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Cross-references

South America, Lakes Review

ANTARCTIC LAKES

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Antarctica

The Antarctic continent, including its ice shelves, has an area of 13.8 million km², about half the size of North America and 1.3 times the size of Europe. It is also the highest, windiest, coldest, and driest of the continents. Almost the entire land surface of Antarctica is covered by a vast ice cap, with an area more than six times larger than its counterpart in Greenland. In places, the ice cap is 4 km thick. Here, summer temperatures rarely get above –20°C and monthly means fall below –60°C in winter. Vostok station, at 78°South holds the record for the lowest ever temperature recorded at the surface of the Earth (–89.5°C). On the coasts of Antarctica temperatures are generally close to freezing in the summer months (December–February), or even slightly positive, particularly in the northern part of the Antarctic Peninsula. During winter, monthly mean temperatures at coastal stations are generally between –10°C and –30°C, but may briefly rise toward freezing when winter storms bring warm air toward the Antarctic coast. With average precipitation (as snow) amounting to only 100–150 mm of water equivalent a year the area is technically a desert, although

the ice cap contains almost 70% of the world's freshwater and 90% of the world's ice. The surrounding ocean freezes in winter to cover an area 1.5 times the size of the continent.

Only 0.32% of the Antarctic continent is ice-free. This mainly consists of mountain peaks (nunataks) protruding from the polar ice cap. However, 1–2% of this includes coastal oases that have been exposed, both through postglacial retreat of the ice cap and isostatic rebound of the Earth's crust following the most recent deglaciation. The largest oasis is situated near the coast of the Ross Sea and is known as the McMurdo Dry Valleys. Other large oases are found in eastern Antarctica including the Vestfold Hills, Larsemann Hills, Bunger Hills, Schirmacher Oasis, Syowa Oasis, and on the Antarctic Peninsula at Ablation Point on the east coast of Alexander Island. There are also numerous islands surrounding the Antarctic continent south of 60°S. Most lie close offshore but a few form discrete archipelagos 100–500 km from the mainland (e.g., South Shetland Islands and South Orkney Islands), some are active volcanoes (e.g., Deception Island, Ross Island, and the South Sandwich Islands) while others are isolated, far out in the Southern Ocean (e.g., Macquarie Island, Heard Island, and Amsterdam Island). Collectively the ice-free coastal oases of the continent and the ice-free ground on the islands support much of the well-known fauna of seals, penguins, and marine birds, as well as a variety of macro flora including higher plants, mosses and lichens.

Antarctic lake types

Given the limited area of ice-free ground, it is perhaps surprising that the Antarctic continent and subantarctic islands (loosely defined as those areas south of 60°S latitude) are home to one of the most diverse and interesting lake districts on Earth. Indeed, even though the Antarctic is the repository of more than 70% of the world's freshwater, less of it is available in liquid form than on any other continent. Nevertheless, water bodies that contain liquid water for at least part of the year are a common feature of the Antarctic landscape. This is because water accumulates in areas where solar radiation and advected heat promote melting. This process is self-perpetuating since, as bare ground is exposed, its albedo drops and more radiation is absorbed. As a result, liquid water is not uncommon on ice-free ground. However, liquid water also occurs on and beneath the glaciers and ice sheet. Wherever this water accumulates lakes and ponds are formed. Below we describe some of the different lake types found in Antarctica.

Lakes in ice-free areas

Among the most intensively studied Antarctic lakes are those that occur in the ice-free oases on the edge of the continent such as the Vestfold Hills, Larsemann Hills, and McMurdo Dry Valleys, and those on the maritime and subantarctic islands such as Signy Island and King

