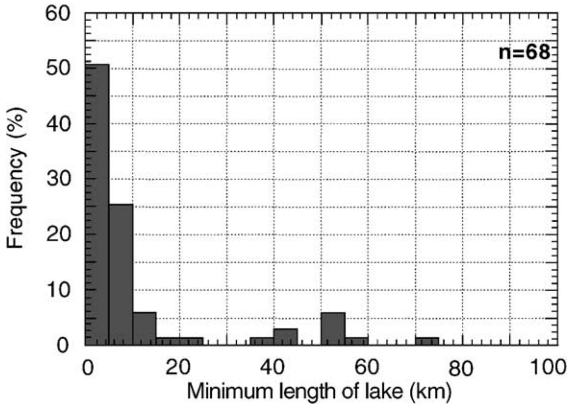


Fig. 3. Observed frequency distribution of the length of Antarctic subglacial lakes, measured from RES records (source: Dowdeswell and Siegert, 1999). Mean lake length is 10.8 km (excluding Lake Vostok).

the Antarctic Ice Sheet, between 1967 and 1979 (Robin et al., 1977). These data were used originally to map the ice-surface and bed topography of the Antarctic Ice Sheet (Drewry, 1983). However, they have been re-examined systematically to provide an inventory of subglacial lake locations, using the following criteria (Siegert et al., 1996; Dowdeswell and Siegert, 1999): (a) strong reflectors at the ice-sheet base, appearing bright and specular on photographic film records, (b) echoes of constant strength along-track, indicating a smooth interface on the scale of the 60 MHz system wavelength, and (c) a virtually horizontal echo character. These characteristics have been used to locate the Antarctic subglacial lakes mapped in Fig. 1, and are illustrated in RES data from six areas of the Antarctic Ice Sheet where subglacial lakes have been identified (Fig. 2).

2.2. Satellite radar altimetry

Extensive, very flat areas on the surface of the Antarctic Ice Sheet, first noted by a Russian aircraft navigator (Robinson, 1964), have been mapped using satellite radar altimetry, a method which provides surface elevations accurate to a few tens of centimeters (Scott et al., 1994). The spatial coincidence of flat regions on the ice surface with strong, specular radio-echo returns from the ice-sheet bed has been demonstrated in several areas of Antarctica (Cudlip and McIntyre, 1987; Ridley et al., 1993; Siegert and Ridley, 1998a,b). This implies that satellite radar altimetric identification of flat areas on the ice surface can be used to infer the presence of subglacial water bodies. The flat ice surface is produced because basal shear stress tends to zero as the ice reaches hydrostatic equilibrium over subglacial lake waters. Lakes smaller than about 4 or 5 km across are unlikely to form this characteristic flat surface, however, as the thick ice above them (a) may not be in hydrostatic equilibrium, and (b) may damp these relatively small-scale changes in basal ice-sheet flow from the ice surface (Dowdeswell and Siegert, 1999). Hence, smaller subglacial lakes can only be observed using RES methods.

The 13-GHz radar altimeter aboard ERS-1/2 has been used to obtain ice-surface elevation data over the Antarctic Ice Sheet to a latitude of 82°S. The ice-surface topography in the Vostok and Dome C areas, in particular, has been examined for flat areas characteristic of the presence of subglacial lakes (Siegert and Ridley, 1998a,b). In addition, no lakes of the magnitude of Lake Vostok (area 10,000 km^2) have been reported from other regions of the Antarctic Ice Sheet for which ERS radar altimeter data are available (J.K. Ridley, 1998, personal communication).

3. Subglacial lake distribution and size

Over 70 subglacial lakes have been identified at the base of the 13 million km^2 Antarctic Ice Sheet

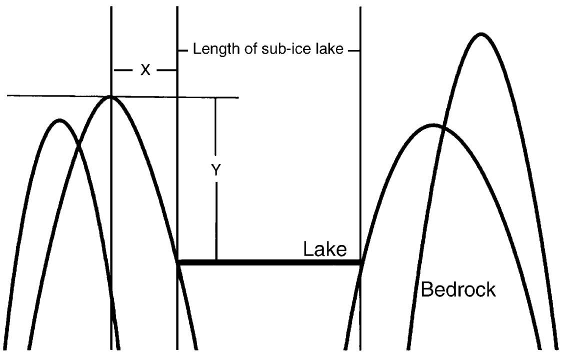


Fig. 4. Sketch showing measurement method for obtaining maximum topographic height and bedrock gradient adjacent to subglacial lakes from RES data. The maximum elevation of the bedrock bordering each lake is *Y*, whilst the bedrock gradient, taken as the distance (*X*) between the lake margin and the crest of nearest hyperbola, is *Y*/*X* (adapted from Dowdeswell and Siegert, 1999).

