The Identification and Physiographical Setting of Antarctic Subglacial Lakes: An Update Based on Recent Discoveries

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We investigate the glaciological and topographic setting of known Antarctic subglacial lakes following a previous assessment by Dowdeswell and Siegert (2002) based on the first inventory of 77 lakes. Procedures used to detect subglacial lakes are discussed, including radio echo sounding (RES) (which was first used to demonstrate the presence of subglacial lakes), surface topography, topographical changes, gravity measurements, and seismic investigations. Recent discoveries of subglacial lakes using these techniques are detailed, from which a revised new inventory of subglacial lakes is established, bringing the total number of known subglacial lakes to 387. Using this new inventory, we examine various controls on subglacial lakes, such as overlying ice thickness and position within the ice sheet and formulate frequency distributions for the entire subglacial lake population based on these (variable) controls. We show how the utility of RES in identifying subglacial lakes is spatially affected; lakes away from the ice divide are not easily detected by this technique, probably due to scattering at the ice sheet base. We show that subglacial lakes are widespread in Antarctica, and it is likely that many are connected within well-defined subglacial hydrological systems.

1. INTRODUCTION

A variety of methods have been used in the discovery and characterization of subglacial lakes and the identification of subglacial water movement in Antarctica (Figure 1). The first inventory of subglacial lakes, recording 77 lake locations, used the technique of radio echo sounding [*Siegert et al.*, 1996]. This was later updated to 145 lakes by *Siegert et al.* [2005]. Several other techniques are available for the detection of subglacial lakes, including surface topography, topographical changes, gravity survey, and seismic investigations. The aim of this paper is to detail all the techniques available for the detection of subglacial lakes, and to pull together recent information regarding lake locations. In doing so, a revised inventory is established, from which an assessment of the dimensions and topographic setting of subglacial lakes is updated [from *Dowdeswell and Siegert*, 2002].

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2. DISCOVERY, IDENTIFICATION, AND CHARACTERIZATION OF SUBGLACIAL LAKES

2.1. Radio Echo Sounding (RES)

2.1.1. Development of the technique. The technique of RES takes advantage of a window in the radio part of the electromagnetic spectrum within which emitted waves will travel freely through both ice and air. As with all E-M waves, reflections occur at boundaries between materials with different dielectric properties and therefore different speeds of

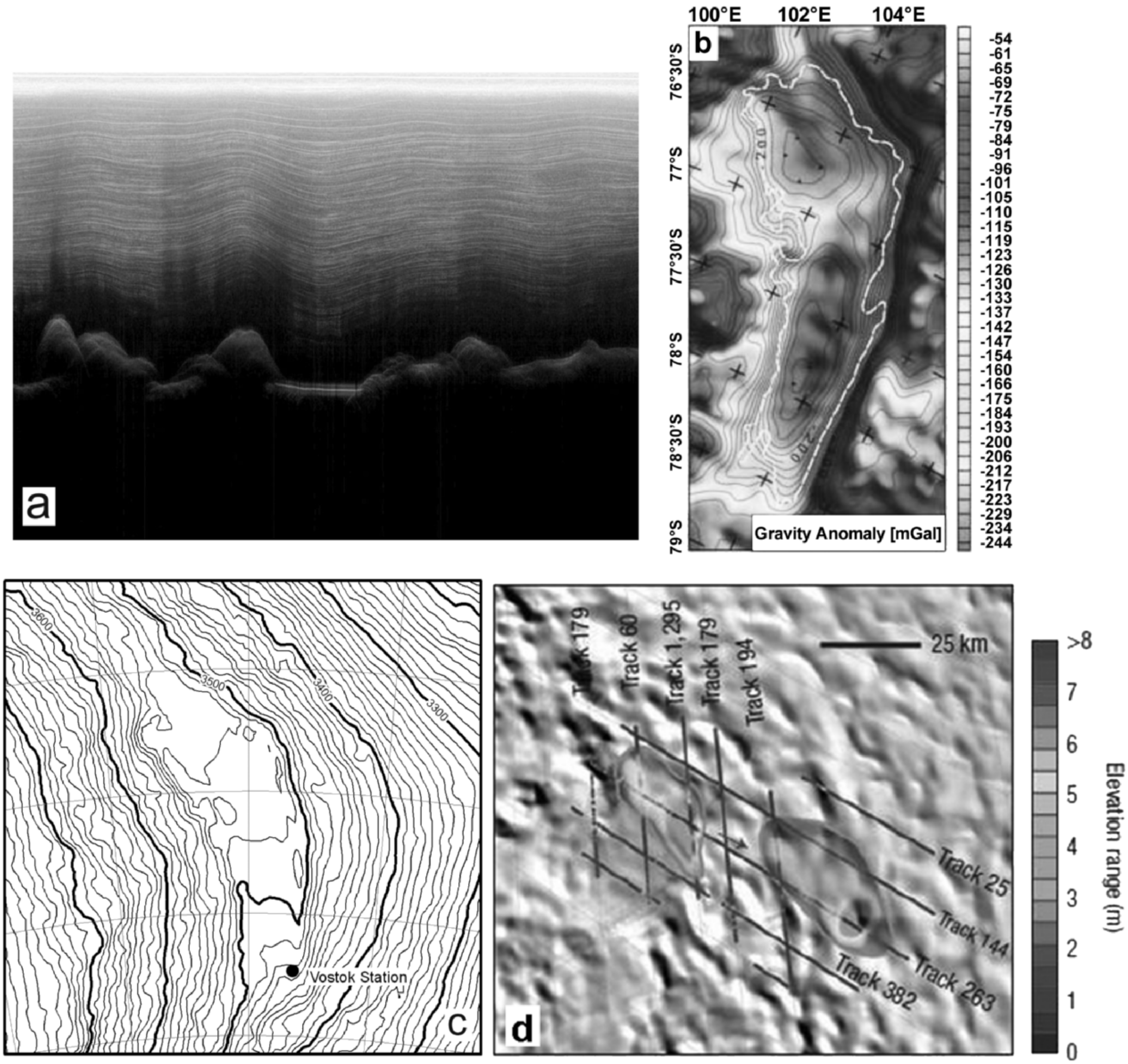

Figure 1. Methods of investigating subglacial lakes: (a) radio echo sounding (RES), a lake reflector is visible in the center; (b) free-air gravitational anomaly (with ice sheet effects removed) detected from the air above Vostok Subglacial Lake [*Studinger et al.*, 2004b]; (c) prominent flat spot in the ice sheet extending north of Vostok Station, 10-m contours from ERS-1 radar altimetry [*Siegert and Ridley*, 1998b]; and (d) vertical surface elevation changes measured by ICESat used to identify two lakes within the catchment of the Byrd Glacier, East Antarctica. Reprinted by permission from Macmillan Publishers Ltd: *Nature Geoscience* [*Stearns et al.*, 2008], copyright 2008.

wave propagation. On entering ice, the speed of the radio wave drops by nearly half, from 300 to 168 m μs^{-1} [*Glen and Paren*, 1975]. An active transmit/receive radar antenna, mounted either near the surface [e.g., *Popov et al.*, 2003] or on an airborne platform [e.g., *Blankenship et al.*, 2001], can therefore be used to detect reflections originating from both within and at the base of a glacier or ice sheet.

The initial investigations of the base of the Antarctic ice sheet were carried out as part of a joint Scott Polar Research Institute (SPRI), National Science Foundation (NSF), and

Technical University of Denmark (TUD) airborne RES campaign. Between 1967 and 1979, this project completed over 400,000 km of line transects, spaced by an average of 50 km, and covering approximately half of the total area of Antarctica [*Robin et al.*, 1977; *Drewry*, 1983].