George Island. These range in size from small ponds to lakes of $>10 \text{ km}^2$, in depth from few mm to over 300 m, and in age from a single summer to several full glacial cycles. Those that contain liquid water throughout the year, with either seasonal or perennial ice insulating the water against heat loss and complete freezing, are generally referred to as lakes while those that freeze to the base during winter (typically $<2 \text{ m}$ deep) are referred to as ponds. Most of these lakes postdate the Last Glacial Maximum, between 25,000 and 18,000 years ago, when the ice sheet expanded over many of the coastal oases and across the continental shelf. As this ice receded it exposed depressions in the landscape, formed either from glacial erosion or the deposition of terminal moraines, or as a result of folds and depressions in the underlying geology. These depressions filled with water, the lakes were colonized by a range of organisms, and began to accumulate the sediments that today reveal their history. In some rare areas lakes survived intact through the Last Glacial Maximum, for example, the Larsemann Hills, Schirmacher Oasis, and Bunger Hills; and in the McMurdo Dry Valleys, lakes have occupied some of the valley floors in different configurations for over 300,000 years, their depth and area being determined by the spatial extent and thickness of bounding ice sheets and glaciers. Lakes on the subantarctic and peri-antarctic islands are often of Holocene age, formed during the retreat of local ice masses and cirque glaciers. Some of the islands further north such as Macquarie Island may have escaped extensive glaciation and are likely to contain older lakes.

Many of the lakes at lower altitudes in ice-free areas are below the Holocene marine limit ($<40 \text{ m}$ in the Antarctic Peninsula, $<8 \text{ m}$ in the Larsemann Hills) and have formed in depressions emerging from the sea as a result of postglacial isostatic rebound (Figure 1a). Conversely, those at higher altitudes and above the Holocene marine limit have had no prior hydrological contact with the ocean. Where the lakes have no surface outflow they are referred to as closed (or endorheic) lakes. Some of these closed lakes have subsequently experienced an excess of evaporation over precipitation and have gradually become saline. Examples of these are found in the Rauer Islands (Figure 1b), Vestfold Hills, Windmill Islands, and McMurdo Dry Valleys. Some saline lakes become stratified for part of the year (monomictic) and others are permanently stratified (meromictic), retaining a trapped layer of salt water below their fresh surface waters. Lakes that have outflow streams are classified as open lakes; these are typically freshwater and do not accumulate salts to the same degree. Both types of lake are common in Antarctic oases such as the Larsemann Hills, Vestfold Hills, Schirmacher Oasis, Bunger Hills, and on the Antarctic Peninsula (Figure 1c) and maritime antarctic islands.

Epishelf lakes are formed in marine embayments or fjords, dammed by advancing glaciers and ice shelves and have been described in the Bunger Hills, Schirmacher