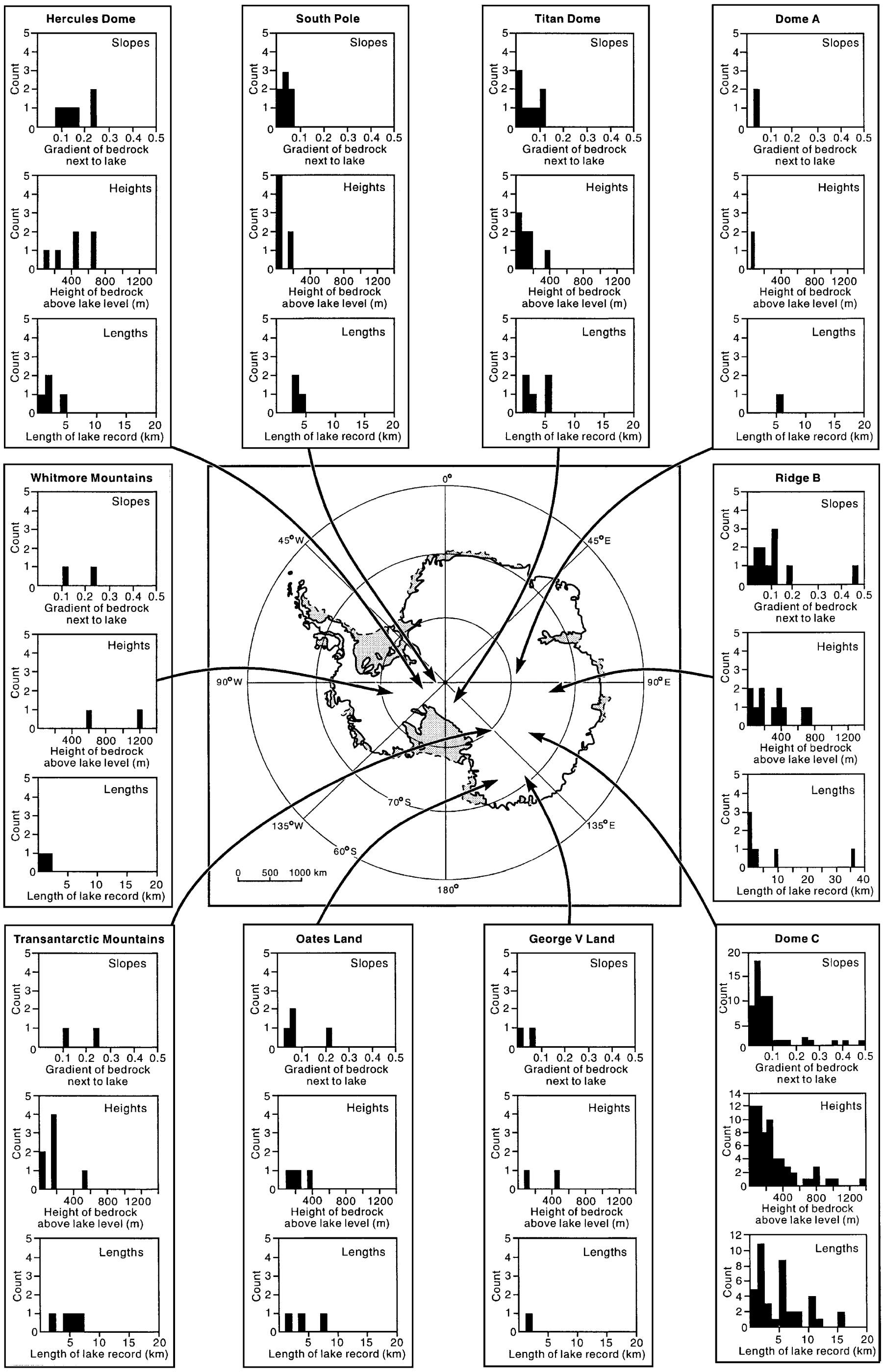


Fig. 5. Ice-sheet bed topography around subglacial lakes in 10 areas of Antarctica. Each area is located on the central map. The slope gradient (degrees) and the height of bedrock (m) close to each lake is given, together with lake lengths (km) in each area. Data are from the analysis of airborne RES records.

(e.g. Oswald and Robin, 1973; Siegert et al., 1996; Dowdeswell and Siegert, 1999), using the distinctive, mirror-like reflectors observed on airborne RES records (Figs. 1 and 2). The thickness of ice above these subglacial lakes is between about 2500 and 4000 m. The bulk of the lakes are located in the interior of the Antarctic Ice Sheet, at or close to ice divides in the form of domes and ridges, where ice velocity is low (Dowdeswell and Siegert, 1999). Almost 60% of the lakes are found within 200 km of an ice crest, remembering that ice flowlines from divide to margin are often over 1000 km long in Antarctica (Fig. 1). Only about 15% of the subglacial lakes are positioned more than 500 km from an ice divide.

The largest Antarctic subglacial lake is that located near Vostok Station in central East Antarctica (Fig. 1). The dimensions of this lake, known as Lake Vostok, have been mapped from a combination of airborne RES and satellite radar altimetric measurements (Kapitsa et al., 1996; Siegert and Ridley, 1998a). The lake is about 230 km long and has an area of approximately 10,000 km^2, similar to that of Lake Ontario (Kapitsa et al., 1996). A maximum water depth of 510 m was measured using seismic methods, although mean water depth is thought to be nearer 200 m. The estimated volume of Lake Vostok is a little less than 2000 km^3.

The other 70 or so subglacial lakes identified beneath the Antarctic Ice Sheet are one to two orders of magnitude smaller than Lake Vostok. Although