The SPRI-NSF-TUD survey was able to penetrate even the thickest ice in Antarctica using a 60-MHz frequency radar. By measuring the time elapsed between transmit and receive, it was shown that an ice thickness greater than 4 km existed over large parts of East Antarctica [*Drewry*, 1983]. Nearly 40 years later, this is still the greatest aerial coverage of any single aerogeophysical survey in Antarctica. More recent airborne RES surveys have been characterized by smaller spatial coverage but much higher spatial resolution [e.g., *Rémy and Tabacco*, 2000; *Popov et al.*, 2002; *Rippin et al.*, 2003; *Studinger et al.*, 2003a, 2004a; *Holt et al.*, 2006a; *Vaughan et al.*, 2006]. In several instances, these surveys have targeted areas not covered, or only sparsely covered by the SPRI-NSF-TUD data, with the result being a patchwork of bed information. Despite these efforts, however, a number of large gaps still exist where our knowledge of the ice sheet bed remains poor [e.g., *Le Brocq et al.*, 2008].

Several reviews detail both developments in the techniques of radioglaciology and the resulting enhancements in our understanding of the ice sheets [e.g., *Plewes and Hubbard*, 2001; *Dowdeswell and Evans*, 2004; *Bingham and Siegert*, 2007]. This subject will therefore not be discussed further here.

2.1.2. The discovery of subglacial lakes. The discovery of the first subglacial lake occurred near the Russian station at Sovetskaya during the 1967/1968 season of SPRI-NSF-TUD radio echo sounding [*Robin et al.*, 1970]. An area of unusually low signal fading and short duration of the returned pulse, indicating a specular reflection, was found to coincide with low attenuation of the transmitted signal and a near-horizontal, flat bed geometry. This was, at first tentatively, best explained as the result of a sub-ice water body [*Robin et al.*, 1970]. During the 1971/1972 season, an extension of the RES survey over the Dome C area identified a further 16 similar locations, indicating that the occurrence of pockets of liquid water, or subglacial lakes, beneath the central regions of the ice sheet might be relatively commonplace [*Oswald and Robin*, 1973]. Owing to the lack of penetration through water of radio waves at megahertz frequencies, the depths of these newly discovered features could not be determined, only that a sufficient depth (i.e., a few meters or more) must exist to permit the continuous, strong, and flat echo returns observed [*Oswald and Robin*, 1973].

2.1.3. Characterization of bed reflections. Radio echo sounding has been used to gather much of what is currently known about the subglacial environment of Antarctica. When the velocity of the radar pulse is known, or can be estimated, the thickness of the ice can be calculated by measuring the time difference between echoes received from the air/surface and ice/bed interfaces. A time series of such echoes recorded as the observer moves over the ice surface can be used to create a pseudo-cross-section of the ice sheet and of the underlying bed. These data combined with measurements of the surface elevation can be used to reconstruct the topography of the underside of the ice sheet [*Drewry*, 1983; *Lythe et al.*, 2001].

It was soon realized that much more information about the subglacial environment could be obtained from an analysis of the echo returns. In particular, the strength [*Neal*, 1976] and shape [*Berry*, 1973, 1975] of the returned pulse is related to the degree of scattering at the interface and therefore to the microtopography of the subglacial surface. Early studies were limited to the use of "incoherent" radar-sounding apparatus. Modern RES equipment can record both amplitude and phase of reflected pulses ("coherent" radar) allowing a moving platform to operate in the Synthetic Aperture (SAR) mode [*Gogineni et al.*, 1998]. Coherent integration both allows the detection of radar reflections where they would otherwise be obscured by scattering from crevasses, etc. and improves the ability to quantify reflection and scattering from a subglacial interface [*Peters et al.*, 2005].

Radar reflections within ice are caused by changes in dielectric permittivity (ε_r) due to changing density or crystal fabric orientation and by changes in electrical conductivity, due largely to varying acidity associated with the fallout of volcanic aerosols [*Fujita et al.*, 1999]. Basal reflections are generally caused by the large difference in dielectric impedance between ice and the basal material, the magnitude of the reflection being proportional to the change in impedance. Dielectric constants for the various types of bedrock, observed in Antarctica, range from a minimum of ~4 to a maximum of ~9. This is very much closer to the value for glacier ice (ε_r = 3.2) than is the dielectric constant of pure water (ε_r = 80). For this reason, a basal reflection from an ice-water subglacial interface is much brighter than the equivalent reflection from a dry interface or from frozen sediments [*Bogorodskiy et al.*, 1985]. *Shabtaie et al.* [1987] showed that the minimum sub-ice water thickness required for a water-dominated reflection is between a few tens of centimeters to a few meters, depending on salinity.

The shape of a smooth ice/bed or ice/water interface is an additional factor which can affect the strength of the returned echo in the same way that a concave or convex mirror acts to focus light [*Tabacco et al.*, 2000]. In tests conducted over a floating ice tongue, isolated geometrical effects have been shown to influence the total received power by ±6–8 dB [*Bianchi et al.*, 2004].

2.1.4. Identifying subglacial lakes by RES. The strength of the radio echo from the base of the ice sheet has been used by several authors to infer information about basal conditions in various glaciated regions [e.g., *Bentley et al.*, 1998; *Gades et al.*, 2000; *Catania et al.*, 2003; *Peters et al.*, 2005, 2007]. To do this, the proportion of energy reflected at the bed (the basal reflection coefficient) must be distinguished from the many other factors which can affect the strength of the signal received at the antenna. Probably, the most significant of these is the dielectric power loss during transmission through the ice. This depends sensitively on ice temperature and can vary spatially by 15–20 dB km^{-1} [*Peters et al.*, 2007]. While subglacial water will always produce a bright radar reflection, an "absolute brightness" criteria for lake identification can be misleading. Rather, it is the brightness of a particular feature "relative" to its surroundings, which can be more useful in identifying subglacial lakes [*Carter et al.*, 2007].

Amplitude fading is the fluctuation in radio echo amplitude as the observer moves at a fixed distance from an interface, it is caused by interference from different scattering centers fore and aft of the observers position and can be used to obtain useful information about bed roughness [*Oswald*, 1975]. Very low fading (or alternatively, a very large "fading distance") implies a continuous, flat, mirror-like or "specular" reflection. A purely specular reflection can only occur where the interface is smooth on the scale of the radar footprint. A substantial body of water at the bed of an ice sheet will exhibit a smooth ice-water interface that will also satisfy the criteria of hydrostatic equilibrium. This states that due to the different densities of ice and water, and assuming that the water supports the full overburden pressure of the ice, the ice-water interface will have a slope 11 times greater and in the opposite direction to the slope of the ice surface. Calculations of the hydrological potential field can therefore be useful in evaluating subglacial lake candidates from their radar profile [*Oswald*, 1975; *Carter et al.*, 2007].

The electrical properties of liquid water act to inhibit the transmission of electromagnetic waves. For this reason, RES cannot normally be used to determine the depths of subglacial lakes. An exception to this has been found in shallow regions of some lakes surveyed with the SPRI-NSF-TUD radar, where bottom reflections have been recorded from depths of up to 21 m below the lake's surface [*Gorman and Siegert*, 1999]. These observations confirm that these lakes are, in fact, substantial bodies of water, but indicate only their minimum depths.

2.2. Identification of Subglacial Lakes From Ice Surface Topography

Even before subglacial lakes had been firmly identified in RES records, their surface expressions had been noted by pilots traversing the center of the continent. Unusually flat areas of the ice sheet were often referred to as "lakes" and were frequently used as landmarks for navigation before any connection was made to the subglacial environment [*Robinson*, 1960].

When an ice sheet flows over a localized body of water, the weight of the ice is taken by the incompressible fluid. Provided that there is no outlet channel for the water to escape, this will lead to the establishment of local hydrostatic equilibrium. This has a significant affect on the flow regime of the ice and, for a large enough lake, can result in the morphological expression of an extremely flat and featureless ice surface, similar to that of a floating ice shelf.

Satellite observations with the Seasat radar altimeter identified a prominent flat area, in Terre Adelie, East Antarctica, the position of which was shown to correspond to a subglacial reflector identified in the SPRI-NSF-TUD radar record [*Cudlip and McIntyre*, 1987]. This technique achieved greater success when several RES lake reflectors in the area to the north of Vostok Station [*Robin et al.*, 1977] were shown to lie beneath a single, continuous flat surface area observed with the ERS-1 satellite [*Ridley et al.*, 1993; *Kapitsa et al.*, 1996]. A finding later confirmed and elaborated on using more sophisticated radar altimetry techniques [*Roemer et al.*, 2007] and laser altimetry [*Studinger et al.*, 2003a].