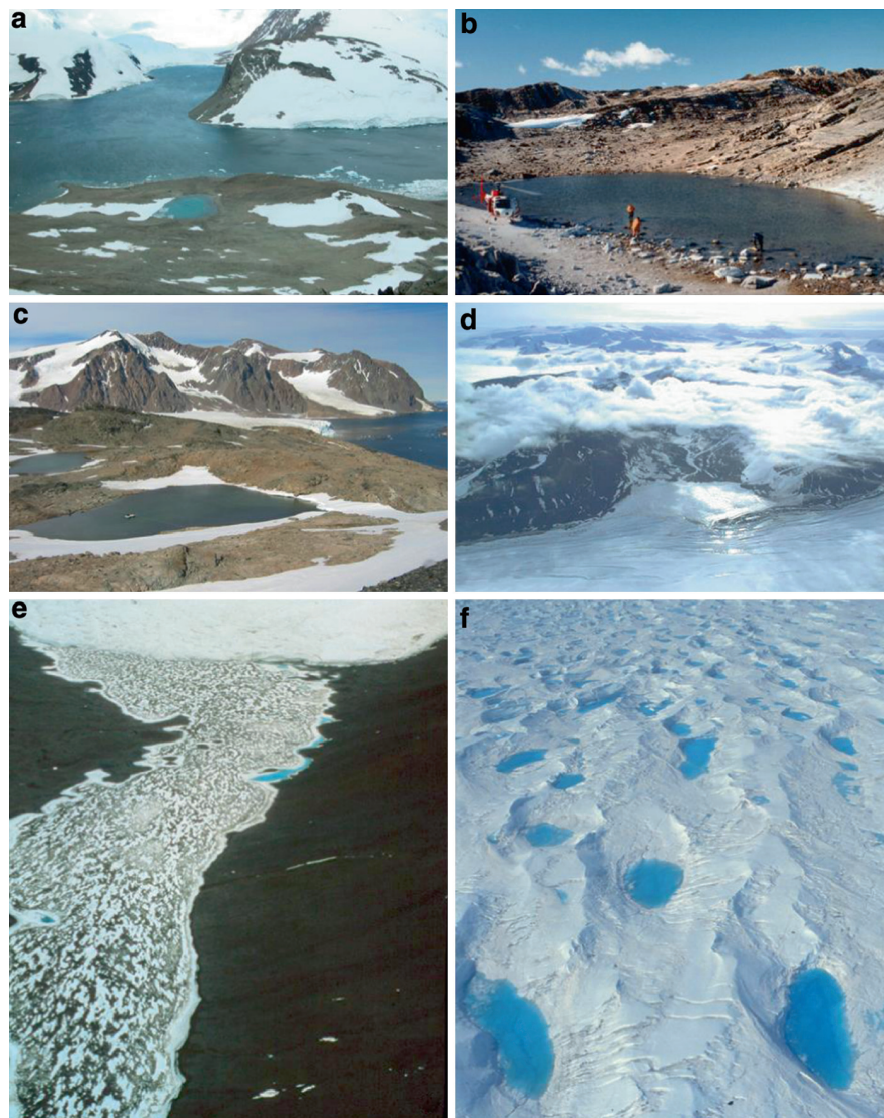
Oasis, Amery Oasis, and Antarctic Peninsula. In these lakes the marine water is replaced over a period of time by fresh melt water from glaciers and snow. In some cases the bounding ice forms an incomplete seal and a hydraulic connection to the sea persists under the ice shelf or glacier, sometimes more than 100 m below sea level. When this happens the epishelf lake becomes stratified with freshwater overlying a layer of dense saline water. Where the seawater flows freely under the ice shelf or glacier a tidal regime can be maintained, which is revealed at the surface by, often characteristic, tide cracks that appear in the ice around the edges of the lakes. Two examples of tidal epishelf lakes are found on the coast of Alexander Island (Moutonnée Lake (Figure 1d) and Ablation Lake). Other epishelf lakes are currently isolated from the sea, formed during earlier periods of relative sea-level rise, lifting grounded ice masses and allowing sea water to penetrate into the lower part of the water column, or connected to marine waters only during periods of reduced freshwater input.

Lakes beside, on, and under the ice

Liquid water is also found against glacier fronts or beside ice shelves, in depressions on glaciers, ice sheets, and ice shelves, and beneath the Antarctic ice sheet. These are called epiglacial, supraglacial, and subglacial lakes, respectively.

Epiglacial lakes are usually formed in depressions at the boundary between areas of rock and ice and are often perennially ice-covered. They are found around the edges of Antarctic nunataks, at the snouts of glaciers, and along the grounded edges of glaciers and ice shelves. They are among the most common lake types in Antarctica and can be found deep in the interior of the continent to within a few hundred kilometers of the pole. Along the Antarctic Peninsula and on the subantarctic islands the lakes are often ice-free in summer with snowmelt from the rock catchment, and meltwater from the bounding ice both contributing to the standing body of liquid water. Although mainly seasonal, epiglacial lakes may persist for several years, often with frequent changes in water level and morphology on account of glacial movements and changing meltwater inputs. Some, such as Lake Untersee in East Antarctica, are older than 500 years. Further south, they can be permanently ice covered with occasional moats forming as a result of advected heat on the landward sides melting the lake ice during warmer summers. This glacial meltwater can also occasionally flood the surface and refreeze restoring the “flat” surface of the lake as seen at Edge Lake in Davis Valley in the Dufek Massif. Some of the largest epiglacial lakes are found at glacier fronts in the McMurdo Dry Valleys (e.g., Lake Fryxell and Lake Hoare, Figure 1e).