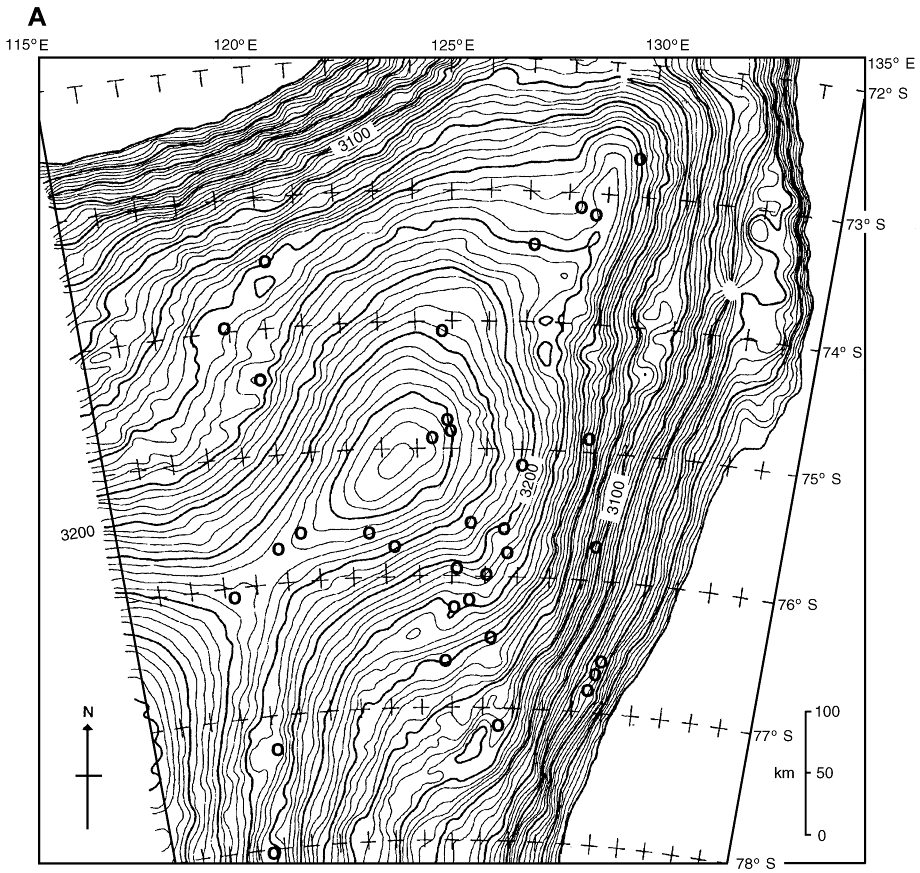


Fig. 6. Ice-surface and bedrock topography, and the locations of subglacial lakes (shown as open circles), in the Dome C region of Antarctica (located in Fig. 1). (A) Ice-surface topography from satellite radar altimetry. Contour interval 4 m (source: Siegert and Ridley, 1998b). (B) Subglacial bed topography, contoured at 500-m intervals (source: Drewry, 1983). (C) Grid of airborne RES flight lines used to map subglacial topography and lake locations. The RES record shown in Fig. 2A is located.

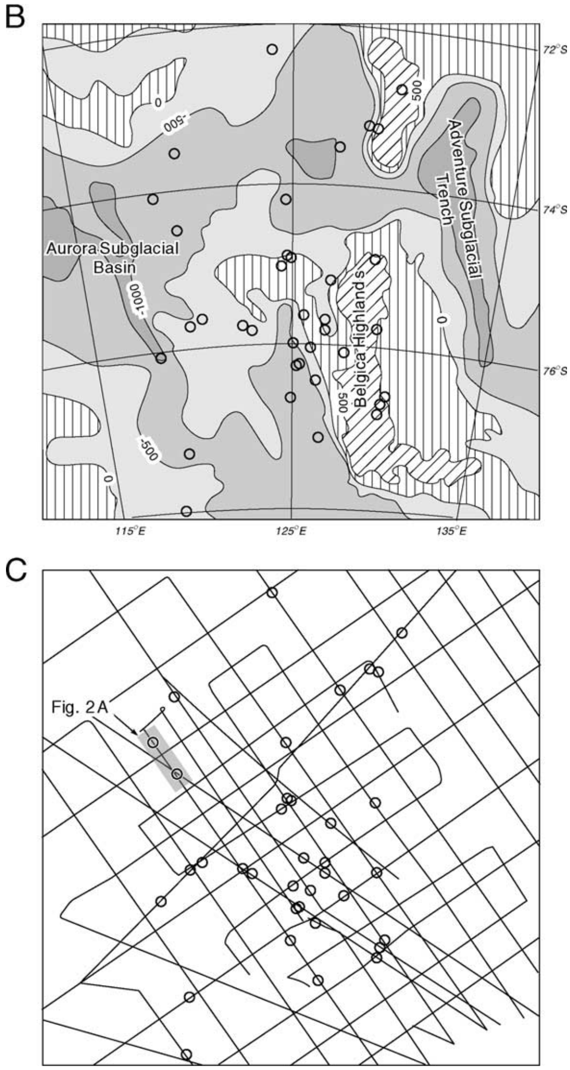


Fig. 6 (*continued*).

airborne RES data are restricted to about 400,000 km of flight tracks over the ice sheet, satellite radar altimeter data demonstrate that no other lakes of the size of Vostok exist beneath the ice sheet. The frequency distribution of lake lengths, derived from airborne RES, is shown in Fig. 3. About 75% of lakes have observed lengths of less than 5 km. Only Lake Vostok is longer than 50 km.

The volume of water held in Antarctic subglacial lakes can also be calculated after certain assumptions have been made. First, lakes are assumed to be circular, with the radio-echo-derived length providing a minimum value for lake diameter. Secondly, water depth is inferred, from measurements of the bedrock topography surrounding the set of lakes (Fig. 4), to be between about 50 and 250 m. Over 50% of the lakes are likely to contain less than 5 km^3 of water, and only 10% store more than about 100 km^3.

The total volume of water stored in lakes beneath the Antarctic Ice Sheet has been calculated by Dowdeswell and Siegert (1999). It is estimated to be between approximately 4000 and 12,000 km^3, on the assumptions that the size-frequency distribution of subglacial lakes observed from airborne RES can be extended over the whole ice sheet, and that 2000 km^3 of water is held in Lake Vostok (Kapitsa et al., 1996). The large uncertainty in this calculation is due to the unknown mean water depth of subglacial lakes other than Lake Vostok. This volume of water, in the very unlikely event of being released at a single time, would raise global sea level by 10–35 mm. Most of the larger Antarctic lakes probably contain a few hundred cubic kilometers of water at most.

4. Subglacial lakes and regional bed topography

The bed topography bordering Antarctic subglacial lakes is characterised in two ways using airborne RES data (Fig. 4). First, the maximum heights of hyperbolic RES reflectors, representing the bedrock close to the lake margin, are recorded. Secondly, the gradient between the maximum bedrock height and the edge of the lake inferred from RES is calculated (Fig. 4). It should be noted that rough subglacial terrain is displayed as a series of hyperbolae on radio-echo records (Fig. 2). On such unmigrated records, the hyperbola crests represent real data points, whereas the trailing edges are artefacts of the RES technique (e.g. Harrison, 1970).