Subsequent analysis of ERS-1 data identified flat surface features associated with a further 28 subglacial lakes known from RES records in the Dome C and Terre Adelie regions [*Siegert and Ridley*, 1998a]. Small subglacial lakes (dimensions <4 km) are generally not found to have a corresponding flat surface feature. Furthermore, flat areas of ice, meeting the criteria for identification of a subglacial lake, have also been shown to occur where no lake exists [*Siegert and Ridley*, 1998a]. Water-saturated sediments can cause a similar reduction in basal stress and, therefore, induce a similar surface expression. For this reason, a surface flat area alone is not normally sufficient evidence for a lake discovery [*Siegert and Ridley*, 1998a].

In addition, for floating ice, the retarding force of the basal shear stress is reduced to zero. As a result, ice flowing from a solid bed onto a subglacial lake experiences acceleration. The resulting extensional flow has been shown to cause a local thinning of the ice and a lowering of the surface on the upstream side of the lake [*Shoemaker*, 1990; *Gudmundsson*, 2003; *Pattyn et al.*, 2004]. Conversely, a thickening of the ice can occur over the downstream lake shore, where the return of basal drag causes compressive flow.

Until recently, it was thought that no other subglacial lakes of a similar scale to Vostok Subglacial Lake (hereinafter referred to as Lake Vostok) existed beneath Antarctica [*Siegert*, 2000]. Imagery from the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite, however, has now been used to determine large surface areas for two lakes (90°E Lake and Lake Sovetskaya) that were previously known only from relatively short sections of RES survey [*Bell et al.*, 2006]. Further discoveries of four large lakes in the upstream region of the Recovery Ice Stream have been made using MODIS imagery to locate the lake surfaces, which have then been shown to possess surface ridge and trough features consistent with the direction of ice flow [*Bell et al.*, 2007].

2.3. Discovery of Active Subglacial Lakes by Measurements of Surface Height Change

It is now becoming widely recognized that subglacial drainage systems are generally dynamic in nature. Changes associated with the movement of water either between known lakes or between lakes and a distributed hydrological system are apparently common occurrences [*Siegert et al.*, 2007]. Movement of subglacial water has been known, or suspected, as the cause of vertical displacements of the ice surface of valley glaciers for a number of years [e.g., *Iken et al.*, 1983; *Fatland and Lingle*, 2002]. Not until recently, however, have the means, in the form of repeat satellite measurements, been available to observe such local surface height changes in the remote regions of the Antarctic plateau.

Gray et al. [2005] were the first to identify vertical movement of the Antarctic ice sheet that could be attributed to the movement of subglacial water. They used the technique of Interferometric Synthetic Aperture Radar with repeat-passes of the RADARSAT satellite to detect areas of vertical displacement in upstream areas of Ice Streams C ("Kamb Ice Stream") and D ("Bindschadler Ice Stream") in the Siple Coast region of West Antarctica. The surface height changes measured in this study have several features in common with a large number of events identified by other authors since. The measured vertical displacements averaged ~0.5 m, they occurred within an orbital period of 24 days, and were smoothly varying in amplitude over roughly spherical regions 10–20 km across. In the case of the Ice Stream D event, an upstream surface lowering was observed over the same time period as a downstream surface rise representing an approximately equivalent change in volume [*Gray et al.*, 2005].

Further evidence for subglacial water movement beneath the Siple Coast ice streams was presented by *Fricker et al.* [2007] and *Fricker and Scambos* [2009]. This was obtained from repeat-pass laser altimetry with the ICESat mission to identify areas of raising and lowering together with differencing of MODIS images in which discrete areas of surface change are visible. While these features demonstrated the scale and activity of the subglacial water system beneath the fast flow features of West Antarctica, *Wingham et al.* [2006] used the radar altimeter on the ERS-2 satellite to identify similar phenomena occurring beneath the thick interior ice of the Adventure Subglacial Trench in East Antarctica. In this case, a single lake was discovered to be deflating (~3 m drop over a surface area of ~600 km^2) upstream along a predicted flow path from several smaller lakes found to be inflating. Unlike the RADARSAT data, this work showed lakes draining and filling over a period of many months and inferred water transport over a distance of around 260 km. Further work has shown that a significant fraction of the water discharged from the upstream lake during this event was retained by the downstream lakes and that a distributed model of subglacial water transport is needed to explain the observed travel times [*Carter et al.*, 2009].

The launch of the ICESat laser altimeter has greatly improved the spatial coverage of Antarctica and has resulted in a large number of new lakes discovered by the effects of their filling and draining on the ice sheet surface. *Smith et al.* [2009] analyzed all ICESat repeat tracks between 2003 and 2008 for indications of anomalous surface height changes that could not be explained by normal glaciological processes [see *Gudmundsson*, 2003; *Sergienko et al.*, 2007]. They detected new lakes throughout the continent (130 in total) with concentrations centered under several of the major outlet glaciers of both East and West Antarctica. Especially significant among them are two large lakes in East Antarctica, the discharge of which was found to have coincided with a 10% increase in the flow speed of the Byrd Glacier, located directly downstream of the lakes [*Stearns et al.*, 2008].

As a footnote to this section, *Richter et al.* [2008] conducted a high-resolution ground-based GPS survey over Lake Vostok over the period 2002–2007. Their results indicated no surface height change that could be attributed to any change of the water level within the lake, a conclusion that is supported by 1-year period repeat laser altimetry from the ICESat satellite [*Shuman et al.*, 2006].

2.4. Seismic Survey

Unlike other methods described above, the analysis of reflected pressure waves allows information to be collected from below the surface of subglacial lakes. Longitudinal seismic or "p" waves have the unique ability to penetrate large distances through ice, rock, and liquid water. This means that by timing reflections from the various subglacial interfaces, seismic studies can be used to infer the depth of water in subglacial lakes and the thickness of any unconsolidated sedimentary layers at their bed.

Seismic investigations, however, are time and labor intensive to carry out and provide only one data point for each "shot" taken. High levels of background noise on the Antarctic plateau can also make interpretation of the returns difficult. During the 1960s, a seismic survey carried out around Vostok Station [*Kapitsa and Sorochtin*, 1965] prior to the drilling of a deep ice core failed to identify the presence of a subglacial lake. The same data set would later provide the first indications of the depth of Lake Vostok after reexamination in the light of knowledge of the lake's surface extent gained from satellite altimetry [*Ridley et al.*, 1993]. The initial data indicated a water depth of around 500 m at a site located a few kilometers from Vostok Station [*Kapitsa et al.*, 1996]. More recent seismic investigations have revealed the maximum depth of the lake to be over 1100 m [*Masolov et al.*, 2006]. A separate basin, with a small surface area, but up to 680 m deep, has also been found to exist immediately below Vostok Station [*Masolov et al.*, 1999].

Lake Vostok was the first, and for many years the only, subglacial lake to have a direct depth measurement by seismic sounding. Recently, however, a subglacial lake situated very near the South Pole [*Peters et al.*, 2008] and another near the Ellsworth Mountains in West Antarctica [*Woodward et al.*, 2010] have been the targets of seismic surveys. At the South Pole Lake, *Peters et al.* [2008] used the amplitude variation with offset technique, which utilizes the observation that seismic reflectivity varies as a function of angle in different ways for different subglacial materials. In this way, they were able to identify liquid water beneath the South Pole independently of the RES data that had originally located the lake. In addition, they used traditional seismic processing to determine the depth of the water column in South Pole Lake to be around 32 m.

As well as characterizing the water depth in subglacial lakes, seismic sounding is currently the only method for investigating the physiography of lake beds and particularly for determining thicknesses of sediments. At Lake Vostok, several of the available seismic records show multiple reflections from around the bed of the lake; these, however, can be interpreted in different ways. Reflections spanning a range of 0.1–0.5 s from a number of different sites above Lake Vostok are thought to represent between 100 and 350 m of sediments with seismic velocity between 1700 and 2100 m s^{-1} [*Masolov et al.*, 1999, 2001]. However, it has also been suggested that these secondary bottom echoes may represent side reflections due to either steep side slopes or high basal roughness at the bed of the lake and, therefore, that the water layer is in direct contact with the seismic basement across the entire lake bottom [*Masolov et al.*, 2006; *Popov et al.*, 2006]. *Filina* [2007] tested these hypotheses and determined that some of the reflections could be due to a sloping lake bed but that, nevertheless, the seismic data were best explained by the presence of a 200- to 300-m thick layer of sediment.