Supraglacial lakes are found on the surface of the ice sheet, glaciers, and ice shelves and range from cryoconite holes, less than a meter across, to meltwater lakes that can extend to several square kilometers. They are typically seasonal, forming during the summer melt (Figure 1f).



Antarctic Lakes, Figure 1 Photographs showing selected Antarctic lake types, (a) an isostatically uplifted “isolation basin” lake on Pourquoi-Pas Island, Antarctic Peninsula (in the foreground), (b) a hypersaline closed basin lake in the Rauer Islands, East Antarctica, (c) an open basin freshwater lake on Horseshoe Island, Antarctic Peninsula (d) Moutonnée Lake – an epishelf lake on Alexander Island, formerly a marine basin, now a stratified lake impounded by George VI ice shelf (in the foreground), (e) epiglacial Lake Hoare in the McMurdo Dry Valleys, and (f) ephemeral supraglacial lakes on the Sörsdal Glacier in the Vestfold Hills, East Antarctica, each of these lakes is approx. 250 m wide.

The larger meltwater lakes occupy depressions formed by the stress of moving ice and areas that will later become crevasses. Cryoconite holes are small cylindrical depressions in the ice, likely formed by the presence of wind-blown material including mineral sediments and desiccated microbial mat that provide small concentrations of advected heat sufficient to melt down into the ice. The subsequent growth of microbial mats in these depressions can often serve to enhance this process and so a more-or less self-maintaining ecosystem is formed containing liquid water and supporting a surprising diversity of

biological communities. It is not surprising, therefore, that they have been proposed as one of the main refugia for the eukaryotic biota in the controversial Snowball Earth hypothesis, when the Earth underwent extreme freeze-drying events between 750 million and 580 Ma ago. Kettle ponds can also form in depressions on ice-cored moraines where the rock promotes the melting of ice through reduced albedo and advected heat. Many of these contain diverse and productive biological communities, the most well-known examples being found on the surface of the McMurdo Ice Shelf at Bratina Island.

Subglacial lakes, rivers and wetlands, deep beneath the Antarctic ice cap were revealed by airborne radio echo sounding in the 1970s. These lakes, which lie up to 4,200 m under the Antarctic ice sheet, range in size from 1 km to 241 km long. The largest and deepest of these is Lake Vostok. This lake covers an area of 14,000 km² (about the same size as Lake Ontario, Canada), has a mean depth of 150 m, and a water residence time estimated to be around 50,000 years. Others are found in the Dome C and Ridge B regions of eastern Antarctica (Siebert et al., 2001). To date the subglacial lakes in Antarctica have remained unexplored except using remote technology. The intriguing question is what these subglacial lakes are likely to contain biologically, and what their accumulated sediments might reveal about the history of the ice sheet. In terms of life, the evidence to date suggests that scientists might discover communities of micro-organisms, as the ice core extracted from above Lake Vostok has revealed a diversity of yeasts, Actinomycetes, algae, and spore-forming bacteria. Some of these organisms have remained viable in the ice for 36,000 years. Since the ice above Lake Vostok is over 500,000 years old, there is speculation that the lake will contain microbial genomes which have been isolated from the rest of the biological world for that period. The prospect of analyzing these subglacial communities, their genetics and physiology might open up a wide variety of questions concerning Antarctic biogeography and microbial evolution (Doran et al., 2004).