The bed-topographic setting of subglacial lakes in 10 areas of the Antarctic Ice Sheet is shown in Fig. 5. More than 60% of lake records have maximum local bedrock elevations of less than 400 m adjacent to their margins and bed gradients of less than 0.1 (Fig. 5). The implication of these measurements is that the majority of Antarctic subglacial lakes are found in areas of relatively low bed relief. In addition, comparisons of these two topographic parameters with estimated subglacial lake length indicate that large lakes tend to occur where bed topography is subdued. A clear exception to this is Lake Vostok, where an extensive alpine terrain exists, particularly to the west of the lake, with bedrock elevations of about 1000 m above the lake level within 10 km of its margin (Kapitsa et al., 1996).

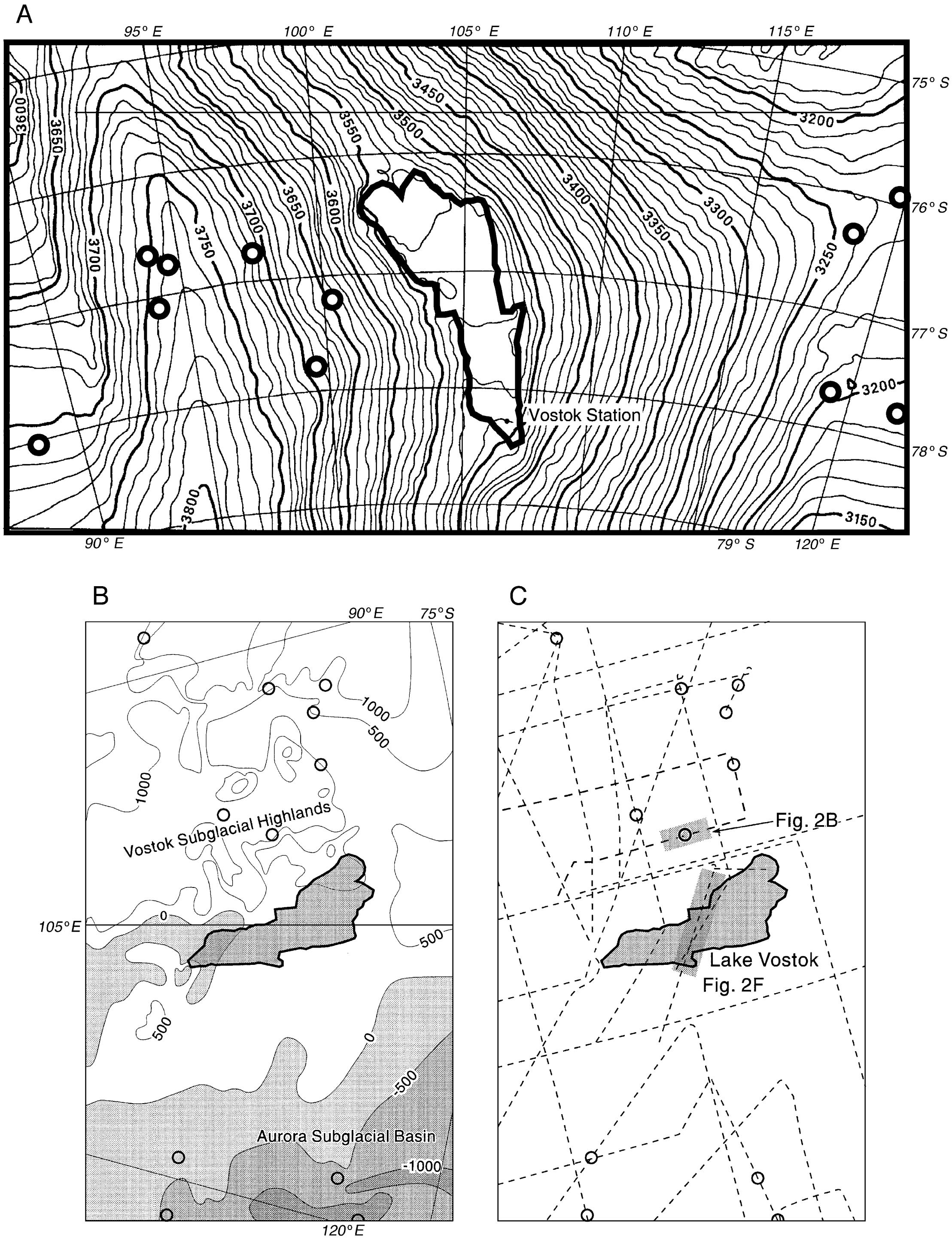
Ice-sheet bed topography is rather flat in many regions, which represent large subglacial basins, and bedrock gradients are seldom greater than 0.2 (Fig. 5). Examples include the South Pole area, together with many of the domes and ridges near the ice-sheet centre, where surface topography and ice velocity are also very low. An RES record of two subglacial lakes located in low-gradient terrain in the Dome C region is shown in Fig. 2A, and the bulk of lakes around Dome C are also found in relatively flat terrain. Examples of relatively steep bed topography are shown in the radio-echo records for lakes in the Whitmore Mountains and near Hercules Dome (Fig. 2D,E), where subglacial lakes can be seen perched within steep mountain terrain.

5. Topographic setting of subglacial lakes: examples

5.1. Dome C region

The association between subglacial lake locations and smooth areas of the ice-sheet surface can be seen clearly in Fig. 6. Here, lake locations are superimposed on a digital elevation model of the ice surface around Dome C, contoured with an interval of 4 m from ERS-1 satellite radar altimetry (Ridley et al., 1993). This relationship between lakes and low ice-surface slopes is typical for larger subglacial water bodies, and indicates that the ice has reached hydrostatic equilibrium with the underlying fluid. The match between lake locations and particularly flat surface terrain does not extend to lakes smaller than about 4–5 km, for two reasons. First, the ice above these smaller lakes is not necessarily in hydrostatic equilibrium due to the effects of bedrock sidewalls. Secondly, the satellite radar altimeter, with a footprint of 18 km, does not always resolve very small areas of flat surface.