In 2007/2008, seismic measurements were made on Ellsworth Subglacial Lake (hereinafter referred to as Lake Ellsworth) in West Antarctica [*Woodward et al.*, 2010; *Ross et al.*, this volume]. Based on an assessment of sidewall slopes bordering the lake, the water depth was previously hypothesized to be at least several tens of meters [*Siegert et al.*, 2004]. The seismic data upheld this hypothesis and recorded a depth of around 160 m in long location. This result has been used as the basis for the forthcoming exploration of Lake Ellsworth (in 2012/2013), detailed by *Ross et al.* [this volume].

2.5. Characterization of Subglacial Lakes by the Survey of Gravity Anomalies

Geologists use measurements of the free-air gravitational anomaly in Antarctica to map density variations below the surface that are the result of both geological structures and of the topography. If the surface and bed topographies of the ice sheet over a subglacial lake are known (e.g., from RES survey), then the effect of ice sheet geometry can be removed from the free-air gravity anomaly. For a large subglacial lake, such as Lake Vostok, the thickness of the subglacial water column then dominates the remaining gravity signal [*Studinger et al.*, 2004b].

This method has been used to map the bathymetry of Lake Vostok at a higher spatial resolution than is possible with seismic methods alone [*Studinger et al.*, 2004b]. Two separate basins were identified in this way, a larger and deeper southern basin separated by a 40-km-wide bedrock ridge from a smaller and shallower northern one. *Roy et al.* [2005] took the next step by using gravity data to produce a complete model of Lake Vostok including both water column and sediment thickness. Both these studies used aerogeophysical data collected during the 2001/2002 Antarctic summer [*Holt et al.*, 2006b]. Neither model, however, corresponded precisely with the water and sediment depths indicated by more recent seismic studies [e.g., *Masolov et al.*, 2006]. Further work with the original gravity data combined with recent seismic studies has produced a refined bathymetry/sediment model for Lake Vostok [*Filina et al.*, 2008]. This indicates a deep (~1200 m) maximum water depth underlain by ~300 m of unconsolidated sediments in the southern basin and shallower water (~250 m) overlying a thicker sedimentary layer (~350 m) in the northern basin.

The only other subglacial lake to have been characterized at any level of detail using gravity measurements is Lake

Concordia. A University of Texas/Support Office for Aerogeophysics (SOAR) airborne survey covered the region of the lake in 1999/2000 and collected gravity data [*Studinger et al.*, 2004a; *Filina et al.*, 2006]. Inversion modeling of gravity data from the six survey lines crossing the lake was then undertaken by both *Tikku et al.* [2005] and *Filina* [2007]. Gravity results, along with simultaneously acquired RES data, were then used to determine that the lake has a large surface area of between 600 and 800 km^2, but a relatively shallow average water column thickness of ~59 m (maximum depth 126 m), and consequently a volume of just 70 km^3 [*Filina*, 2007; *Thoma et al.*, 2009]. Since the lake is relatively shallow, any underlying sedimentary layer has not been resolved in the gravity data.

The inherent noisiness of airborne gravimetry (due to the sensor being subjected to nongravitational accelerations resulting from aircraft motion) means that extensive low-pass filtering is required to extract that part of the recorded signal, which is of geological origin [*Childers et al.*, 1999]. Analysis of repeat lines and crossovers has determined an accuracy of 1–2 mGal for the surveys of both Lake Vostok and Lake Concordia [*Holt et al.*, 2006b]. This, combined with the thickness of the overlying ice (necessitating that data be acquired at an effective altitude of more than 4 km above the ice base target), currently imposes a limit of around 8–10 km on the resolution of aerogravity surveys over central Antarctica [*Holt et al.*, 2006b]. Modern aerogravity equipment, as used in commercial exploration, has the potential to provide submilligal accuracy to future surveys of the Antarctic subglacial environment [*Studinger et al.*, 2008]; however, as yet, no subglacial lake studies have been published with this kind of resolution. Further errors can potentially be introduced into lake bathymetries determined solely by gravity survey due to the unknown nature of the underlying geology. Unknown or uncertain spatial variation in rock density can be indistinguishable from changes in lake volume in gravity surveys; hence, the use of seismic data is desirable in verifying gravity inversion models [e.g., *Filina et al.*, 2008].

3. GEOGRAPHICAL DISTRIBUTION, DIMENSIONS, AND RELATION TO TOPOGRAPHIC AND GLACIOLOGICAL SETTING

3.1. Inventory of Known Subglacial Lakes

The first published inventory of subglacial lakes is the work of *Oswald and Robin* [1973]. At this time, just 17 lakes had been discovered by the SPRI-NSF-TUD RES program, 14 of which lay beneath the Dome C area of East Antarctica, a region which would later become known as the "Antarctic Lake District."

By the time another systematic catalog of all known lakes was produced [*Siegert et al.*, 1996], the total number had increased to 77. The large majority of these lakes were still to be found under the thick ice of central East Antarctica with two clusters in particular, beneath the Dome C and Ridge B areas, accounting for 77% of the total number [*Siegert et al.*, 1996]. Lake Vostok was included in this inventory. Its large volume, at least two orders of magnitude greater than any other lake, would dominate calculations of water storage beneath the ice sheet [*Dowdeswell and Siegert*, 1999].

The most recent inventory of subglacial lakes [*Siegert et al.*, 2005], while still only incorporating lakes identified by RES, drew upon a larger number of studies including, most significantly, the Italian survey of the Dome C area [*Tabacco et al.*, 2003], the Russian airborne RES of the Dome A and Dome F regions [*Popov and Masolov*, 2003], and the U.S. surveys of the Vostok and Wilkes Basin areas [*Studinger et al.*, 2003a, 2004a]. The tally for this inventory reached 145 separate lakes, even after six individual reflectors from the previous inventory had been reclassified as parts of larger lakes [*Siegert and Ridley*, 1998a].

Since the publication of this inventory, a number of recent studies have further added to our knowledge of subglacial lakes:

1. *Popov and Masolov* [2007] reported 29 new lakes identified during ground-based RES work aimed at mapping the shoreline of Lake Vostok. Most of these are small lakes (0.5- to 10-km-long reflectors) located within valleys several hundred meters deep. Two further small lakes (4 and 26.5 km^2) were detected during an overland traverse between Mirny and Vostok [*Popov and Masolov*, 2007].

2. A systematic categorization of RES reflections from the 1998–2001 SOAR campaigns covering the Pensacola-South Pole transect, the Wilkes Basin Dome C transect, and a survey of the Lake Vostok area by *Carter et al.* [2007] resulted in the identification of 22 new "definite" lakes and a further 58 classed by the authors as "dim lakes" (see section 2.1.4). This reanalysis also determined that several features previously thought to be separate lakes, in fact, belonged to the same water bodies, thereby reducing the total of *Siegert et al.* [2005] by 5. A complete list of all "lake-type" reflectors identified in this study is given by *Blankenship et al.* [2009].

3. As mentioned in section 2.2, *Bell et al.* [2006] contributed revised dimensions for two large lakes at 90°E (~2000 km^2) and at Sovetskaya (~1600 km^2). Similarly, four lakes with surface areas 1500–4500 km^2 have been identified at the head of the Recovery Ice Stream [*Bell et al.*, 2007].