Physical, chemical, and biological features of the lakes

Physically, the lakes experience low temperatures (<10°C) and have varying degrees of ice cover usually between 1.5 and 6 m thick during winter. Some ice cover is permanent (perennial) while in other lakes increased summer temperatures can cause the ice to melt completely, or peripherally forming moats. The ice forms a thermal barrier that prevents most lakes from freezing to the bottom. Nevertheless, a minority of shallow lakes are not sufficiently protected from the wind and can freeze to the bottom such as Lake Ferris in the Larsemann Hills, or freeze to within a few centimeters of the bottom where the ice overlies a thin layer of hypersaline brine such as Lake Vida in the McMurdo Dry Valleys and Forlidas Pond in the Dufek Massif. These are known as dry-based lakes. Other lakes are ice-free or nearly ice-free all year round on account of hypersalinity, examples being Deep Lake in the Vestfold Hills, Don Juan Pond in the McMurdo Dry Valleys, and some lakes in the Rauer Islands. Ice and snow cover results in low levels of annual photosynthetically available radiation in the lakes. However, when the ice melts in summer, the high transparency of the water column can transmit so much light that it has an inhibiting effect on photosynthesis.

Chemically, the lakes range from some of the freshest lakes in the world to hypersaline lakes with concentrations of salt exceeding eight times that of seawater, preventing

them from freezing over, even during winter when their water column temperatures can drop below –10°C. Many saline lakes exhibit seasonal or permanent stratification of their water columns due to temperature and salinity gradients. Epishelf lakes such as Kakapon Bay in the Bunger Hills can exhibit full marine conditions together with a marine flora and fauna including seal populations. Others, like Moutonnée Lake on Alexander Island, have marine water restricted to the lower parts of the water column. Depending on the degree of chemical influence from the sea, versus interior climate regimes, lakes are often classified as “coastal maritime” or “coastal continental.” The nutrient status of Antarctic lakes is typically oligotrophic, with eutrophy usually restricted to those which are directly influenced by visiting marine mammals, birds, or people.

Biologically the lakes contain few zooplankton and no fish. Mosses are the highest forms of aquatic plant life on the continent, while higher plants and some emergent vegetation are present in lakes on the peri-antarctic and sub-Antarctic islands (e.g., South Georgia). Phytoplankton and bacterioplankton populations are present in most lakes and experience large seasonal variations in their populations, often related to the light climate. However, the bulk of the biomass and primary productivity is benthic, consisting of cyanobacteria, diatoms, and green algae, often in luxuriant mats several meters thick (Vincent, 2000; Ellis-Evans, 1996). The mats can be grazed by communities of rotifers, ciliates, and crustacea, though usually these zooplankton are present at low densities. Benthic microbial mats are less common in the saline lakes, but even the most saline ones contain some biota. Other biological habitats include pockets within the lake ice, the under surface of the lake ice, and the micro stratified chemoclines of meromictic lakes where gradients of conductivity, oxygen, pH, and sulfur provide numerous niches for photosynthetic sulfur bacteria, other anoxic bacteria, and methanogenic Archaea.

The biological communities of Antarctic lakes utilize truncated food chains characterized by the microbial loop (Laybourn-Parry, 1997) in which heterotrophic and phototrophic bacteria and small eukaryotic phytoplankton are consumed by heterotrophic nanoflagellates (HNAN), which are themselves consumed by larger protozoa and then metazoa, linking the energy lost as dissolved organic matter (DOM) back (loop) to zooplankton and other consumers of net plankton. DOM can enter the pelagic environment from a variety of sources: excretion of dissolved organic carbon (DOC) by algal cells, algal cell lysis by inefficient grazing by mesozooplankton, or diffusion from fecal pellets. The food web is therefore driven by recycled carbon.

Despite a biological composition that is primarily microbial, what the Antarctic lake biota lacks in size, is more than makes up for in biomass and species diversity; both considerably greater than that found in adjacent Antarctic terrestrial environments (Vincent, 2000). In fact, with many higher organisms unable to survive there, the

Antarctic continent could be seen as a microbial world with the lakes being its principal bastion. A recent study of the species composition of benthic microbial mats from selected lakes in the Larsemann Hills, Vestfold Hills, and McMurdo Dry Valleys found 1500 strains of bacteria (in a subset of 9 lakes), 60 strains of cyanobacteria (24 lakes), 230 strains of fungi (17 lakes), 91 strains of algae (3 lakes), and 50 protozoans (6 lakes). These were identified using combinations of morphology, phenotypic, chemotaxonomic, and molecular taxonomy. For bacteria, 320 clones were obtained from a single mat sample that would fit into a teaspoon! Technological advances have enabled scientists to study species compositions ranging from aerobes to anaerobes, from primary producers to degraders and brought a new level of detail to understanding of Antarctic lake food-web ecology.