Fig. 7. Ice-surface and bedrock topography, and the locations of subglacial lakes (shown as open circles), in the Ridge B region of Antarctica (located in Fig. 1), including Lake Vostok. (A) Ice-surface topography from satellite radar altimetry. Contour interval 10 m (source: Siegert and Ridley, 1998a). (B) Subglacial bed topography, contoured at 500-m intervals (source: Drewry, 1983). (C) Grid of airborne RES flight lines used to map subglacial topography and lake locations. Subglacial lakes are shown as circles with the exception of Lake Vostok, which is outlined in detail. The RES records shown in Fig. 2B and F are located.


A
95° E
100° E
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110° E
115° E
75° S
76° S
77° S
78° S
79° S
90° E
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3600
3650
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3750
3800
3550
3500
3450
3400
3350
3300
3250
3200
3150
Vostok Station
B
90° E
75° S
105° E
120° E
1000
500
0
-500
-1000
Vostok Subglacial Highlands
Aurora Subglacial Basin
C
Fig. 2B
Lake Vostok
Fig. 2F

Over 40 subglacial lakes are concentrated around Dome C, and over 80% of these are located in areas of relatively subdued bedrock topography within large subglacial basins (Fig. 6B). Bedrock gradients around the majority of lakes are less than 0.1, and the surrounding highs are often significantly less than 200 m in elevation (Fig. 5). The radio-echo record in Fig. 2a is typical of much of the Dome C region. Two strong and very flat RES reflectors of between 5 and 10 km in length are identified as subglacial lakes within a rather smooth bedrock terrain. The frequency-distribution diagrams for Dome C in Fig. 5 also show that a few subglacial lakes are associated with relatively steep bedrock gradients of greater than 0.3 and surrounding highs of over 1000 m, but these are the exception and are found around the margins of the subglacial basin (Fig. 6B).

5.2. Ridge B area

The ice-surface topography of the Ridge B area is contoured at 10-m intervals (Fig. 7A). The ice surface at Ridge B has a maximum elevation of more than 3800 m. To the east, an extensive area of several thousand square kilometers of very flat ice represents the surface manifestation of subglacial Lake Vostok (Kapitsa et al., 1996; Siegert and Ridley, 1998a). At the coarser resolution of this satellite altimeter-derived surface contour map, few of the other, smaller subglacial lakes show up clearly in the ice-surface topography (Fig. 7A).

Bedrock topography in the Ridge B area is shown in Fig. 7B, and is derived from analysis of the network of RES data acquired along the flight lines shown in Fig. 7C. Lake Vostok appears to be located in a topographic basin, with relatively lower slopes to the east and steeper terrain to the west. A radio-echo transect across Lake Vostok is shown in Fig. 2F. The remaining, smaller lakes around Ridge B fall into two types of location. First, several are located on the flanks of the bed-topographic ridge, to the west of Lake Vostok, which has its surface manifestation in Ridge B itself (Fig. 7A). It should be noted that the radio-echo record shown in Fig. 2B runs parallel to the contour of this bedrock high, and the bed topography around the lake located here is, therefore, minimised in this record. The second cluster of lakes is positioned in the east of the region, within the Aurora Subglacial Basin mapped in Fig. 7B, which is an area of low bedrock gradients that are generally less than 0.1 (Fig. 5).

5.3. South Pole region

Around the South Pole, the ice-sheet bed topography is generally subdued (Fig. 8A). Bedrock ele-

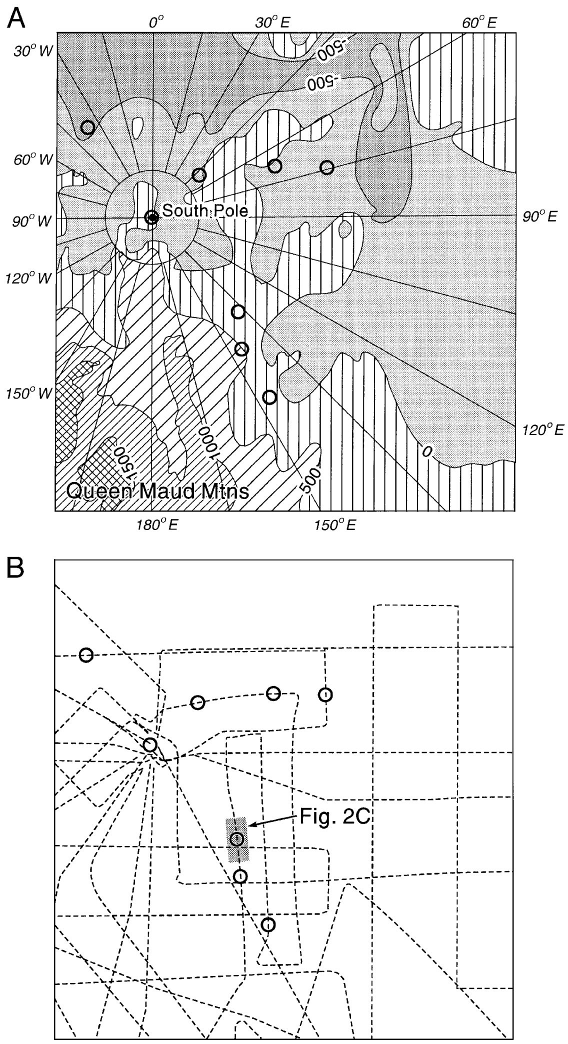

Fig. 8. Ice-sheet bedrock topography and the locations of subglacial lakes (shown as open circles) in the South Pole region of Antarctica (located in Fig. 1). (A) Subglacial bed topography, contoured at 500-m intervals (source: Drewry, 1983). (B) Grid of airborne RES flight lines used to map subglacial topography and lake locations. The RES record shown in Fig. 2C is located.

vations in the vicinity of subglacial lakes do not exceed 200 m above the lake surface, and bedrock gradients are less than 0.1 (Fig. 5). The eight lakes observed in the South Pole area are located in low gradient basal settings on the margins of and within a large subglacial basin, which is also close to an ice-surface ridge. An example is shown in a radio-echo record of a lake from the Titan Dome area (Fig. 2C).