4. Five new lakes were reported by *Cafarella et al.* [2006] as a result of Italian RES work during 2003. Four of these are small (1- to 3-km-long reflectors) and are located within the

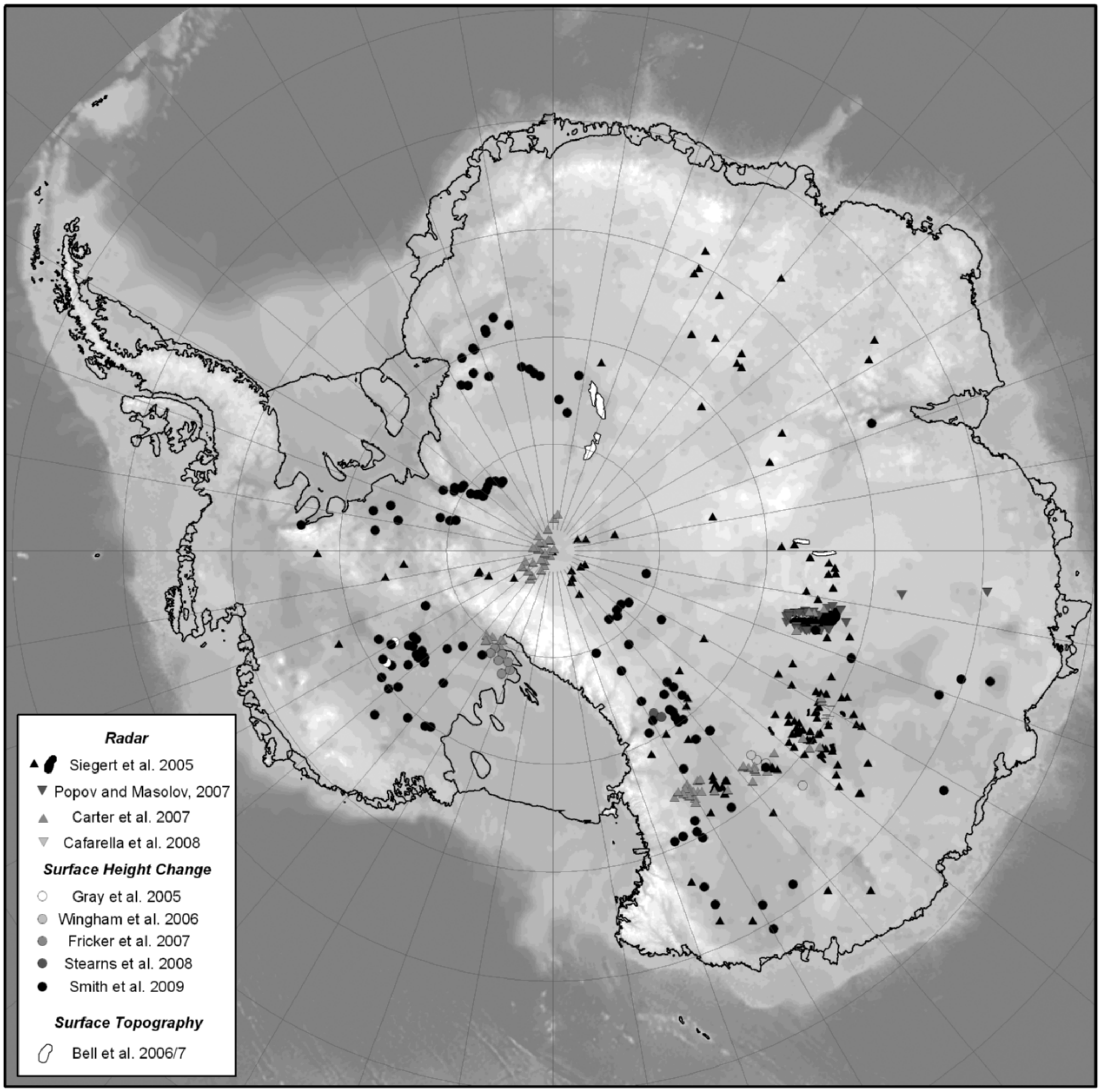

Figure 2. Map of subglacial Antarctica showing the locations of all lakes known from radio echo sounding and all sites of surface height change consistent with lake activity detected by satellite. Larger lakes are shown in outline; smaller lakes and those of unknown surface area are indicated by triangular (RES) and circular markers (satellite). Lakes included in the previous inventory of *Siegert et al.* [2005] are shown in black; lakes discovered since that time are shaded according to the publication in which they were first identified.

Belgica Subglacial Highlands, and one is larger (~10 km) and situated in the southern Aurora Basin.

5. Finally, several active subglacial lakes have been identified in individual studies throughout East and West Antarctica [*Gray et al.*, 2005 (2); *Wingham et al.*, 2006 (4); *Fricker et al.*, 2007 (7); *Stearns et al.*, 2008 (2)]. A systematic catalog of all lakes that were active (and crossed by more than one ICESat track) between 2003 and 2008 has been

produced by *Smith et al.* [2009]. This work added 113 previously unrecorded lakes.

The total number of lakes described in the literature as of October 2009, therefore, stands at 387 (see Figure 2).

3.2. The Distribution of Subglacial Lakes

3.2.1. Distribution with ice thickness and with distance from subglacial flow divide. The direction of subglacial water flow at any point on the ice sheet can be shown to depend only upon the slopes of the ice surface and of the bedrock [*Shreve*, 1972]. Thus, given a digital elevation model of the ice sheet surface [e.g., *Bamber et al.*, 2009] and of the bed [*Lythe et al.*, 2001], flow lines can be calculated for subglacial water throughout the ice sheet [e.g., *Wright et al.*, 2008]. The slope of the ice surface has an order of magnitude greater effect on the direction of subglacial water flow than does the topography of the bedrock [*Shreve*, 1972]. The flow lines therefore, largely follow the direction of ice flow. As a consequence of this, an equivalent subglacial watershed is situated approximately beneath the ice divide.

The upstream distance from a lake along the flow path to the subglacial flow divide is a useful parameter in characterizing the distribution of subglacial lakes. Figure 3 shows histograms of this distance to the divide for (a) all lakes, (b) lakes detected by RES fieldwork, and (c) lakes detected by satellite measurements of height change. Figure 3a clearly shows that the densities of all known lakes increase nearly exponentially with approach to the flow divide. Histograms for lakes detected by RES and for active lakes detected from space, however, produce very different results. The total number of lakes from RES surveys (256) is greater than the total for active lakes (128) and the distribution is more heavily skewed; hence, the pattern for radar lakes dominates that for all lakes. (Four lakes beneath the head of the Recovery Ice Stream are known by their surface expression only [see *Bell et al.*, 2007]. One lake (Lake Mercer) is identified by both surface height change and in RES records.) The active lakes, so far, reported do not show a strong relationship to upstream distance to the flow divide. The modal value for this distance is 750 km, which for lakes detected by RES falls within the upper 5% tail of the distribution. This demonstrates that the method of lake detection, or perhaps the type of lake detected, has a significant effect on the distribution of lakes with regard to the flow divides.