The origin of the biota in Antarctic lakes

With this remarkable diversity of life present in Antarctic lakes, there has been an ongoing debate on its origins (see Gibson et al., 2006 for an authoritative account). The key question is whether the biota are primarily postglacial colonists, arriving through dispersal from sub-Antarctic islands and more northerly continents (e.g., South America) that had remained ice-free, or whether they are vicariant, surviving glacial advances in lacustrine refuges, and then recolonizing newly deglaciated areas. The latter model allows for a greater degree of endemism and the possibility that Antarctic lakes could contain species that are relicts of Gondwana.

Recent field data has provided the first hard evidence of zooplankton that have survived an entire glacial cycle. Thus, it is likely that non-glaciated lakes, epiglacial lakes, and cryoconite holes, for example, have provided refugia for many of the species found in Antarctic lakes, during past glacial cycles. There is also evidence of species that have become extinct in particular environments during glaciation and species that have dispersed to the Antarctic in the present interglacial from the maritime and sub-Antarctic islands and from the other higher latitude continents of the southern hemisphere (South America, Australasia). The different groups that comprise the vicariant species and the colonizers are usually differentiated by their life history, in particular the presence or absence of a life history stage capable of dispersal across the formidable barriers of the polar frontal zone and the circumpolar winds of the Southern Ocean.

Antarctic paleolimnology

Many Antarctic lakes accumulate sediment deposits that incorporate the products of glacial erosion together with biological and chemical fossils. These inorganic, biological, and chemical deposits respond rapidly to changes in temperature, precipitation, evaporation, light environment, ice cover, and glacial extent. Thus, lake sediments

can document both the lake's development and changes in the surrounding environment and have proved invaluable not only in determining the lakes' histories but also in addressing some major questions in Earth system science (Hodgson et al. 2004). For example, the onset of sedimentation in lake basins has provided data on the extent and timing of glaciation and deglaciation and environmental change. Lakes situated below the Holocene marine limit that have been isolated from the sea contain a record of the isolation event and this can be dated using radiocarbon technologies. From this it is possible to construct a history of marine transgressions and hence the relationship between relative sea-level change, ice thickness, global eustatic sea-level change, and isostatic rebound. Such data are enabling ice sheet modelers to accurately reconstruct the past, and better predict the future, contribution of Antarctic ice to global sea-level change. This is a pressing task as predicted increases in global temperature over the coming decades threaten the stability of some parts of the Antarctic ice sheet which, in total, has sufficient ice to raise global sea levels by as much as 70 m. Although this volume is highly unlikely to melt, evidence from the last interglacial, which was only very slightly warmer than our own (1–2°C), shows that global sea levels were 5 m higher than they are today and it is likely that high latitude ice reservoirs provided the source.

Epishelf lakes are also yielding valuable paleolimnological information on the ice shelves and glaciers that impound them. For example, sediments from Moutonnée Lake on Alexander Island have revealed that the currently extant George VI Ice Shelf broke up in the early Holocene, following a period of atmospheric warmth and at the same time as an intrusion of warm water under the shelf. The history of ice shelves is important as ice shelves help restrain the glaciers that flow into them, on account of being pinned to submerged rises in the ocean floor. Without the restraining ice shelves it is proposed that the inland ice of Antarctica could flow at an accelerated rate into the ocean and thereby increase the Antarctic contribution to global sea-level rise.