No lakes have been identified beneath ice in the more mountainous terrain rising to over 1500 m above sea level that marks the Queen Maud Mountains flank of the Transantarctic Mountains, despite a relatively comprehensive network of airborne RES flight lines (Fig. 8B). In the easternmost part of the area mapped in Fig. 8, radio-echo flight lines are more sparse and the lack of observed lakes may be, in part at least, an artefact of this coarser grid spacing.

5.4. Hercules Dome and Whitmore Mountains

The Hercules Dome and Whitmore Mountains are located progressively westwards of the South Pole, and a part of Fig. 9 is the only area of the West Antarctic Ice Sheet discussed in this paper (Fig. 1). Bedrock reaching to over 2000 m above sea level forms the Whitmore, Thiel and Horlich subglacial mountains (Fig. 9A). These bedrock massifs are separated by lower-lying subglacial terrain. The easternmost part of the region, closest to the South Pole, has significantly more subdued topography than the rest of the region, representing part of a major subglacial basin. However, the remainder of the area has the most complex and mountainous bedrock topography of the four regions discussed here (Fig. 9A).

The two subglacial lakes located in the Whitmore Mountains are both in mountainous terrains (Fig. 5). This is illustrated clearly in the radio-echo record in Fig. 2C, where a subglacial lake about 5 km in length is positioned between surrounding mountains rising over 1000 m above it. The four subglacial lakes in the Hercules Dome area appear from Fig. 9A to be set in more gentle bedrock relief than the Whitmore Mountains. One, nonetheless, has a marginal gradient of 0.2, and the two lakes recorded in Fig. 2E are in relatively rough bedrock terrain, although the absolute amplitude of the surrounding highs is less than 500 m.

6. Discussion: subglacial lakes, thermal structure and ice dynamics

6.1. Characterisation of bed-topographic setting of subglacial lakes

From an examination of the dimensions, glaciological and topographical settings of Antarctic subglacial lakes, we can characterize subglacial lakes into several groups, as outlined below.

6.1.1. Lakes in subglacial basins in the ice-sheet interior

The majority of Antarctic subglacial lakes are located within 200 km of ice divides in the interior of the ice sheet (Fig. 1). The bedrock topography of the ice-sheet interior is characterized by 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 towards the centre of subglacial basins. The radio-echo record of two lakes in the Dome C region provides an example (Fig. 2A). Secondly, some lakes occur in significant topographic depressions, often closer to subglacial basin margins, but still near the slow-flowing centre of the Antarctic Ice Sheet. Lake Vostok is a good example of this type of lake (Fig. 2F). Where bed topography is very subdued, deep subglacial lakes like Lake Vostok are unlikely to develop.

6.1.2. Lakes perched on the flanks of subglacial mountains

These perched subglacial lakes are found mainly in the interior of the ice sheet, on the flanks of subglacial mountain ranges (Fig. 9A). In several cases, we have observed small (< 10 km long) subglacial lakes perched on the stoss face of large (>300 m high), steep (gradient >0.1) subglacial hills. An example is shown in a radio-echo record of a perched lake in the Whitmore Mountains of West Antarctica (Fig. 2D).

6.1.3. Lakes close to the onset of enhanced ice flow

At least 16 subglacial lakes occur at locations which are close the onset of enhanced ice flow, some hundreds of kilometers from the ice-sheet crest (Sie-