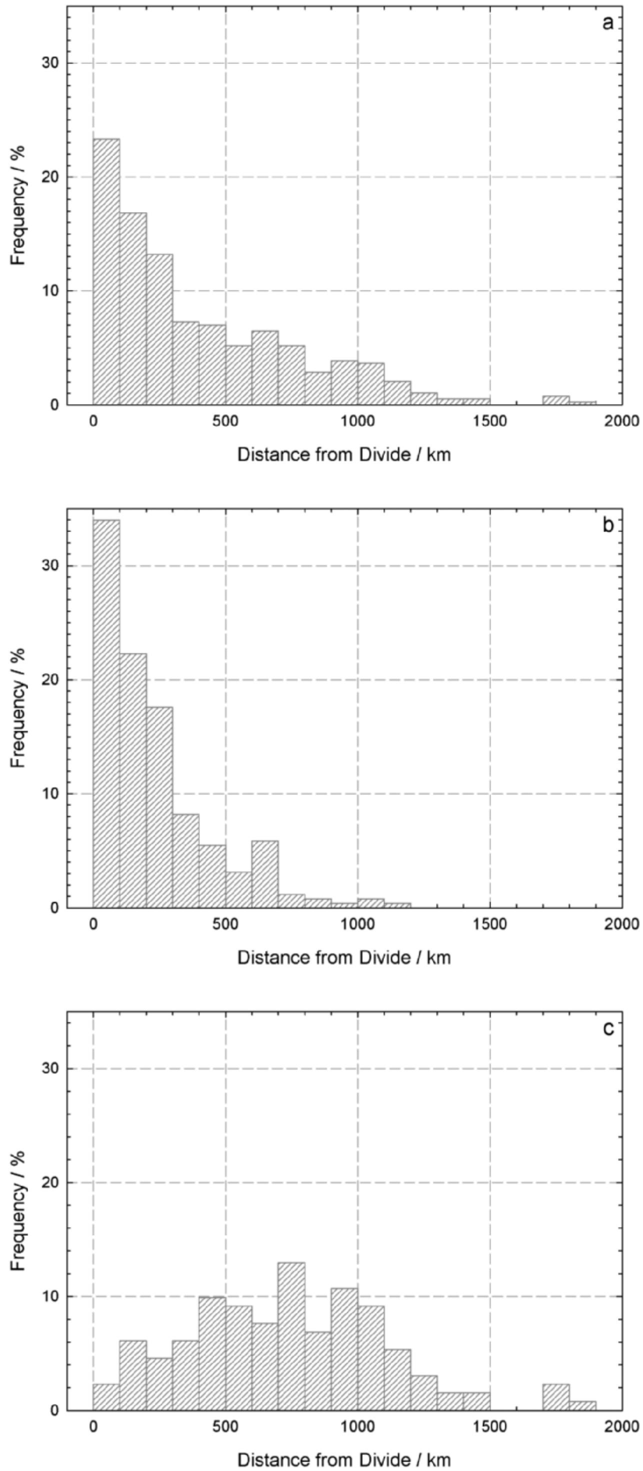

Figure 3. (opposite) Distribution of subglacial lakes in terms of distance along the flow line to a major ice divide. The histograms show (a) all known subglacial lakes, (b) lakes identified by their RES reflection, and (c) lakes identified by satellite measurements of vertical surface movement.

The distribution of subglacial lakes with respect to the thickness of overlying ice is also of interest when categorizing subglacial lake physiography. For lakes identified by RES, ice thickness can be determined from the same data set. For those identified by other means, the ice thicknesses used here have been taken from the BEDMAP digital elevation model, which uses interpolation to fill the gaps between RES and seismic measurements of the ice thickness [*Lythe et al.*, 2001].

Figure 4a shows that the ice thickness distribution for known lakes (bars) is skewed toward thicker ice compared with the distribution of all grounded ice in Antarctica (line). Plotting separate histograms for lakes identified by RES (Figure 4b) and by satellite (Figure 4c) demonstrates that the observed skew [cf. *Dowdeswell and Siegert*, 1999] is due entirely to a skew in the lakes recorded by RES. By comparison, apart from an unobserved peak in ice thickness between 1800 and 2200 m, the distribution of lakes discovered by satellite is in much closer agreement with the overall distribution of ice thickness across the continent (Figure 4c).

The difference in the distribution of overlying ice thickness with measurement technique is likely to be associated with the spatial dependence of the technique. RES has been demonstrated to be very good at detecting subglacial lakes near the center of the ice sheet, but less good at identifying them in the often warmer and more heavily crevassed ice toward the margins. *Dowdeswell and Siegert* [2002] thought this was possibly due to scattering at the ice sheet base that occurs as a consequence of basal sliding, though no evidence for this was available at the time. Conversely, satellite measurements of ice surface changes have revealed many lakes close to the ice margin, but not so many near the divide. This is possibly due to the periodicity of lake drainage that is a function of lake size and the input flux of water. Small lakes toward the ice margin that are filled by high rates of water flow are likely to drain regularly and produce a greater surface height change signal when they do. In comparison, larger lakes nearer to the ice divide, where the input of water is more restricted, are likely to drain less frequently and, for a similar discharge volume, produce a much smaller surface height change [*Siegert et al.*, 2007]. This may then be below the detection threshold for satellite altimetry.

3.2.2. Bias in the distribution due to data collection methods. The SPRI-NSF-TUD survey is currently the only available source of information for around 16% of the known subglacial

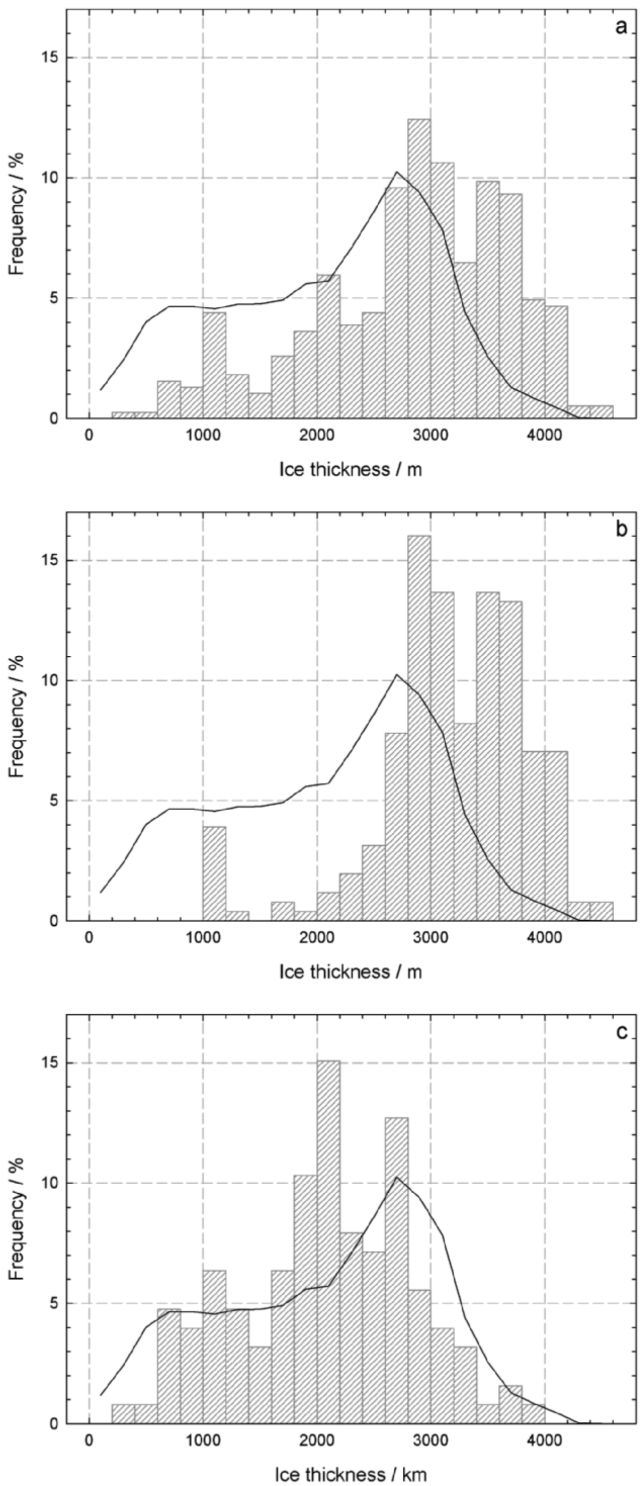

Figure 4. (opposite) Distribution of subglacial lake locations in terms of thickness of overlying ice. The histograms show (a) all known lakes, (b) lakes identified during RES studies, and (c) lakes identified by satellite measurements of vertical surface movement. The distribution of ice thickness for the whole ice sheet (black line) is shown for comparison.

lakes; 32% have been discovered by satellite during the past 5 years, while the remainder have been characterized by RES surveys undertaken for specific study areas since the 1970s. While the SPRI-NSF-TUD survey, together with the Russian surveys in East Antarctica, constitutes an approximately representative sample of the ice sheet [e.g., *Dowdeswell and Siegert*, 1999], recent RES projects, in general, do not. The high density of survey lines flown in the area around Lake Vostok, for example, have identified a large number of small lakes under thick ice and close to the flow divide, thus tending to skew the distributions for RES lakes in Figures 3 and 4.