Paleolimnological studies have also tracked changes in lake salinity from which the atmospheric moisture budget can be inferred and compared with the evidence from Antarctic ice cores. Other studies have tracked the origin and development of the lake biota and, from this, made inferences about the nature and direction of environmental change.

Despite clear signs of marked recent environmental changes in the Antarctic we, as yet, have only a limited perspective on how Antarctic climates and environmental conditions have varied in the past. As long-term monitoring programs in high-latitude regions have only been established for the past several decades, paleolimnological methods will continue to have a role in developing our understanding past environmental changes and helping us to anticipate the magnitude, nature, and direction of future change.

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ANTARCTIC SUBGLACIAL LAKE ELLSWORTH

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Introduction

Subglacial Lake Ellsworth is located near the Ellsworth Mountains in West Antarctica at 78.9°S 90.6°W. The lake basin is in the center of the West Antarctic Ice Sheet (WAIS) in the Pine Island Glacier drainage basin, 20 km from the ice divide with the Institute Ice Stream. The lake is believed to be approximately 10 km long and over 3 km across at its widest point. The gradient of the bed surrounding Lake Ellsworth is at least twice as great as the lake surface, which implies that the depth of the lake could be of the order of tens if not hundreds of meters (Siebert et al., 2004). The ice overlying the lake is between 3.2 and 3.4 km thick, suggesting that the lake surface

is over 1 km beneath present sea level. Lake Ellsworth is located within a distinct topographic hollow, which is ~1.5 km deeper than the surrounding bed. The basin is fjord like in its topographic setting, and is one of a series of fjord-like over-deepenings on the western flank of the Ellsworth Subglacial Highlands.

This summary of Lake Ellsworth will first document the series of radio-echo sounding (RES) transects from which the lake has been identified. Basal thermal regime and ice flow conditions which are believed to control the lake will then be described. The final section will describe future plans for the exploration of Lake Ellsworth (Lake Ellsworth Consortium, 2007).

Radio-echo sounding data

Subglacial lakes can be identified on RES records (see entry for “Antarctic Subglacial Lakes”). Two independent airborne and one ground-based RES campaigns have identified Lake Ellsworth:

1. The first knowledge of Lake Ellsworth is reported in Siebert et al. (2004), and is restricted to one RES line, acquired in 1977–1978 (Figure 1). Later RES profiles (described below) suggest that the sounding line is near parallel to the lake’s long axis, and is also near parallel to ice flow over the lake. This fortuitous occurrence is ideal for modeling the lake environments. The mean gradient of the lake surface reflector is 0.02, about ~11 times the ice surface slope, suggesting the lake is in hydrostatic equilibrium with the overriding ice. The slope of the ice base across Lake Ellsworth is not entirely constant; being concave over the lake’s upstream side and convex across its downstream side. In other words, the ice sheet “sags” as it flows onto the lake, and buckles against the sidewall as it regrounds. The same features have been identified over Lake Vostok and are an expected characteristic of deep-water subglacial lakes. In the cases of both lakes, the strength of the reflections from the ice–water interface varies near the shores, as a consequence of the reflector’s shape (Siebert et al., 2004).
2. In austral summer 2004–2005, the British Antarctic Survey flew a sounding line across Lake Ellsworth in the form of a bow, crossing the lake twice (Figure 1). Part of a 35,000 km grid pattern being collected over Pine Island Glacier also crossed the lake and identified other lake-like reflectors in the surrounding area. These lines were collected using 150 MHz ice-sounding radar (PASIN) (Vaughan et al., 2006). The new PASIN lines confirm the bright specular nature of the reflector and show a much shorter reflector than the 1977–1978 survey, of between 1.5 and 2.3 km in length. This suggests that the lake is long relative to its cross-profile, occupying a fjord-like basin on the flanks of the Ellsworth Subglacial Highlands.
3. In January 2006, a ground-based Chilean expedition traversed the Institute Ice Stream to Lake Ellsworth and acquired several RES transects over the lake.

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