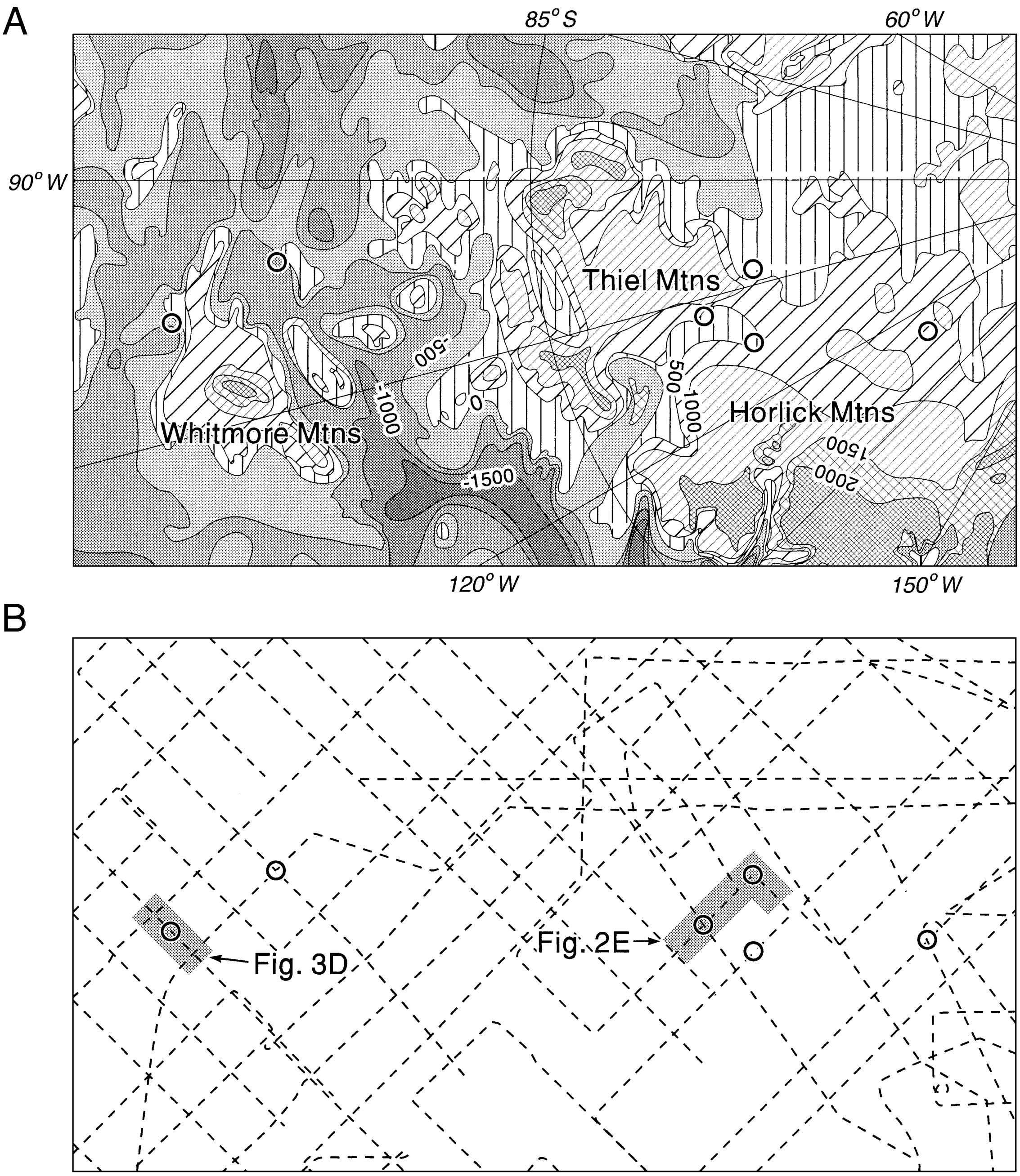

Fig. 9. Ice-sheet bedrock topography and the locations of subglacial lakes (shown as open circles) in the Whitmore Mountains and Hercules Dome region of Antarctica (located in Fig. 1). (A) Subglacial bed topography, contoured at 500-m intervals (source: Drewry, 1983). (B) Grid of airborne RES flight lines used to map subglacial topography and lake locations. The RES records shown in Fig. 2D–E are located.

gert and Bamber, in press). An example is provided by three subglacial lakes near the onset of fast flow into Byrd Glacier (Fig. 1). 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 major subglacial basins in the ice-sheet interior.

6.2. Lakes and ice-sheet thermal structure

Although it can be assumed that the temperature of the ice-sheet base above subglacial lakes is at the pressure melting point (Siegert and Dowdeswell, 1996), information about the subglacial thermal regime across Antarctica is limited mainly to numerical model calculations. Huybrechts (1992) used a thermally coupled ice-sheet model of the Antarctic Ice Sheet to estimate the distribution of subglacial temperatures. The results indicate that pressure melting conditions occur across two distinct zones beneath the ice sheet. The first is around the centre of the ice sheet, where ice is generally thickest and acts to insulate the ice-sheet base, kept warm by geothermal heat, from the cold conditions at the ice surface. Thicker ice also acts to reduce the value of the melting temperature because of the overburden pressure of several kilometers of ice. The second warm-based region determined by Huybrechts (1992) is where the friction involved in the enhanced flow of ice provides a source of heat, in addition to the geothermal flux, that causes subglacial melting. In general, as the rate of ice flow increases, so too will this frictional heat source. Pressure melting conditions are, therefore, expected beneath fast-flowing outlet glaciers and ice streams, despite the fact that the thickness of ice within these fast-flowing regions is often considerably less than in the ice-sheet interior (Drewry, 1983). Between these two warm-based regions, Huybrechts (1992) calculated that subglacial freezing occurs.

At a continental scale, the locations of Antarctic subglacial lakes tie in well with the distribution of a bed at the pressure melting point close to the ice-sheet centre and beneath fast-flowing outlets (Fig. 1). However, around a large number of subglacial lakes at the centre of the ice sheet, relatively high topographic relief results in regional variations in ice thickness and, because of this, potential modification in the subglacial temperature around the lake.

It is not yet fully understood why some lakes form across the stoss flank of large subglacial hills. However, we can speculate that subglacial mountains may act as a barrier to the flow of water, thus causing it to build up at the upstream side.

6.3. Melting and freezing at Lake Vostok

A clear example of a location where the ice sheet is likely to be at the pressure melting point is the northern end of Lake Vostok in central East Antarctica (Siegert et al., 2000, 2001). Several RES lines were flown across the lake, parallel to the direction of ice-sheet flow, as determined from interferometric synthetic aperture radar (InSAR) measurements (Kwok et al., 2000). Internal layers within RES data represent isochronous horizons and are often traceable continuously across large distances (Millar, 1981; Siegert et al., 1998) (Fig. 2F). Such layering, deep beneath the ice-sheet surface, reflects the flow paths of ice particles. As ice flows across the north of Lake Vostok, the distance between the lowest internal layers and the ice-sheet base decreases (Fig. 2F). This effect is recording a loss of ice, which is due to subglacial melting at a rate of several cm year^{-1} (Siegert et al., 2000). Further, in the southern part of the lake, around Vostok Station, the distance between internal layers and the ice-sheet bed increases, due to the accretion of ice to the underside of the ice sheet (Bell et al., 2002). The lowest 200 m of the Vostok ice core is known to comprise ice refrozen from the lake waters (Jouzel et al., 1999). This implies that there is a circulation of water within Lake Vostok, driven by geothermal heat, which causes subglacial melting over the northern part of the lake (where ice thickness is around 4.1 km), and refreezing to the south (where ice is thinnest at about 3.7 km) (Siegert et al., 2000, 2001). The sparsity of InSAR ice velocity data across the Antarctic interior precludes the application of the findings from Lake Vostok to other subglacial lakes, since the direction of ice flow cannot be established unequivocally.