Satellite techniques also suffer from bias. The separation of ICESat flight tracks decreases toward southerly latitudes (from ~30 km at 70°S to ~5 km at 85°S) to the southern limit of the orbit at 86°S, below which there is no coverage. This leads to an increase in the number of lakes detected together with a decrease in the average size of the lakes as the satellite moves toward this limit, while the area around the South Pole cannot be sampled at all [*Smith et al.*, 2009]. Other forms of geographical bias also apply, such as discrimination against areas that experience high levels of cloud cover and several others recognized by the authors of the inventory.

Very little overlap exists between the inventories of lakes identified by RES studies and those shown to be active through satellite measurements. Satellites have detected lakes (e.g., Engelhardt Subglacial Lake) situated underneath large outlet glaciers, which have not been identifiable in RES records from the same site. The reasons for this are still uncertain, though RES studies have always had difficulties in imaging the bed in very active regions of the ice sheet. In many cases, active lakes occur beneath or in close proximity to the fast flowing ice associated with surface crevassing and basal fluting. The weaker attenuation of the radar signal due to thinner ice cover and the increased likelihood of general basal lubrication in such areas also combine to reduce the contrast in bed reflection power between wet sediment and liquid water lakes at the bed.

3.3. Dimensions and Volumes of Subglacial Lakes

Figure 5 is a histogram showing the distribution of subglacial lake lengths (taking the longest dimension if several records are available). Lake Vostok, 90°E Lake, Sovetskaya Lake, and the Recovery Lakes are left out of the diagram simply because their size skews the graph adversely. The bulk of subglacial lakes are less than 10 km in length with the modal size being just 5 km. Several large lakes exist, with dimensions in excess of 20 km, and these will comprise the bulk of the water currently stored beneath the ice sheet (see below).

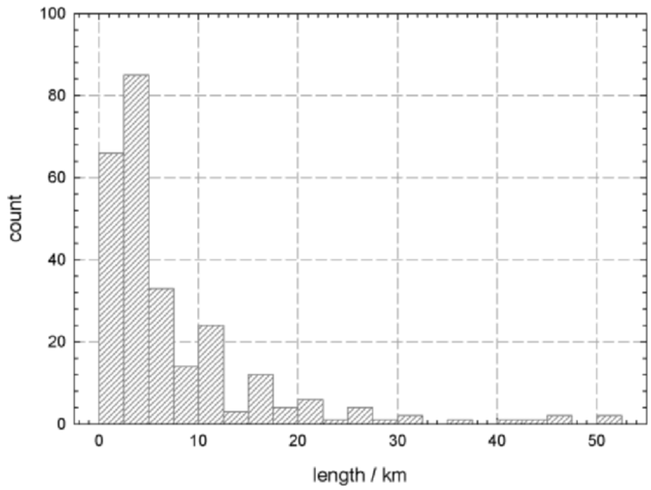

Figure 5. Distribution of known subglacial lake lengths <55 km.

Dowdeswell and Siegert [1999], working from the SPRI-NSF-TUD airborne RES records, identified four distinct regions of subglacial lake occurrence: Dome C, Ridge B, Hercules Dome, and the area around the South Pole. Following the two assumptions that subglacial lakes were scattered randomly throughout each of these areas and that the RES data from each region was organized to cover a representative sample of the ice sheet, they were able to estimate (assuming a circular approximation for the area of lakes crossed by RES records at a random orientation) the total area of subglacial lakes in each region and, hence, the total stored volume of water for a range of mean lake depths. Their calculations led them to predict a total volume for water stored beneath the ice sheet of between 4000 and 12,000 km^3.

Since then, the total number of known lakes has increased, and many lakes have been discovered outside of the regions identified by *Dowdeswell and Siegert* [1999]. The scale of the RES surveys from which these lakes have been discovered is much smaller than the earlier SPRI-NSF-TUD work and can no longer be taken to cover a representative sample of a larger region; rather, detailed surveys have been undertaken of local areas. Therefore, we cannot now update the estimate for total subglacial water storage, as the survey lines are too unevenly distributed. We can, however, estimate, using the same principles, the total known surface area of subglacial lakes and also a range for the total stored volume based on likely mean depths.

Using the circular approximation for lakes crossed by just a single survey line [*Dowdeswell and Siegert*, 1999] and reported surface areas for lakes with multiple crossings or with prominent flat surface features, we estimate the total surface area of known lakes to be ~50,000 km^2. This value, of course, does not take into account undiscovered lakes or those discovered by surface elevation change alone, as length/area measurements for most of these lakes are not yet published. Nevertheless, this value already exceeds that estimated by *Dowdeswell and Siegert* [1999] (~40,000 km^2) for the whole of the ice sheet. The large lakes in the Ridge B area (Vostok, 90°E, Sovetskaya) comprise 35% of this total surface area, while the four lakes proposed at the head of the Recovery Ice Stream contribute a further 27%, leaving only 38% to be accounted for by all the other smaller lakes.

Using estimates of between 50 and 250 m mean water depth based on RES observations of surrounding topography [*Dowdeswell and Siegert*, 1999], and actual volumes for lakes where depth measurements are available, we obtain an envelope for the total stored water volume within known subglacial lakes of 9000–16,000 km^3. Once again, this is an increase from the range estimated by *Dowdeswell and Siegert* [1999] and can be regarded as a minimum for the whole of Antarctica, as many lakes are likely yet to be discovered. Only three lakes (Vostok ~5400 km^3, Concordia ~30 km^3, Ellsworth, 1.8 km^3) have reasonably well-constrained volumes.

4. SUBGLACIAL LAKE CLASSIFICATION, BASAL HYDROLOGY, AND ICE FLOW

Dowdeswell and Siegert [2002] analyzed the first inventory of subglacial lakes [*Siegert et al.*, 1996] to outline four forms of subglacial lake: (1) those where topography is subdued in the middle of large basins, (2) lakes that occupy entire discrete basins, which are often large, (3) lakes perched against the sides of subglacial highlands, and (4) lakes located at or near the onset of major outflow units. Based on the new inventory (of 387 lakes), and following recent discoveries concerning the role of subglacial lakes in basal hydrology, we offer the following revision to the classification.

A necessary condition for the occurrence of a subglacial lake is that the ice sheet base must be at the pressure melting point. This is most likely to be the case where either the ice is thick (>3 km) and, therefore, a high-pressure environment exists at the bed that is well insulated from cold surface temperatures or where vigorous internal deformation and basal sliding are actively generating heat at the ice base through friction [*Wilch and Hughes*, 2000].

Subglacial lakes can be divided into three groups, those associated with thick ice and the trapping of geothermal heat near the ice divides in the interior of the continent, those associated with the onset regions of fast flow features nearer to the margins of the ice sheet, and those situated beneath the trunks of outlet glaciers and ice streams.

4.1. Lakes in the Ice Sheet Interior

The subglacial topography of the Antarctic interior is characterized by several very large, deep, likely sedimentary basins separated by mountainous ridges known as subglacial highlands [*Drewry*, 1983; *Lythe et al.*, 2001]. The summits, or "Domes," of the Antarctic interior are connected by a line of ridges or "ice divides." The ice sheet in the vicinity of these divides is characterized by very low surface slopes and very slow ice flow. The subglacial lakes so far discovered beneath the thick ice of the interior can be divided into three categories based on the characteristics of their surrounding bed topography [*Dowdeswell and Siegert*, 2002; *Tabacco et al.*, 2006].

First, the majority of interior lakes are found where the ice is thickest, and therefore, conditions are favorable for melting at the bed. This most often occurs toward the centers of the deep subglacial basins such as the Aurora, Vincennes, and Wilkes basins. The subglacial topography here is characterized by low relief; *Dowdeswell and Siegert* [1999] found that for more than 60% of the then known lakes, the maximum elevation of the nearest topographic highs was no more than 400 m above the level of the lake, with a maximum gradient of no more than 0.1 adjacent to the lake shore. Many of these lakes consequently have little depth potential for the size of their surface area. Several large lakes fall into this category, e.g., Lake Concordia, Vincennes Lake, and Aurora Lake [*Tabacco et al.*, 2006]. In some cases, features previously identified as lakes in RES records or by flat surface features may be areas of water-saturated sediments, rather than true lakes [*Carter et al.*, 2007].

Second, there are those lakes which are closely related to significant topographic depressions in the bedrock; these are frequently found toward the margins of subglacial basins but still near to one of the major ice divides of the interior. Lake Vostok is an example of this kind of lake, as are the large lakes at 90°E and beneath Sovetskaya Station [*Bell et al.*, 2006]. These lakes inhabit topographic depressions with the elongate, rectilinear morphology characteristic of tectonically controlled features [*Meybeck*, 1995; *Tabacco et al.*, 2006]. Geophysical investigation has confirmed that Lake Vostok is situated within a rift feature forming part of a continental collision zone [*Studinger et al.*, 2003b]. Several smaller examples of this type of lake have been reported including Lake Ellsworth in West Antarctica [*Woodward et al.*, 2010].

The third category is composed of lakes situated on the flanks of subglacial mountain ranges. These are characteristically small (<10-km long) features constrained within steep local topography. Consequently, their presence is not found to leave an imprint on the ice surface morphology.

Several cases have been identified of lakes perched on the stoss face of subglacial mountains [*Dowdeswell and Siegert*, 2002].

Subglacial lakes located near drainage divides in the ice sheet interior are likely to have relatively small catchment areas from which they receive runoff. They are, therefore, likely to be inactive or to have long periodicity between flood discharge events due to the associated low refilling rates [*Evatt et al.*, 2006].

4.2. Lakes Associated With the Onset of Enhanced Ice Flow

A second class of subglacial lakes was postulated by *Siegert and Bamber* [2000], when the association was first made between the locations of some subglacial lakes and the onset regions of fast ice flow features recently identified as extending farther into the interior of Antarctica than previously thought [*Bamber et al.*, 2000]. At least 16 subglacial lakes from the inventory of *Siegert et al.* [1996] could be associated with onset regions of enhanced ice flow [*Dowdeswell and Siegert*, 2002]. These lakes are located relatively large distances (approximately a few hundred kilometers) from the nearest major ice divide, are small (<10 km in length), and probably shallow. *Dowdeswell and Siegert* [2002, p. 234] state that "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."

More recently, four subglacial lakes, each with large (>1000 km^2) surface area have been identified near the onset of fast flow at the head of the Recovery Ice Stream, the fast flow feature that penetrates deepest into the interior of East Antarctica [*Bell et al.*, 2007]. These lakes appear to have more in common with the large lakes in the Ridge B-Vostok region, as they also exhibit signs of tectonic origin, though they appear to be much shallower than Lake Vostok [*Bell et al.*, 2007].

Not all fast ice flow features are associated with subglacial lakes, and the mechanism by which subglacial lakes, where they do occur, influence the initiation of fast ice flow is uncertain. Suggestions include the direct lubrication of the ice/bed interface through the constant supply of water, modification of the basal thermal regime by the release of latent heat during freeze-on of lake water to the underside of the ice sheet and through the creation of subglacial conduits during periodic drainage events [e.g., *Kamb et al.*, 1985; *Bell et al.*, 2007]. Recent work by *Stearns et al.* [2008] has shown that outlet glaciers can speed up as a response to the draining of upstream lakes. That the movement of subglacial water can influence outlet glacier dynamics is an important observation, however, this relationship has probably operated as long as liquid water has been present at the base of the ice sheet and does not represent a new instability.

4.3. Lakes Beneath the Trunks of Ice Streams

Recent satellite studies, aimed at measuring rapid fluctuations in the ice surface height [e.g., *Smith et al.*, 2009], have been very successful in detecting active subglacial systems beneath the fast flowing trunks of ice streams and glaciers in both East and West Antarctica [*Gray et al.*, 2005; *Fricker et al.*, 2007; *Fricker and Scambos*, 2009].

Due to the nature of the techniques with which they have been detected, all the lakes so far discovered beneath ice streams have been actively filling or discharging. Despite significant developments in the collection and processing techniques for synthetic aperture RES [e.g., *Peters et al.*, 2007], studies using this method, which is capable of detecting static lakes, still experience significant difficulties in imaging the bed of ice streams due to a high degree of scattering from both surface crevasses and from basal fluting. Such surveys have, therefore, not yet been able to detect lakes located in very fast flowing regions of the ice sheet.

This newly discovered class of lakes appears to be generally of smaller size, and the lakes are probably more transient in nature, with large proportions of their water volume filling and draining on an annual or semiannual basis [*Smith et al.*, 2009].

5. DISCUSSION AND SUMMARY

Following the first inventory of 77 subglacial lakes, *Dowdeswell and Siegert* [2002] provided an assessment of lake classifications. In recent years, several new data sets have increased the number of known subglacial lake features to 387 and have greatly improved our understanding of their role in the hydrological system beneath the ice sheet.

The traditional (and earliest) method of subglacial lake detection is from radar sounding (either ground-based or airborne). Radar provides an actual measurement of the ice-water interface and an along-track recording of the extent of this water. Several subglacial lakes have been investigated through a grid of radar transects, detailing with a high level of certainty the lake extent.

Over large lakes, the ice sheet surface slope is noticeably flat as a consequence of ice floatation. In some cases, the outline of lake extent can be mapped from these surface features. The first lake to be outlined in this way was Lake Vostok [*Kapitsa et al.*, 1996], shortly followed by several lakes at Dome C [*Siegert and Ridley*, 1998a], Lake Concordia, two large lakes near Ridge B (90°E and Sovetskaya) [*Bell et al.*, 2006], and a collection of lakes at the head of the Recovery Ice Stream [*Bell et al.*, 2007].

Satellite altimetry time series data have recently been used to determine the location of subglacial lakes that display noticeable outpouring or influx of water; the net change causing the ice sheet surface to fall or rise accordingly and, hence, the outline of the "active" lake detected [e.g., *Wingham et al.*, 2006; *Fricker et al.*, 2007; *Smith et al.*, 2009].

The water depths of subglacial lakes are best measured using seismics, as unlike radio waves, sound can travel well in water. Only a few subglacial lakes have been the subject of seismic surveys (Lake Vostok, South Pole Lake, and Lake Ellsworth). For the latter two cases, seismics have proved beyond doubt the existence of the subglacial lake, as radar data alone was insufficient for some scientists to accept lake detection [e.g., *Price et al.*, 2002].

Water depths can also be modeled using gravity data, although this has been applied only to Lake Vostok and Lake Concordia at present, revealing the former to comprise two distinct basins. As seismic exploration takes considerable time to undertake (Lake Ellsworth, which is only 10-km long, needed a whole season for five lines), gravity data acquired from aircraft provides an efficient means by which the depths of larger lakes can be estimated prior to seismic analysis.

The number of known subglacial lakes has risen from 17 in 1973, to 77 in 1996 and 145 in 2006. The new total, as of January 2010, now stands at 387. Subglacial lakes are widespread beneath the east and west Antarctic ice sheets. Many have been shown to be "active" (i.e., discharging and/or receiving water). Such water flows beneath the ice sheet in an organized hydrological system that connects distinct groups of lakes. Lakes will not be "interconnected," as the flow of water is likely to be one directional. However, there will be a hierarchy of lakes, from source feeder lakes to downstream receiver lakes.

As the basal hydrology in Antarctica is now known to be far more active than had been considered even 5 years ago, the question now is whether the observed movement of water can affect ice flow. *Stearns et al.* [2008] showed that subglacial discharges have indeed affected the flow of Byrd Glacier, albeit for a relatively short time. As a consequence, subglacial lakes at the heads of major ice streams may well have an influence on the flow downstream and may be influential in ice stream changes (e.g., those changes identified in the Siple Coast).

While one can classify subglacial lakes into various categories depending on their size, location, overriding ice thickness, etc, the prevailing view at present is of a common hydrology involving a well-defined hydrological network fed by melting ice and periodic discharges of lake water.

Even beneath the coldest most stable ice sheet of the Cenozoic Era, basal hydrology and subglacial lakes will have represented dynamic physical systems. This has almost certainly always been the case. Our understanding of past, present, and future ice sheet changes requires an awareness of basal hydrology, especially as one considers that the next 10 years may well see the number of subglacial lakes, and their associated dynamics and effects on modern flow processes increase considerably.

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