6.4. Bed topography, lakes and ice-stream onset

Recent calculations of Antarctic Ice Sheet velocities suggest that transition between the slow-flowing ice sheet interior and enhanced flow at the onset of ice streams is likely to be associated with the occurrence of warm-based subglacial conditions within bed-topographic channels (e.g. Joughin et al., 1999; Bamber et al., 2000). The distribution of Antarctic subglacial lakes shows that 16 are located close to the transition to enhanced ice-sheet flow (Siegert and Bamber, 2000). This implies that a number of tributaries to major outlet glaciers, several hundred kilometers from the ice margin, are warm-based regions. Examples of subglacial lakes located close to areas where fast glacier flow begins include the head of David Glacier, which drains through the Transantarctic Mountains into the Ross Embayment, and a lake at the mouth of the Astrolabe Subglacial Basin in East Antarctica (Fig. 1). Warm-based fast-flowing ice streams provide a possible route by which subglacial lakes, located at the onset of enhanced ice flow, may establish a hydrological connection with the ice-sheet margin.

Observations of subglacial lakes located close to major Antarctic ice drainage features (Siegert and Bamber, 2000) act as a potential model for the subglacial environment of Quaternary ice sheets. Shaw (1996) has suggested that the topography of a number of large drumlin fields in Canada was developed during large outburst floods of subglacial water from the Laurentide Ice Sheet during the last deglaciation. In East Antarctica at present, it is unlikely that lakes beneath the centre of the ice sheet (such as those at Dome C and Ridge B, and Lake Vostok) could outburst to the ice margin because they would require rapid large-scale decoupling of frozen parts of the ice-sheet base. Evidence from recent jokülhlaups in Iceland indicates that outburst floodwaters follow a relatively organised subglacial pathway, controlled by water pressure gradients. Subglacial floods are therefore more likely to issue through existing, albeit rapidly enlarged, subglacial conduits and channels. In Antarctica, such subglacial hydrology is associated with enhanced ice drainage units.

We suggest that, if subglacial floodwater escapes to the margin of the East Antarctic Ice Sheet at all, it is most likely to have originated from a subglacial lake associated with enhanced ice flow. During the decay of an ice sheet, as the ice margin retreats, the head of ice streams and outlet glaciers may migrate toward the present-day ice divide into the formerly frozen ice base. This could allow other subglacial lakes to become involved in the release of water to the base of enhanced ice-flow features and, thus, to the proglacial region. The glacimarine sedimentary record in the waters around Antarctica should hold evidence of such events, if indeed they have taken place.

7. Conclusions

Large water bodies were identified beneath the Antarctic Ice Sheet during the 1970s (e.g. Oswald and Robin, 1973; Robin et al., 1977). The size and distribution of these subglacial lakes have recently been investigated systematically at a continent-wide scale using airborne RES and satellite radar altimetry (e.g. Ridley et al., 1993; Siegert et al., 1996; Dowdeswell and Siegert, 1999). The following represent the main conclusions of this work concerning the physiography of lakes beneath the Antarctic Ice Sheet today.

- Over 70 subglacial lakes have been identified beneath the 13 million km^2 Antarctic Ice Sheet (e.g. Oswald and Robin, 1973; Siegert et al., 1996; Dowdeswell and Siegert, 1999), using the distinctive, mirror-like reflectors observed on airborne RES records (Figs. 1 and 2). Almost 60% of lakes are found within 200 km of an ice divide, remembering that ice flowlines from crest to coastal margin are often over 1000 km in length (Fig. 1). Only about 15% of subglacial lakes are located more than 500 km from an ice divide. The total volume of water stored in lakes beneath the Antarctic Ice Sheet is estimated to be between about 4000 and 12,000 km^3 (Dowdeswell and Siegert, 1999).
- The bedrock topography of the ice-sheet interior is characterized by large subglacial basins separated by mountain ranges (Drewry, 1983). More than 60% of lake records have maximum local bedrock elevations of <400 m adjacent to their margins and bed gradients of less than 0.1 (Fig. 5), implying that many Antarctic subglacial lakes are found in areas of relatively low bed relief. Over 40 subglacial lakes are concentrated around Dome C, and over 80% of these are found in relatively subdued bedrock topography within large subglacial basins (Fig. 6B). Lake Vostok, near Ridge B, appears to be located in a topographic basin, with relatively lower slopes to the east and steeper terrain to the west.

• Many lakes are found in and on the margins of subglacial basins. First, there are those located where subglacial topography is relatively subdued, often towards the centre of subglacial basins. Secondly, some lakes occur in significant topographic depressions, often closer to subglacial basin margins, but still near the slow-flowing centre of the Antarctic Ice Sheet. Lakes are also found perched on the flanks of subglacial mountains, mainly in the interior of the ice sheet (Fig. 9A).

• At a continental scale, the locations of Antarctic subglacial lakes match the modeled distribution of pressure melting at the bed (Huybrechts, 1992), which is found close to the ice-sheet centre and beneath fast-flowing outlets. It is assumed that the temperature of the ice-sheet base above subglacial lakes is at the pressure melting point (Siegert and Dowdeswell, 1996).

• The distribution of Antarctic subglacial lakes also shows that 16 are located close to the transition to enhanced ice-sheet flow. This implies that a number of tributaries to major outlet glaciers, several hundred kilometers from the ice margin, are warm-based regions. An example is provided by three subglacial lakes near the onset of fast flow into Bryd Glacier (Fig. 1). Warm-based fast-flowing ice streams could provide a possible route by which subglacial lakes, located at the onset of enhanced ice flow, might establish a hydrological connection with the ice-sheet margin.

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